THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

January 1981

Met.O. 942 No. 1302 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1302, January 1981, Vol. 110

551.573:551.584.43

The duration of leaf wetness

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Summary

The rate of evaporation of rain or dew from plant canopies has been investigated with the help of a multi-layer micrometeorological model of crops. The results demonstrate the much smaller rates of evaporation of surface moisture from foliage near the soil surface compared to those from upper parts of dense canopies. The hypothesis that leaves remain wet while the screen relative humidity remains above 90% (used in the Meteorological Office operational plant disease warning scheme) is shown to be reasonably accurate only when applied to evaporation of dew, or of rain from very sparse canopies.

1. Introduction

Fungal diseases such as potato blight, apple scab, *Septoria* (in wheat) and *Rhynchosporium* (in barley) can cause severe loss of yield or quality in crops if unchecked by chemical sprays. These sprays are expensive to apply and may be used wastefully if employed on a purely routine basis without regard to either the current level of infection in the crop, or the suitability of recent weather for the spread of infection.

Most fungal diseases require a period of leaf wetness in order to complete a cycle of infection ending in the production of further infective spores. However, the duration of surface wetness is not measured routinely at more than a few research stations or commercial holdings in the British Isles. Hence the operational schemes run daily by the Meteorological Office to estimate, from synoptic observations, the likelihood of fungal diseases developing (Adams and Seager 1977) incorporate the hypothesis that plants remain wet after rain or dew while the relative humidity at screen height remains above 90%. An experimental study reported by Smith (1962) compared duration of surface wetness in an orchard, measured by a wetness recorder (Hirst 1957), with relative humidities at a nearby synoptic station. The experiment confirmed that the duration of surface wetness was close to the period given by the 90% humidity criterion. However, this orchard formed a sparser and much better-ventilated canopy than many crops, and it is unlikely that intercepted rain or dew would have evaporated in much the same way from dense crops such as potatoes or the cereals. This was confirmed in a qualitative sense by Hirst (1957) in an experiment in which a wetness recorder in a potato crop showed longer periods of surface wetness than those given by a dew balance with its sensing surface placed just above the crop. It accords also with everyday experience: inspection of, for example, long grass after a night of heavy dew shows that the surfaces of the upper leaves will dry completely while surfaces deeper in the sward remain wet.

It is useful to have a available a quantitative method of estimating the relative rates of evaporation of surface water from different crops, at different heights within these crops, in order to assess the utility of the 90 per cent humidity criterion. An extended series of field observations would eventually provide such information, but the problem may be tackled theoretically, and with greater flexibility, by modelling the processes controlling the rate of evaporation of water from the leaves. The remainder of this paper describes the application of a multi-layer model of crop canopies to the problem.

2. Modelling the micrometeorology of crop canopies

The concepts of a suitable model are described conveniently by first considering the crop canopy as a single layer. The energy balance of the crop is then given by

$$H + \lambda E = R_N(0) - G \quad \ldots \quad (1)$$

where H and E are the upward flux densities of heat and water vapour from the crop, $R_N(0)$ is the downward net radiation at the crop surface, G is the flux of heat into the ground and λ is the latent heat of vaporization. $R_N(0) - G$ is usually called the available energy. Monteith (1965), extending the treatment of Penman (1948), showed that the partitioning of the available energy into sensible and latent heat fluxes could be calculated from meteorological measurements made some distance above the crop provided the physiological control by the plants of water losses from their leaf tissues was properly described. His results are formalized by the Penman-Monteith equation

$$\lambda E = \frac{\Delta(R_N(0) - G) + \rho c_p \delta q / r_a}{\Delta + c_p(1 + r_s/R_a)/\lambda} \quad \ldots \quad (2)$$

where Δ = $\partial q_s/\partial T$
q_s = saturated specific humidity
δq = specific humidity deficit (saturation specific humidity in screen minus screen specific humidity)
T = air temperature
ρ = air density
c_p = specific heat capacity of air at constant pressure
r_a = resistance to transfer of heat and water vapour from bulk swath up to screen height
r_s = bulk crop resistance (bulk resistance to transfer of water vapour from within the leaves to the leaf surface via the leaf stomata: r_s and r_a are similar in size ($\approx$ 30 s m^{-1}) for a dense crop with its stomata fully open when screen-level winds are about 3 m s^{-1}).

When the foliage is wet there is no plant physiological control of water loss from the canopy; heat and water vapour fluxes follow similar resistance pathways to the free atmosphere above the canopy, and the bulk crop resistance is then zero. Equation (2) then provides a very simple method of calculating total evaporation from the crop but of course can give no indication of the differing rates of evaporation at different heights in the canopy. However, by dividing the crop into a number of horizontal layers and applying to each the principles used in deriving equations (1) and (2), it is possible to obtain a set of equations which when solved give the rates of loss of heat and water vapour from each layer, and the temperature and specific humidity of the layers (Waggoner and Reifsnyder 1968). The method is shown in outline in Fig. 1. The foliage of the plant canopy is visualized as being concentrated at the mid-levels of $n - 1$ layers, each of thickness $h/(n - 1)$ where h is the height of the canopy. The processes within the canopy are driven by net radiation $R_N(0)$ at the top of the canopy, by wind speed $u(z)$, temperature $T(z)$ and specific humidity $q(z)$ at a height z, and by a heat flux G into the soil: these external variables are assumed to be known. A sensible heat flux H_i leaves the ith layer and encounters first a leaf (laminar) boundary-layer resistance r_i and then a turbulent resistance R_i before reaching the $(i - 1)$th layer of foliage above. The flux is driven by a potential P_i. Similarly the water vapour flux E_i from the ith layer, which is driven by a potential ϵ_i, encounters a layer stomatal resistance r_{si}, boundary layer resistance r_i and turbulent resistance R_i before it reaches the next layer above. Heat storage within each layer, and energy used in photosynthesis are assumed negligible and so the radiation absorbed by a layer is equal to the sum of the sensible and latent heat fluxes leaving it. At the soil surface the sensible heat flux from the soil H_n is controlled by the laminar boundary-layer resistance of the soil surface r_n rather than a leaf boundary layer resistance before entering the turbulent air above. The water vapour flux from the surface is assumed to encounter a surface resistance r_{sn} (akin to a stomatal resistance) before reaching the surface laminar boundary layer above. The heat balance of the ith layer is given by

$$H_i + \lambda E_i = R_N(i - 1) - R_N(i) \qquad \text{(3)}$$

and at the soil surface is

$$H_n + \lambda E_n = R_N(n - 1) - G \qquad \text{(4)}$$

The potential of the ith layer for heat transfer is

$$P_i = \Theta_i \rho c_p \qquad \text{(5)}$$

where Θ_i is the difference in temperature between leaves in the ith layer and the air just above the canopy top. The resistance equations for the differences of potentials between layers are then

$$\left.\begin{aligned} \rho c_p \Theta_1 &= H_1 r_1 + R_1 \sum_{p=1}^{n} H_p \\ &\cdots\cdots\cdots\cdots \\ \rho c_p(\Theta_i - \Theta_{i-1}) &= H_i r_i + R_i \sum_{p=i}^{n} H_p - H_{i-1} r_{i-1} \\ &\cdots\cdots\cdots\cdots \\ \rho c_p(\Theta_n - \Theta_{n-1}) &= H_n r_n + R_n \sum_{p=n}^{n} H_p - H_{n-1} r_{n-1} \end{aligned}\right\} \qquad \text{(6)}$$

By adding the equations successively a more convenient set is obtained:

$$\left.\begin{aligned} \rho c_p \Theta_1 &= H_1 r_1 + R_1 \sum_{p=1}^{n} H_p \\ &\cdots\cdots\cdots\cdots \\ \rho c_p \Theta_i &= H_i r_i + R_1 \sum_{p=1}^{n} H_p + \ldots + R_i \sum_{p=i}^{n} H_p \\ &\cdots\cdots\cdots\cdots \\ \rho c_p \Theta_n &= H_n r_n + R_1 \sum_{p=1}^{n} H_p + \ldots + R_n \sum_{p=n}^{n} H_p \end{aligned}\right\} \qquad \text{(7)}$$

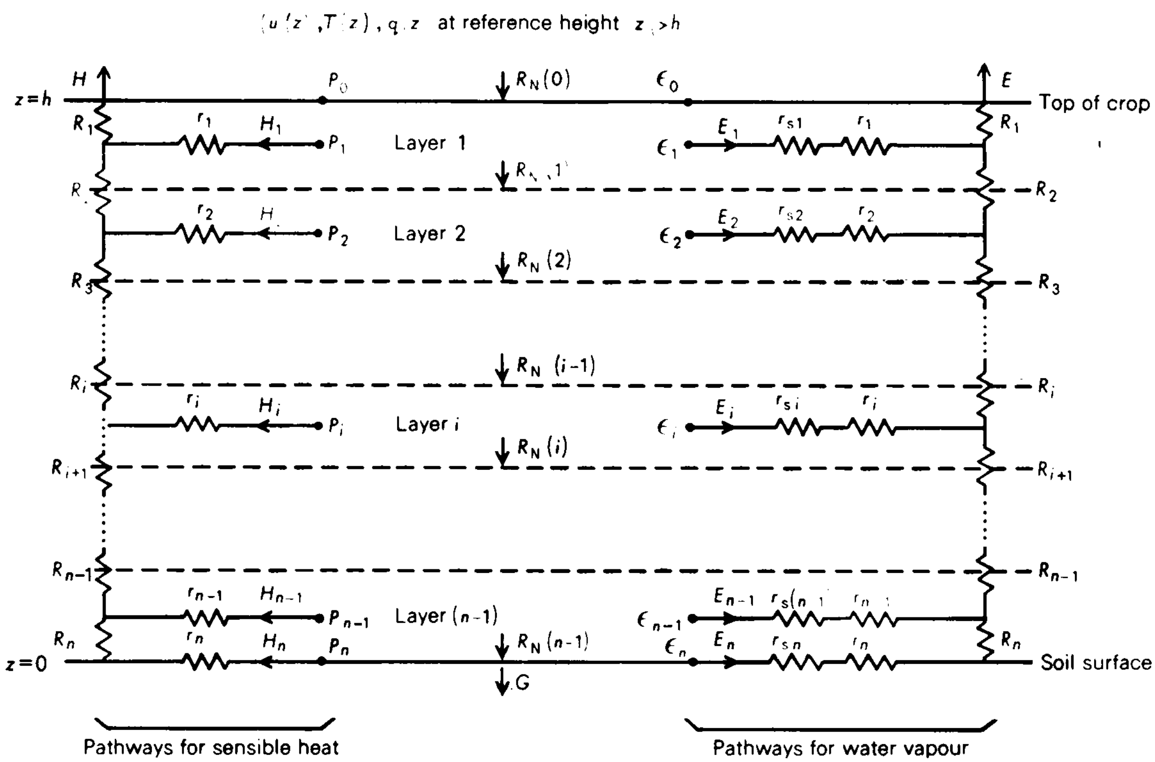

Figure 1. Outline of canopy model.

These equations become after expansion:

$$\left.\begin{aligned}
\rho c_p\Theta_1 &= H_1(r_1 + R_1) + R_1 H_2 + \ldots + R_1 H_n \\
&\ldots\ldots\ldots\ldots \\
\rho c_p\Theta_i &= H_1R_1 + H_2(R_1 + R_2) + \ldots + H_{i-1}(R_1 + \ldots + R_{i-1}) + \\
&\quad + H_i(r_i + \sum_{p=1}^{i} R_p) + H_{i+1}\sum_{p=1}^{i} R_p + \ldots + H_n\sum_{p=1}^{i} R_p \\
&\ldots\ldots\ldots\ldots \\
\rho c_p\Theta_n &= H_1R_1 + \ldots + H_{n-1}(R_1 + \ldots + R_{n-1}) + H_n(r_n + \sum_{p=1}^{n} R_p)
\end{aligned}\right\} \quad \ldots \quad \ldots \quad (8)$$

In the case of water vapour transfer the potential of the ith layer is

$$\epsilon_i = \rho Q_i \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (9)$$

where Q_i is the difference of specific humidity between that in the leaf stomata and that just above the canopy top. The usual assumption is that air in the stomata is saturated so that

$$\left.\begin{aligned}
Q_i &= q_s(T = T_i) - q(h) \\
Q_i &= \Delta\Theta_i + \delta q
\end{aligned}\right\} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (10)$$

where T_i is the foliage temperature in the ith layer.

A set of equations for water vapour transfer may then be derived in the same way as those for heat transfer (equation (8)):

$$\left.\begin{array}{l} \cdots\cdots\cdots\cdots\cdots \\ \rho(\Delta\Theta_i + \delta q) = E_1R_1 + E_2(R_1 + R_2) + \ldots + E_{i-1}(R_1 + \ldots + R_{i-1}) \\ \quad + E_i(r_{Si} + r_i + \sum_{p=1}^{i} R_p) + E_{i+1}\sum_{p=1}^{i} R_p + \ldots + E_n\sum_{p=1}^{i} R_p \\ \cdots\cdots\cdots\cdots\cdots \end{array}\right\} \quad \ldots \quad (11)$$

The set of $3n$ equations given by the general forms (3), (8) and (11) contains $3n$ unknowns (Θ_i, H_i, E_i) and may be readily solved for these when the coefficient values are entered.

Net radiation at the canopy top is given by (Monteith and Szeicz 1961)

$$R_N(0) = ((1 - \alpha)/(1 + \beta))\, SF_1 \sin\theta + L_0F_2 \quad \ldots \quad \ldots \quad \ldots \quad (12)$$

where α = short-wave albedo ($\approx$ 0.25 for green crops)
β = heating coefficient ($\approx$ 0.15 for crops of medium height not under water stress) introduced to allow for enhanced back radiation caused by elevation of crop temperature above screen temperature
θ = solar elevation angle
S = solar constant
F_1 = transmitted fraction of short-wave radiation
F_2 = transmitted fraction of long-wave radiation
L_0 = a long-wave radiation term (-60 W m^{-2} by day, -70 W m^{-2} by night).

Gadd and Keers (1970) give expressions for F_1 and F_2 which include the effects of cloud and have been used in the present case: however, their expression for F_1 was based partly on data of Lumb (1964) from weather ships and has been reduced therefore by 15% to allow for more turbid atmospheres over land. S is obtained from standard relationships (e.g. Hughes *et al.* 1977). Following Denmead (1976) the net radiation within the canopy is assumed to decline with increasing penetration into the canopy, being made proportional to an exponential function of the total foliage area above the measuring point. The distribution of the foliage in the vertical varies widely with the type of plant involved but a convenient approximation for many crops is that the distribution is normal, about a height of $h/2$ or $3h/4$. Values of the coefficients in the set of equations (3) are completed by specifying G which during the day is assumed to be a function of net radiation and total canopy leaf area A (per unit ground area)

$$G = 0.4\, R_N(0)/(1 + 0.2\, A) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (13)$$

and to lie between 0.5 $R_N(0)$ and 0.8 $R_N(0)$ (for dry and wet soils respectively) at night: these values are reasonably consistent with observations by Monteith (1958) and Utaaker (1966).

Values for R and r (equations (8) and (11)) may be estimated provided the vertical profiles of wind speed and eddy diffusion coefficient (K) within the crop canopy are specified. The latter are assumed to show an exponential decrease towards the soil surface

$$U(z)/U(h) = K(z)/K(h) = \exp(-m(1 - z/h)) \quad \ldots \quad \ldots \quad \ldots \quad (14)$$

(Denmead 1976, Uchijima 1976), with m around 2.5. The values at the top of the canopy ($U(h)$,$K(h)$)

may be derived from synoptic observations of wind using flux-profile relations given by Dyer and Hicks (1970) for unstable (daytime) conditions and integrated by Paulson (1970), and by Webb (1970) for stable (night-time) conditions: the relations require prior knowledge of H and E in order to allow for the effects of departure from neutral stability, but these fluxes are not known until the set of $3n$ resistance equations is solved, and so iteration following initial guesses for H and E (based on the assumption of neutral atmospheric stability) is used to obtain a convergent solution. R is the reciprocal of conductance and is obtained from the expression

$$R_i = \int_{z_{i-1}}^{z_i} (1/K(z))\,dz \qquad (15)$$

where z_{i-1} and z_i are the heights of the middle of the $(i-1)$th and ith layers above the soil surface.

Laminar boundary layers over the leaf surfaces introduce a resistance r which has to be overcome before the property being transferred from the leaf can enter the generally turbulent airflow in the plant canopy. It has been shown that in the case of heat transfer the boundary-layer resistance per unit surface area of a flat surface of width l exposed tangentially to an airflow u is

$$r_H \approx 1.2(l/uv)^{\frac{1}{2}} = (1.2/u)(\mathrm{Re})^{\frac{1}{2}} \qquad (16)$$

where v is the kinematic viscosity and Re the Reynolds number (e.g. Monteith 1973). The corresponding resistance r_V for water vapour transfer is about 10% smaller. Monteith (1973) suggests that the resistances for leaves may be somewhat less (by 20–30%) than those given because leaves are rougher than the flat plates for which the above expressions were obtained. It will be assumed therefore that

$$r_H = r_V = r = (0.9/u)(\mathrm{Re})^{\frac{1}{2}} \qquad (17)$$

For cereals the average width of the leaves is assumed to be 0.01 m, leading to the expression

$$r = 23/u^{\frac{1}{2}} \qquad (18)$$

where r is expressed in units (s m^{-1}). The total surface area of leaves in the ith layer is A_i and so the effective boundary layer resistance of the foliage in this layer (the sum of the resistances of the separate leaf surfaces in parallel) is

$$r = 23/A_i u^{\frac{1}{2}} \qquad (19)$$

At the soil surface the boundary resistance r_n is obtained by using equation (17) with l put equal to the typical size of clods of soil (a few centimetres).

The leaf stomata are assumed to be closed at night and the stomatal resistances per unit leaf surface are then very large ($\approx$ 5000 s m^{-1}, Denmead 1976). However, this resistance is short-circuited when the leaves are wet and r_{Si} is then zero. Stomatal opening during the day is a function of the intensity of incident light and of soil moisture deficit but this latter control of r_S will be ignored. The stomata are assumed to be fully open when the incident short-wave radiation R_S is 500 W m^{-2} or greater. The resistance per unit surface area is then about 120 s m^{-1} for barley leaves (Monteith *et al.* 1965) and similar values have been found for wheat, potatoes and grass. The results of Monteith *et al.* for lower light intensities support a relation of the form

$$r_{St} = a(1 + b/R_{St})/A_t \quad \ldots \quad (20)$$

(a and b are constants) which has been used in the present case, with R_S assumed to be attenuated within the crop canopy in the same way as R_N. The surface resistance of the soil r_{Sn} is assumed to be 100 s m^{-1} when the soil is wet (Grant 1975) and very large (10^4 s m^{-1}) when dry. The model does not consider a partially wet surface.

Dewfall is simulated when the calculated flux of water vapour from a model layer is negative and r_S is then put equal to zero for the layer in question. The treatment of rainfall interception is based on results obtained by Couturier and Ripley (1973) for grassland. It is assumed that a layer will intercept about 40% of rain incident on it until half the interception capacity is reached, and then 15% up to maximum interception capacity. Typical values for this last are 0.05–0.10 mm per unit foliage area.

The model is programmed to run with meteorological data interpolated at 10-minute intervals from hourly synoptic observations. The outputs at the end of each 10-minute period include foliage temperature, air temperature and specific humidity in each layer, and heat and water vapour fluxes from the layers. Surface water budgets are constructed from the vapour fluxes and the water contents of the layers at the start of each period. A difficulty arises in the application of the model if the temperature and humidity data obtained at screen level over short grass are assumed to represent conditions at the same height above ground when the underlying vegetation is much taller. Included in the calculations therefore is a conversion of screen data to a reference height of 10 m; it is assumed that conditions at this height will vary insignificantly with variations in the type of vegetation covering the underlying ground, provided $h \leqslant 10$ m (say $0 < h < 1$ m).

3. Some results from the model

(a) *Simulation of evaporation of intercepted water from cereals*

Two periods were selected from June 1978 during each of which hourly data from Honington showed overnight rain followed by weather reasonably favourable to the evaporation of intercepted water from plants. In the first case (16 June) 23 mm fell overnight, ceasing shortly before 0900. On the second occasion (28 June) 2 mm of rain fell in two periods overnight, the second finishing at about 0900. In both cases mature cereal canopies would have intercepted around 1 mm of rain and been close to saturation by the time the rain ceased. Rough estimates of rates of evaporation of intercepted rain made using equation (2) showed that less than 40% of this water would have evaporated in the 2 hours following cessation of rain and yet on both dates the relative humidity at screen height had fallen to less than 90% in this period.

The rain ceased on both occasions following the passage of a cold front and subsequent drying of the crop canopy occurred in an advective situation. This might have accounted for the 90% criteria being rather wide of the mark, especially in the first case when the humidity fell to less than 90% within about 20 minutes of the rain stopping. However, application of the multi-layer model to these examples demonstrated clearly that, following saturation of a crop by rainfall, the lowest layers will remain wet for prolonged periods even when relative humidities above the crop have fallen to less than 70%. The results on which this assertion is based are given in Table I. The simulations were carried out for an 8-layer canopy assumed to be about 0.8 m tall. The leaf area was assumed to be distributed normally about a height of 0.75 h, with a standard deviation of 0.45 h, in order to give a realistic representation of a typical cereal canopy. Total leaf area per unit ground area (hereafter called simply 'leaf area') was about 12 for the earlier case, increasing to 14 by 28 June in order to represent further maturing of the crop. An interception capacity of 0.1 mm per unit leaf area was assumed. On 16 June the lower part of the canopy was calculated to be still wet 5 hours after cessation of rain, and evaporation from the

Table I. *Surface water in each model layer*

(a) *16 June 1978*

Layer mid-height (m)	Relative leaf area in layer	0900	0920	0940	1000	1020	1040	1100	1120	1140	1200	1300	1500
		Surface water (mm)											
0·75	0·9	0·18	0·17	0·15	0·13	0·10	0·06	0·02	0	0	0	0	0
0·65	1·0	0·20	0·19	0·18	0·17	0·15	0·13	0·10	0·07	0·03	0	0	0
0·55	1·0	0·20	0·19	0·19	0·18	0·17	0·16	0·15	0·13	0·11	0·09	0	0
0·45	0·9	0·18	0·18	0·18	0·17	0·17	0·16	0·16	0·15	0·14	0·13	0·09	0
0·35	0·8	0·15	0·15	0·15	0·15	0·15	0·15	0·14	0·14	0·13	0·13	0·11	0·05
0·25	0·6	0·12	0·12	0·12	0·12	0·12	0·12	0·12	0·11	0·11	0·11	0·10	0·07
0·15	0·4	0·09	0·09	0·09	0·09	0·09	0·09	0·09	0·09	0·08	0·08	0·08	0·07
0·05	0·3	0·06	0·06	0·06	0·06	0·06	0·06	0·06	0·06	0·06	0·06	0·05	0·05

(b) *28 June 1978*

Layer mid-height (m)	Relative leaf area in layer	0900	0920	0940	1000	1020	1040	1100	1120	1140	1200
		Surface water (mm)									
0·84	0·9	0·20	0·18	0·15	0·11	0·05	0	0	0	0	0
0·73	1·0	0·22	0·21	0·19	0·16	0·13	0·09	0·04	0	0	0
0·62	1·0	0·22	0·21	0·20	0·19	0·17	0·15	0·12	0·09	0·05	0
0·51	0·9	0·20	0·20	0·19	0·19	0·18	0·17	0·15	0·14	0·12	0·10
0·39	0·8	0·17	0·17	0·17	0·17	0·16	0·15	0·15	0·14	0·13	0·12
0·28	0·6	0·13	0·13	0·13	0·12	0·12	0·12	0·12	0·11	0·11	0·10
0·17	0·4	0·08	0·08	0·08	0·08	0·08	0·08	0·08	0·08	0·08	0·07
0·06	0·3	0·05	0·05	0·05	0·05	0·05	0·05	0·05	0·05	0·05	0·05

lowest two layers in this period was very small. There were substantial amounts of cloud, however, and maximum available energy was estimated to be less than 160 W m^{-2}; clearly evaporation of surface water would have been substantially more rapid had a cloudless day followed the rain. Nevertheless the results give a clear indication of the slow rates of drying of the middle and lower parts of dense canopies compared to foliage at the canopy top. The simulation for 28 June produced fairly similar results. Cloud decreased to small amounts by early afternoon and the rather larger available energies and higher wind speeds led to somewhat faster drying, but the bottom part of the canopy remained wet until after midday.

The assumed interception capacity of 0.1 mm per unit leaf surface area may be rather high for typical cereals and a further simulation was carried out for 16 June using now only half the interception capacity. The top layer was then calculated to dry out by 1020 (1 hour earlier) and the fourth layer by 1220 (nearly 2½ hours earlier). The lowest layers still dried very slowly. Halving the leaf area would also have accelerated the drying out because the interception capacity would have been correspondingly reduced, while most of the radiant energy incident on the canopy would still have been intercepted, leading to available energy only slightly less than before. The evidence is, however, still for the lowest layers of fairly mature cereal canopies (total leaf area greater than say 6) requiring some hours longer to dry than is given by the 90% humidity criterion.

(b) *Interception of rain and dew by grass, and subsequent evaporation*

Some of the results described for cereals may have been biased by the assumption that temperature and humidities measured over grass at Honington would have been representative of observations over the much taller cereal crop after the extrapolation to 10 m in height which the model performs. A more direct test was made therefore, in which the model was run with Honington data for 16 June in a simulation of short grass (0.1 m high). The assumed leaf area of 7 was distributed about the mid-height of the canopy with standard deviation 0.04 m. The assumed interception capacity of 0.1 mm per unit leaf area is probably more realistic than smaller values because grass swards usually contain substantial amounts of senescent leaf material which has a higher interception capacity than living tissue (Couturier and Ripley 1973). The calculated drying out of the grass was at a somewhat faster rate than for the cereals with the same interception per unit leaf area, partly reflecting the smaller total interception of water by the grass, but the uppermost 5 layers still required about 5 hours to lose all their moisture.

These and the earlier results suggest that, following substantial rainfall (several millimetres), the 90% criterion gives no reliable indication of the duration of leaf wetness of a dense canopy, even in the highest layers. However, the situation regarding the duration of leaf wetness following dewfall or very slight rainfall may be substantially different. Detailed studies in potato canopies (Hirst *et al.* 1954) and in wheat (Penman and Long 1960) have demonstrated that when dew forms there is usually water vapour transport downwards above, and upwards (from the soil) within the crop, suggesting that dew may be deposited throughout the crop canopy unless the soil is dry. However, radiational cooling of the canopy at night will be greatest at its upper surface and maximum deposition of dew is expected therefore at the top of the crop. Monteith (1973) suggested that the maximum dewfall in a single night will be around 0.4 mm, and with these values the interception capacity of the upper foliage may be exceeded, with some dripping and wetting of lower leaves. In most cases, though, the deposit will be smaller, with negligible dripping, and in these circumstances a simple criterion of duration of surface wetness such as the 90% humidity criterion might be expected to be more consistently successful than indicated by the preceding calculations for foliage thoroughly wetted by rain.

Smith (1962) in his paper on the 90% humidity criterion included a diagram indicating the variation with time of the amount of water accumulated by a surface wetness recorder on a dew night, and the evaporation of this water the following morning. The recorder was exposed in an orchard towards the end of March when the trees were leafless. There was no indication in the paper of height of exposure of the instrument but the results may be compared qualitatively with a simulation for long grass (assumed to make up the orchard floor). Fig. 2 shows the mass of water accumulated by the surface wetness detector (in arbitrary units) and the corresponding results from the simulation (by summing the calculated surface moisture in all the model layers): meteorological data were from Felixstowe, about 30 km from the orchard. Winds were very light during the night and the three-hourly observations used to interpolate the model inputs reported calms at 00, 03, 06 and 09 GMT. However, the model was unable to treat cases with zero wind speed and so a lowest value of 1 kn was used: the stopping speed of a standard anemometer is probably 2 or 3 kn and a reported calm will often correspond to a light wind below stopping speed. Monteith (1957) showed that genuine dew deposition became small on very calm nights although 'distillation' of water vapour from the soil on to the grass would still have occurred. The model results probably exaggerate slightly therefore the total vapour transfer to the grass by maintaining too high a level of turbulent mixing above the grass-covered surface and hence transfer of vapour downwards. However, the patterns of water accumulation by the wetness recorder and calculated by the model up to the time when evaporation began (around 07 GMT) are clearly very similar. The vertical distribution of surface water calculated by the model during the night showed water accumulating at all levels within the canopy whereas one might expect 'dewfall' chiefly in the upper part. However, the model's treatment of turbulent mixing in the canopy was similar for both day and night-time cases, which is not likely to be realistic. In particular the soil surface is usually warmer than the canopy at night and this encourages enhanced turbulent (convective) mixing; however, in the absence of a simple, realistic method of taking this into account, the limitation has to be accepted.

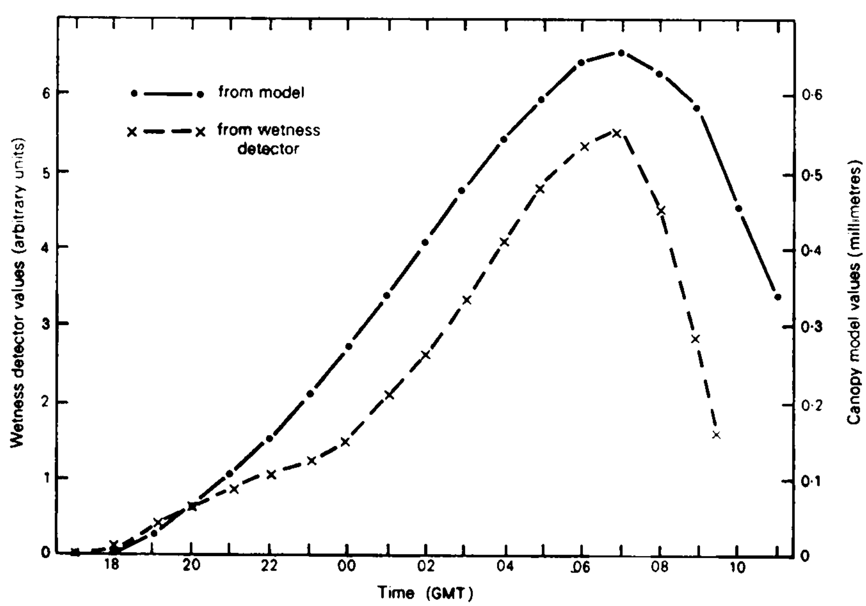

Figure 2. Measured and simulated accumulated surface water, 21–22 March 1957.

Also the method by which the surface temperature is calculated, which relies heavily on the crude estimates of turbulent mixing, leads to unrealistically high surface temperatures on very still nights. This in turn affects the distribution of intercepted water in the canopy, although the total deposit may be comparatively little affected since the upward flux of water vapour from the surface depends largely on the arbitrarily estimated soil heat flux and whether or not the soil surface was wet or dry (it was assumed to be moist in the present calculations because of rain in the period preceding the simulation).

Fig. 2 shows that after 07 GMT the wetness detector dried out much more rapidly than the simulated canopy, indicating the much better drying of a single well-exposed surface compared to a complex canopy.

4. Concluding remarks

It has not been possible to verify these simulations of canopy drying with field data from crops, but the results presented here are in agreement with experience. In particular the performance of a wetness detector exposed *above* a crop-covered surface is unlikely to be representative of the drying of a dense canopy such as is provided by the cereals wheat, barley, oats, etc., gives no indication of the very low rates of drying near the ground surface in canopies, and can at best give only a rough indication of crop drying in sparser canopies such as orchards. The results provide no justification for assuming that the 90% relative humidity criterion will give a satisfactory indication of the duration of leaf wetness in an entire canopy, especially following rainfall of a millimetre or more. Where the 90% criterion is likely to be more successful is in indicating the duration of leaf wetness following rain on very sparse canopies for which the total intercepted water is very small and the ventilation is very good, or alternatively during occasions of light dewfall with a dry soil surface so that 'distillation' is small and the dew is likely to form almost exclusively in the upper part of the canopy.

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Wet working days in the United Kingdom

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Summary
Rainfall statistics for the British Isles are usually expressed in terms of rainfall experienced over 24-hour periods comm:ncing at 0900 GMT. For many outdoor activities values related to the working day are more appropriate. This paper describes a method of estimating the number of wet working days per month from the available 24-hour statistics.

Introduction

Many industrial, commercial and leisure activities are weather sensitive and in recent years requests made to the Meteorological Office for actual and forecast weather information have increased significantly. In the hydrometeorological field the demand for weather records relating to working hours has risen sharply, but often the lack of data on this time-scale has restricted the advice that could be given.

Daytime rainfall is particularly relevant in the construction industry where statistical information is required for planning purposes; actual records are also required to substantiate claims that subsequent delays are due to bad weather. To meet these needs a study has been made of the relationships between working-day and rainfall-day statistics.*

Data source

Measurements of rainfall over the British Isles are reported regularly to the Meteorological Office from some 6500 stations (Meteorological Office 1979). The majority of these stations record 24-hour totals for periods commencing at 0900 GMT, whilst in more remote areas measurements are made less frequently at weekly, monthly or irregular intervals. In addition, some stations make 12-hour measurements at 0900 and 2100 GMT and for a limited number of stations equipped with continuously recording gauges—tilting-siphon rain recorders (TSRs)—hourly returns of both amounts and durations are available.

The 12-hourly, daily, weekly and monthly totals are stored on magnetic tapes and discs in the Meteorological Office rainfall archive at Bracknell, together with hourly returns from selected TSR stations. Tabulated hourly returns on Metforms 3440 from additional TSR stations are also available but are not stored in machinable form.

Data extraction

The study covered the 20-year period from 1957 to 1976, which was selected because it was the longest period for which machinable hourly rainfall records were available and also because it included two periods with relatively high rainfall and the notable 'drought' of 1975–76. Using the computer archive for the hourly stations, frequency counts were made for each station and month in the selected period† of occasions when 1 mm or more of rain (a wet day) occurred in a rainfall day and also in a working day. Ideally, the period 0800–1800 local time was considered most appropriate to the working day but, as this period spans the boundary of a rainfall day, the working day was defined as the period 0900–1800 GMT. At the same time, similar statistics were extracted for a wide range of other rainfall thresholds from nil to 10 mm or more.

To supplement this limited number of stations, a hand analysis of the wet day thresholds in both periods was carried out for additional stations using Metforms 3440 to obtain an enlarged data set of some 60 stations. A further enhancement was made by preparing a separate data set of all stations in the United Kingdom reporting 12-hour rainfall totals (i.e. 0900–2100 GMT and 2100–0900 GMT) and computing the 12-hour and 24-hour wet day frequencies. Fig. 1 shows the locations of all 71 stations for which records were extracted.

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* A rainfall day is defined as a 24-hour period commencing 0900 GMT.

† In cases where a station closed or moved to an adjacent site the counts were used only if 15 years or more of data in the 20-year period were available, or if it was possible to combine records from the old and new site to obtain a continuous 20-year record.

Figure 1. Stations for which rainfall records were extracted.

Analysis of data

Most of the analytical processes were performed on the IBM 360/195 computer at the Meteorological Office Headquarters, Bracknell, using programs specifically written for the task by the Special Investigations Branch (Met O 9), Programming Section, and programs from the University of California BMDP package (University of California 1977a). The analyses were carried out in several stages:

(1) Using a value of 1 mm or more of rain in the periods:

0900–0900 GMT to define a wet rainfall day,
0900–1800 GMT to define a wet working day, and
0900–2100 GMT to define a wet daylight day,

the incidence of each category of wet day for each station in every month in the 20-year period was evaluated and used to determine the mean monthly percentage ratios of the incidence of wet working days to wet rainfall days (R) and of wet daylight days to wet rainfall days (r).

Histograms of the resulting average monthly values of R were prepared and a comparison was made of the inter-station differences through the months of the year. This comparison revealed that over distinct geographical regions there were common features in the profiles of station averages of R month by month through the year. Typical profiles for (a) an inland station and (b) a coastal station are shown in Fig. 2, together with profiles averaged over stations with which those individual stations were considered to be grouped (see (2) below).

(2) The apparent relationships between the monthly profiles of R at different stations, although first classified by eye, were assessed objectively by computer using the University of California program BMDP 2M (University of California 1977b) with the Euclidean distance option chosen for clustering (i.e. classifying the stations into associated groups). Readers interested in the clustering program should refer to Appendix 1 for a synopsis of this analytical technique.

The program, run using the stations with hourly data, successfully identified 17 meteorologically sensible areas (clusters) between which variations in profile could be detected. However, because of the station spacings the boundaries between some of the areas were ill-defined and it was apparent that records from additional stations were required to refine boundaries in areas of sparse data.

(3) To maximize the spatial coverage use was made of the 12-hour wet daylight-day returns from all available stations. Initially the ratio $S = R/r$ was calculated month by month for all available hourly stations and the product of this monthly ratio S from one station and r from an adjacent station was used to calculate R at the adjacent station where R was in fact known. A series of differences between the values of R so calculated (R_c) and the observed values of R (R_o) was evaluated. A cluster analysis based on r was carried out for the enhanced data set and the product of mean monthly values of S (evaluated over various combinations of stations within each cluster so formed) and r from another station within that cluster, where both r and R were known, were used to form R_c and the differences ($R_o - R_c$).

From these experiments it was found that the least scatter of ($R_o - R_c$) was obtained when all the other available stations in the cluster were used to form the mean values of S and that, in general,

$$|R_o - R_c| \leqslant 5\% \text{ of } R_o.$$

Monthly values of R_o varied between about 40% and 65%, so that 5% of R_o would correspond to one wet working day even if every day in a 31-day month were a wet rainfall day (usually, of course, it corresponds to less). Thus, mean monthly values of S could be used as scaling factors to reduce r values from 12-hour stations to produce R values at those stations where R itself was unknown, with an assessed error of less than one wet working day in a month.

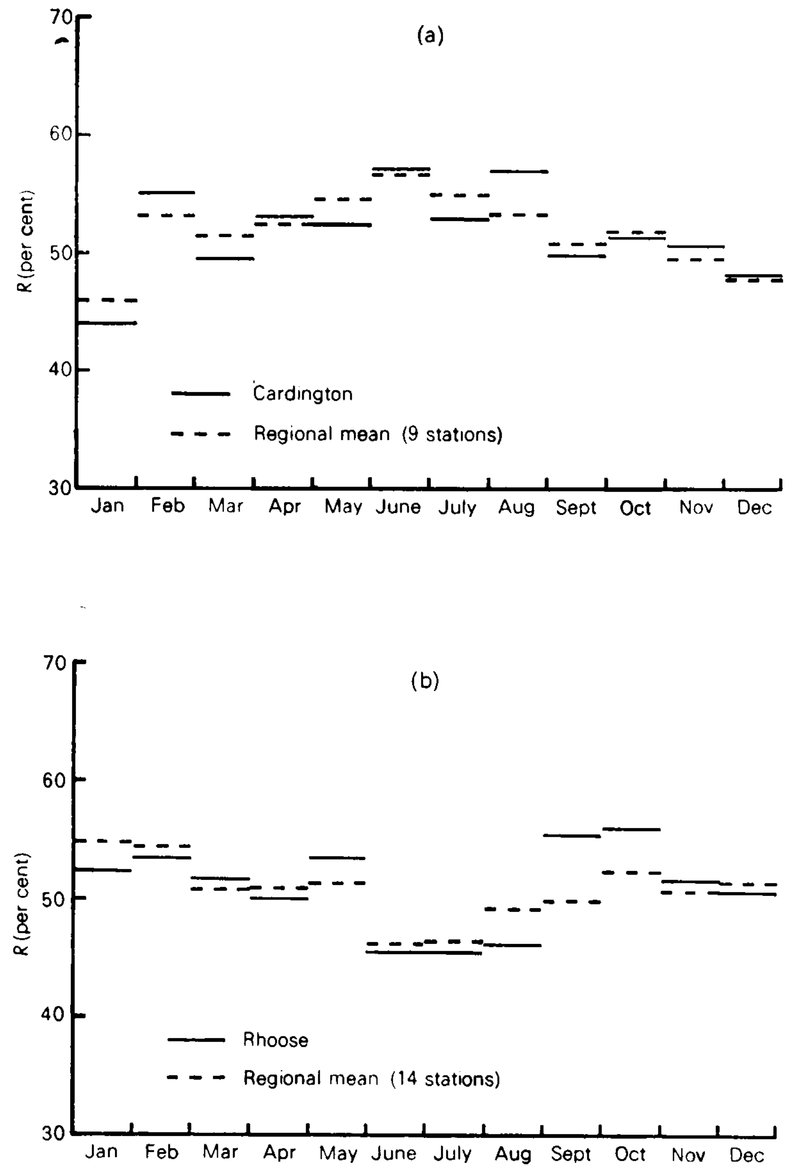

Figure 2. Month-to-month variation of percentage ratio (R) of incidence of wet working days to that of wet rainfall days: (a) inland sites, (b) coaatsl sites.

The clustering process was then repeated using the actual and estimated R values for all 68 stations in the enhanced data set.

(4) With the clustering process complete the boundaries of the various areas were re-examined and adjusted where necessary, depending on the Euclidean distances calculated between stations in adjacent areas. In some parts of the country, notably over hilly regions where no records were available and

where the topographical rainfall characteristics are likely to be different from those at the nearest stations, the lines of demarcation remained subjective. Three additional regions were introduced to cover such areas without data. However, since the object of the investigation was to produce meaningful estimates for areas of high population (and hence maximum building activity) this limitation was not considered too restricting. Fig. 3 shows the final boundaries using the data from all stations.

(5) For each area the mean monthly percentage frequencies of R were computed, together with their standard deviations, and these data are shown in Table I. Mean monthly scaling factors, required to estimate r, are also shown in the Table as such information might provide useful estimates of average wet daylight days for leisure or other activities.

Using records from the 24 stations with hourly data in machinable form, the ratios of wet rainfall-day incidence for 1 mm or more were computed to enable estimates to be made of the average number of days per month on which such events are likely to occur. Table II(a) shows these 'growth factors'. At the same time the incidence of working-day rainfalls for thresholds of 0.1 mm or more, 2 mm or more and 4 mm or more were determined and expressed as percentages of rainfall-day incidence for their associated thresholds. Mean percentages together with standard deviations where available over each area are shown in Table II(b). For some areas no hourly records were available in the computer archive and in such cases recourse was made to the cluster analyses at the 1 mm level to allocate the area to that region having the closest relationship with the area of interest. Areas allocated by this method are indicated in Tables II(a) and II(b) by asterisks.

Application of the technique

At Weather Centres and the inquiry bureaux at Bracknell (Met O 3b and Met O 8c) rainfall statistics relating to the rainfall day are readily available for most of the larger towns and cities. Table I can, therefore, be used directly to estimate mean monthly wet working-day totals.

At other meteorological offices the extent of available rainfall statistics will be more limited. To enable the technique to be used at these offices it was decided to use the rainfall archives to produce wet rainfall-day statistics in map form which could then be used in conjunction with Table I. Some 178 stations were found with a complete 30-year (1941–70) daily rainfall record and the monthly wet rainfall-day totals were retrieved and plotted as percentages of the monthly total of days in the 30-year period. Examples of these monthly maps are shown in Figs. 4 and 5. These maps, together with Tables I, II(a) and II(b), can be used to estimate mean monthly working days with falls equal to or greater than the specified thresholds. Appendix 2 provides an example of the use of the maps and Tables.

Verification of the results

To test the method, hourly rainfall records for two stations, Cardington and Mount Batten, covering the period 1977–78, were retrieved from the archives and working-day and rainfall-day frequency counts determined for each month at each station for thresholds of 0.1 mm or more, 2 mm or more and 4 mm or more.

Estimates of the number of wet working days per month were made (a) using these observed monthly wet rainfall-day totals and the station R factors, (b) using the areal value for R from Table I and these wet rainfall-day totals and (c) using the maps and the areal values as described earlier. The observed monthly wet working-day totals and the corresponding estimated totals obtained by these three methods are shown in Table III(a).

Estimates of the number of days per month when the working-day rainfall reached or exceeded 0.1 mm, 2 mm and 4 mm thresholds were then obtained using the 'growth factors' from Table II(a)

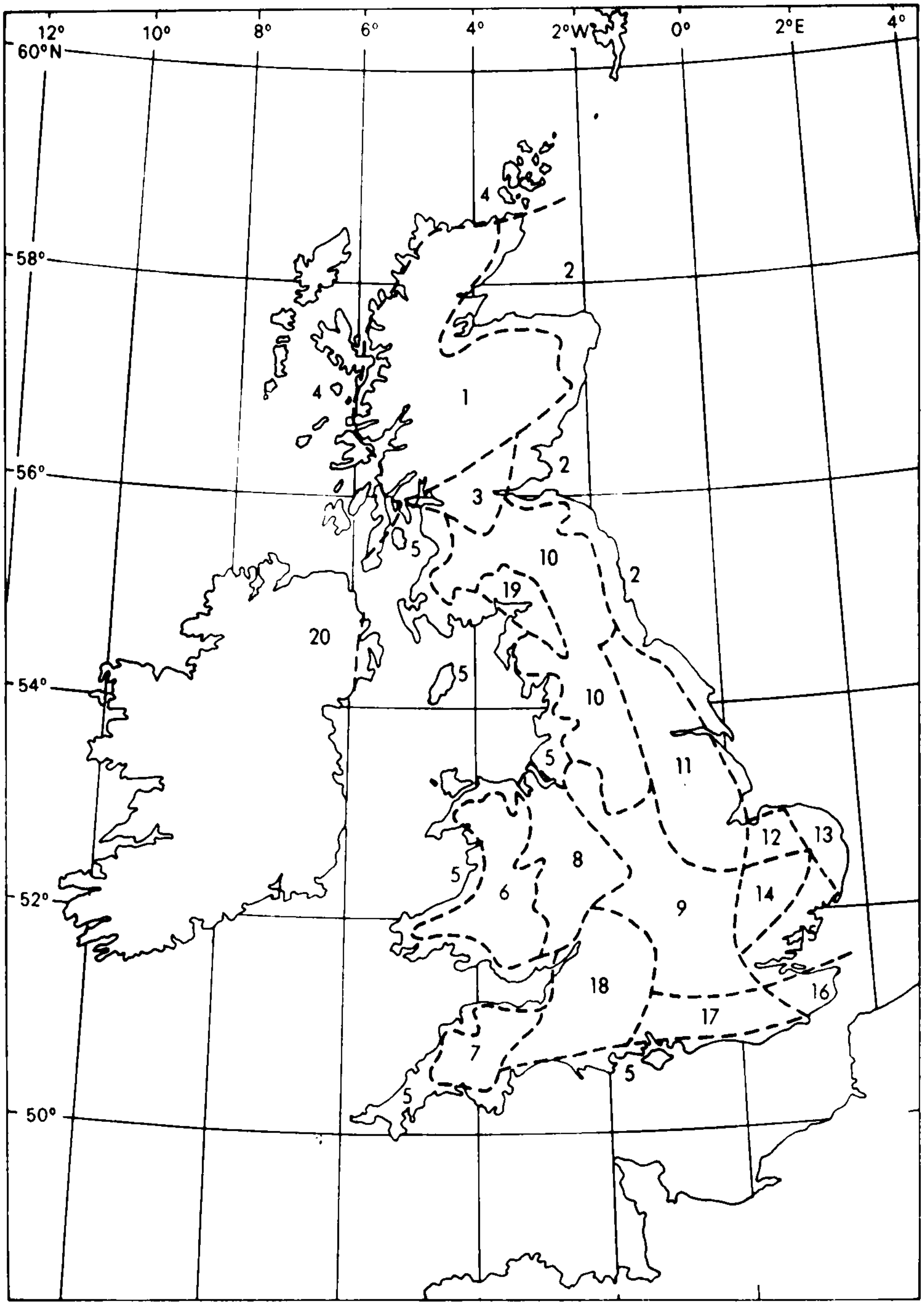

Figure 3. 0900–1800 GMT wet-day cluster analyses. (For the number of stations used for each area, see Table I).

Table I. *Areal wet working days as a percentage of wet rainfall days with standard deviations (whole per cent) and wet daylight-day scaling factors*

Area	Number of stations	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	0	No data available											
2	6	49 (2) 1·3	49 (3) 1·2	44 (5) 1·3	47 (3) 1·3	51 (3) 1·3	49 (3) 1·2	48 (2) 1·3	53 (4) 1·2	47 (2) 1·2	46 (4) 1·2	48 (2) 1·3	48 (3) 1·3
3	1	48 (—) 1·3	51 (—) 1·2	45 (—) 1·3	55 (—) 1·2	59 (—) 1·3	44 (—) 1·3	53 (—) 1·2	54 (—) 1·2	51 (—) 1·3	44 (—) 1·2	50 (—) 1·3	53 (—) 1·2
4	5	57 (3) 1·2	51 (1) 1·3	53 (3) 1·2	47 (1) 1·3	43 (1) 1·3	45 (2) 1·3	44 (2) 1·2	46 (3) 1·3	48 (2) 1·2	54 (2) 1·3	59 (1) 1·2	58 (3) 1·2
5	14	55 (3) 1·2	55 (3) 1·2	51 (3) 1·2	51 (3) 1·2	51 (5) 1·2	46 (4) 1·2	47 (4) 1·3	49 (4) 1·2	50 (4) 1·2	53 (3) 1·2	51 (3) 1·3	51 (2) 1·2
6	0	No data available											
7	0	No data available											
8	5	49 (1) 1·2	61 (3) 1·1	49 (2) 1·2	54 (3) 1·3	54 (4) 1·2	52 (2) 1·2	50 (3) 1·3	57 (2) 1·1	55 (3) 1·2	52 (1) 1·2	47 (2) 1·2	49 (3) 1·2
9	9	46 (1) 1·3	53 (2) 1·2	51 (3) 1·2	53 (2) 1·3	55 (3) 1·2	57 (3) 1·2	55 (2) 1·2	53 (2) 1·2	51 (3) 1·2	52 (3) 1·2	49 (2) 1·2	48 (1) 1·2
10	1	62 (—) 1·1	58 (—) 1·2	57 (—) 1·2	61 (—) 1·2	64 (—) 1·2	55 (—) 1·2	58 (—) 1·2	61 (—) 1·1	63 (—) 1·2	59 (—) 1·2	60 (—) 1·1	59 (—) 1·1
11	6	47 (3) 1·3	53 (3) 1·2	50 (3) 1·2	52 (2) 1·3	55 (2) 1·2	53 (4) 1·2	55 (2) 1·3	56 (3) 1·2	48 (3) 1·2	45 (3) 1·2	47 (2) 1·2	46 (3) 1·2
12	2	48 (2) 1·2	59 (3) 1·2	46 (1) 1·4	48 (2) 1·2	50 (0) 1·1	58 (1) 1·1	55 (0) 1·2	58 (3) 1·2	53 (3) 1·2	50 (1) 1·3	50 (1) 1·2	55 (2) 1·1
13	1	48 (—) 1·2	46 (—) 1·3	42 (—) 1·4	43 (—) 1·2	46 (—) 1·2	57 (—) 1·2	57 (—) 1·2	50 (—) 1·2	50 (—) 1·2	51 (—) 1·3	51 (—) 1·2	55 (—) 1·1
14	2	44 (0) 1·3	50 (1) 1·3	48 (3) 1·3	53 (3) 1·3	53 (4) 1·2	58 (2) 1·2	59 (0) 1·2	52 (0) 1·2	51 (2) 1·2	57 (0) 1·1	50 (1) 1·2	51 (1) 1·2
15	2	47 (2) 1·3	50 (1) 1·3	49 (0) 1·3	51 (0) 1·3	54 (0) 1·2	53 (3) 1·2	54 (1) 1·2	50 (1) 1·2	53 (1) 1·2	51 (1) 1·2	47 (0) 1·2	50 (0) 1·2
16	3	49 (1) 1·2	48 (2) 1·2	50 (3) 1·3	51 (2) 1·2	44 (4) 1·4	45 (2) 1·2	50 (2) 1·2	47 (4) 1·2	51 (2) 1·1	55 (2) 1·2	51 (2) 1·1	48 (4) 1·3
17	1	50 (—) 1·2	54 (—) 1·1	52 (—) 1·2	59 (—) 1·2	49 (—) 1·3	60 (—) 1·2	53 (—) 1·1	52 (—) 1·2	50 (—) 1·3	50 (—) 1·2	51 (—) 1·2	52 (—) 1·3
18	8	52 (3) 1·2	55 (1) 1·2	51 (3) 1·2	52 (2) 1·2	55 (4) 1·2	57 (2) 1·2	51 (4) 1·2	54 (2) 1·1	53 (2) 1·2	53 (2) 1·2	50 (2) 1·1	50 (2) 1·2
19	1	53 (—) 1·2	52 (—) 1·2	50 (—) 1·2	48 (—) 1·3	53 (—) 1·3	50 (—) 1·3	50 (—) 1·2	56 (—) 1·2	54 (—) 1·2	55 (—) 1·2	49 (—) 1·2	51 (—) 1·1
20	1	53 (—) 1·2	55 (—) 1·2	52 (—) 1·3	55 (—) 1·2	60 (—) 1·2	54 (—) 1·2	53 (—) 1·3	57 (—) 1·2	56 (—) 1·2	53 (—) 1·2	49 (—) 1·4	48 (—) 1·2

Note: The bracketed entry is the standard deviation (in whole per cent). The lower entry is the scaling factor by which the wet working-day percentage value (top left value) should be multiplied to obtain wet daylight-day percentages.

and the appropriate percentage values from Table II(b). These estimates, together with the corresponding observed monthly frequencies, are shown in Table III(b).

Statistical tests were made using the independent data to determine the performance of each of the three methods. Using the 24 monthly estimates obtained by each method and the corresponding observed monthly values, the differenced series (observed days minus estimated days) were formed and the mean error, standard deviation and the root-mean-square error were evaluated.

Table II(a). *Growth factors for rainfall-day frequencies for thresholds of 0.1 millimetre or more, 2.0 millimetres or more and 4.0 millimetres or more*

Area	Number of stations	Rainfall threshold	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	0	No data available												
		0·1 mm	1·6	1·6	1·7	1·9	1·8	1·7	1·7	1·6	1·6	1·6	1·6	1·6
2	2	2·0 mm	0·7	0·7	0·6	0·6	0·7	0·7	0·7	0·7	0·7	0·7	0·7	0·7
		4·0 mm	0·4	0·4	0·3	0·3	0·4	0·4	0·4	0·5	0·4	0·4	0·4	0·4
		0·1 mm	1·6	1·7	1·9	1·8	1·6	1·7	1·5	1·6	1·6	1·6	1·6	1·7
3	1	2·0 mm	0·7	0·7	0·7	0·6	0·8	0·7	0·7	0·8	0·7	0·7	0·7	0·7
		4·0 mm	0·4	0·4	0·4	0·4	0·4	0·4	0·5	0·5	0·4	0·4	0·5	0·4
		0·1 mm	1·3	1·4	1·4	1·5	1·5	1·5	1·6	1·5	1·4	1·3	1·3	1·3
4	3	2·0 mm	0·8	0·8	0·8	0·7	0·7	0·7	0·8	0·7	0·8	0·8	0·8	0·8
		4·0 mm	0·6	0·5	0·5	0·5	0·5	0·5	0·5	0·5	0·6	0·6	0·6	0·6
5	7	0·1 mm	1·4	1·5	1·5	1·5	1·4	1·5	1·5	1·5	1·4	1·4	1·3	1·4
and		2·0 mm	0·8	0·8	0·8	0·8	0·8	0·8	0·8	0·8	0·8	0·8	0·8	0·8
19*	0	4·0 mm	0·6	0·5	0·5	0·5	0·5	0·5	0·5	0·5	0·6	0·6	0·6	0·6
6	0	No data available												
7	0	No data available												
		0·1 mm	1·6	1·6	1·6	1·6	1·5	1·6	1·6	1·5	1·5	1·6	1·6	1·6
8	1	2·0 mm	0·8	0·7	0·7	0·8	0·7	0·7	0·8	0·8	0·8	0·7	0·7	0·8
		4·0 mm	0·5	0·4	0·4	0·4	0·5	0·5	0·5	0·5	0·5	0·5	0·5	0·5
		0·1 mm	1·6	1·6	1·6	1·5	1·5	1·5	1·5	1·5	1·4	1·4	1·5	1·6
9	3	2·0 mm	0·8	0·7	0·7	0·7	0·7	0·7	0·8	0·8	0·8	0·8	0·8	0·8
		4·0 mm	0·4	0·4	0·5	0·4	0·4	0·5	0·5	0·5	0·5	0·5	0·5	0·5
		0·1 mm	1·3	1·4	1·5	1·4	1·3	1·3	1·4	1·4	1·3	1·3	1·4	1·3
10	1	2·0 mm	0·9	0·9	0·8	0·8	0·8	0·9	0·8	0·8	0·9	0·8	0·9	0·8
		4·0 mm	0·7	0·6	0·6	0·6	0·6	0·6	0·6	0·6	0·7	0·6	0·7	0·6
		0·1 mm	1·6	1·8	1·7	1·6	1·5	1·6	1·5	1·4	1·5	1·7	1·6	1·7
11	2	2·0 mm	0·7	0·7	0·7	0·6	0·7	0·7	0·8	0·7	0·7	0·7	0·7	0·8
		4·0 mm	0·4	0·4	0·3	0·4	0·4	0·5	0·5	0·5	0·5	0·5	0·5	0·4
12/13*	0	0·1 mm	1·8	1·9	1·8	1·7	1·6	1·5	1·6	1·5	1·5	1·7	1·7	1·7
14	1	2·0 mm	0·7	0·7	0·7	0·7	0·7	0·8	0·8	0·7	0·7	0·8	0·8	0·7
15*	0	4·0 mm	0·4	0·3	0·3	0·4	0·4	0·5	0·5	0·4	0·5	0·5	0·5	0·4
		0·1 mm	1·7	1·7	1·8	1·7	1·7	1·5	1·6	1·4	1·5	1·5	1·6	1·6
16	1	2·0 mm	0·7	0·6	0·7	0·8	0·7	0·7	0·7	0·8	0·8	0·8	0·8	0·7
		4·0 mm	0·4	0·3	0·4	0·4	0·4	0·4	0·5	0·5	0·5	0·5	0·5	0·4
17*	0	0·1 mm	1·5	1·6	1·6	1·6	1·5	1·5	1·5	1·5	1·5	1·5	1·5	1·5
and		2·0 mm	0·8	0·8	0·7	0·7	0·7	0·7	0·7	0·7	0·8	0·8	0·8	0·8
18	1	4·0 mm	0·6	0·5	0·5	0·4	0·5	0·5	0·5	0·5	0·6	0·6	0·5	0·5
		0·1 mm	1·5	1·6	1·5	1·5	1·4	1·4	1·5	1·5	1·4	1·5	1·5	1·5
20	1	2·0 mm	0·8	0·8	0·7	0·7	0·7	0·8	0·8	0·8	0·8	0·7	0·7	0·8
		4·0 mm	0·5	0·5	0·4	0·4	0·4	0·4	0·5	0·5	0·5	0·5	0·5	0·5

Notes: (i) Data are based on records from 24 stations with hourly records in machinable form during the period 1957–76.

(ii) Areas for which no data are available are indicated with an asterisk. Such areas have been allocated to the regions with which stations have the highest degree of association (as indicated by the clustering analysis) at the wet working-day level (i.e. the 1·0 millimetre or more threshold).

The results obtained for the wet working day data (i.e. 1 mm or more) are shown in Table IV(a), whilst Table IV(b) provides the equivalent statistics for the other working-day thresholds of 0.1 mm, 2 mm and 4 mm. These show that:

- Errors are typically larger for Mount Batten than for Cardington, but the errors decrease at both stations as the threshold limit increases. These results are to be expected since the average incidence

Table II(b). *Working-day rainfall as a percentage of rainfall-day falls for thresholds of 0.1 millimetre or more, 2.0 millimetres or more and 4.0 millimetres or more*

Area	Stns	Level of falls	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	0	No data available												
		0·1 mm	67(3)	64(3)	64(3)	61(0)	65(0)	62(0)	58(0)	62(1)	63(1)	66(3)	69(6)	69(6)
2	2	2·0 mm	44(2)	39(0)	34(4)	35(1)	41(4)	40(2)	44(1)	49(2)	43(3)	35(4)	40(0)	41(1)
		4·0 mm	32(2)	30(1)	23(2)	28(3)	37(4)	42(3)	39(2)	42(2)	31(1)	23(0)	29(1)	30(6)
		0·1 mm	69(—)	63(—)	63(—)	65(—)	70(—)	59(—)	62(—)	64(—)	61(—)	61(—)	63(—)	63(—)
3	1	2·0 mm	37(—)	35(—)	40(—)	48(—)	51(—)	40(—)	49(—)	52(—)	44(—)	42(—)	41(—)	44(—)
		4·0 mm	32(—)	22(—)	29(—)	38(—)	48(—)	41(—)	45(—)	43(—)	32(—)	30(—)	37(—)	35(—)
		0·1 mm	77(1)	72(2)	72(1)	65(5)	63(3)	63(4)	59(5)	63(4)	69(2)	74(2)	77(3)	80(2)
4	3	2·0 mm	46(2)	44(2)	41(3)	35(2)	37(2)	39(2)	37(2)	41(6)	40(1)	43(2)	46(3)	45(4)
		4·0 mm	35(5)	31(0)	28(1)	24(4)	28(4)	29(1)	29(4)	33(10)	34(5)	33(3)	31(2)	30(2)
5	7	0·1 mm	69(2)	65(3)	66(4)	64(3)	64(4)	57(2)	57(3)	60(3)	64(5)	67(2)	67(3)	66(3)
and		2·0 mm	49(3)	46(2)	42(2)	43(3)	44(4)	44(3)	43(3)	44(2)	45(4)	48(2)	43(3)	42(3)
19*	0	4·0 mm	38(4)	34(3)	31(4)	35(3)	36(4)	37(4)	39(5)	37(4)	36(3)	38(4)	34(2)	33(6)
6	0	No data available												
7	0	No data available												
		0·1 mm	64(—)	69(—)	63(—)	64(—)	67(—)	61(—)	63(—)	62(—)	68(—)	61(—)	57(—)	57(—)
8	1	2·0 mm	43(—)	51(—)	47(—)	43(—)	55(—)	54(—)	43(—)	51(—)	48(—)	46(—)	43(—)	39(—)
		4·0 mm	35(—)	40(—)	36(—)	39(—)	44(—)	46(—)	39(—)	47(—)	41(—)	38(—)	36(—)	35(—)
		0·1 mm	63(1)	64(1)	65(1)	64(2)	63(3)	66(1)	64(1)	63(4)	63(3)	62(1)	63(1)	61(1)
9	3	2·0 mm	39(1)	45(5)	45(1)	46(5)	49(4)	49(2)	49(1)	49(4)	48(3)	51(4)	42(2)	43(1)
		4·0 mm	32(4)	35(5)	30(3)	31(2)	43(7)	44(9)	45(4)	43(2)	41(4)	43(3)	37(0)	29(1)
		0·1 mm	77(—)	72(—)	73(—)	80(—)	76(—)	73(—)	71(—)	71(—)	74(—)	69(—)	72(—)	72(—)
10	1	2·0 mm	55(—)	53(—)	49(—)	54(—)	57(—)	45(—)	47(—)	53(—)	57(—)	49(—)	53(—)	54(—)
		4·0 mm	47(—)	42(—)	36(—)	41(—)	43(—)	37(—)	40(—)	49(—)	43(—)	40(—)	49(—)	44(—)
		0·1 mm	61(1)	63(1)	63(2)	65(0)	64(4)	59(0)	63(1)	63(1)	61(3)	58(1)	60(2)	58(1)
11	2	2·0 mm	41(1)	47(2)	41(2)	42(2)	47(1)	42(0)	51(2)	52(1)	45(0)	38(1)	43(0)	39(2)
		4·0 mm	37(2)	38(3)	32(4)	30(2)	33(1)	32(1)	46(4)	44(5)	38(2)	28(1)	41(3)	32(7)
12/13*	0	0·1 mm	57(—)	61(—)	60(—)	62(—)	61(—)	61(—)	66(—)	60(—)	62(—)	59(—)	63(—)	59(—)
14	1	2·0 mm	44(—)	44(—)	46(—)	41(—)	49(—)	54(—)	51(—)	48(—)	48(—)	50(—)	48(—)	41(—)
15*	0	4·0 mm	32(—)	39(—)	40(—)	19(—)	42(—)	47(—)	40(—)	40(—)	40(—)	47(—)	36(—)	31(—)
		0·1 mm	59(—)	57(—)	62(—)	61(—)	54(—)	58(—)	61(—)	58(—)	58(—)	59(—)	59(—)	56(—)
16	1	2·0 mm	45(—)	35(—)	41(—)	45(—)	30(—)	38(—)	42(—)	43(—)	48(—)	50(—)	46(—)	39(—)
		4·0 mm	26(—)	30(—)	34(—)	36(—)	32(—)	36(—)	32(—)	33(—)	46(—)	40(—)	42(—)	27(—)
17*	0	0·1 mm	68(—)	61(—)	63(—)	67(—)	66(—)	65(—)	61(—)	66(—)	65(—)	67(—)	64(—)	65(—)
and		2·0 mm	46(—)	46(—)	42(—)	47(—)	47(—)	55(—)	50(—)	47(—)	48(—)	48(—)	43(—)	45(—)
18	1	4·0 mm	36(—)	36(—)	32(—)	35(—)	40(—)	47(—)	36(—)	37(—)	38(—)	34(—)	37(—)	37(—)
		0·1 mm	70(—)	66(—)	66(—)	69(—)	74(—)	69(—)	63(—)	67(—)	69(—)	67(—)	65(—)	65(—)
20	1	2·0 mm	47(—)	41(—)	43(—)	44(—)	50(—)	46(—)	46(—)	52(—)	46(—)	45(—)	37(—)	38(—)
		4·0 mm	33(—)	31(—)	31(—)	38(—)	38(—)	31(—)	38(—)	45(—)	35(—)	33(—)	33(—)	29(—)

Notes: (i) and (ii) as for Table II(a).
(iii) Bracketed entries are standard deviations in whole per cent.

is greater at Mount Batten than at Cardington, whilst events associated with lower thresholds generally occur with relatively higher frequency.

- Mean errors over the series are of the order of less than one day by all three techniques.
- There is no significant deterioration in the accuracy of method (b) over that for method (a). This result leads to the conclusion that the use of areal reduction factors at individual stations within an area is justified.

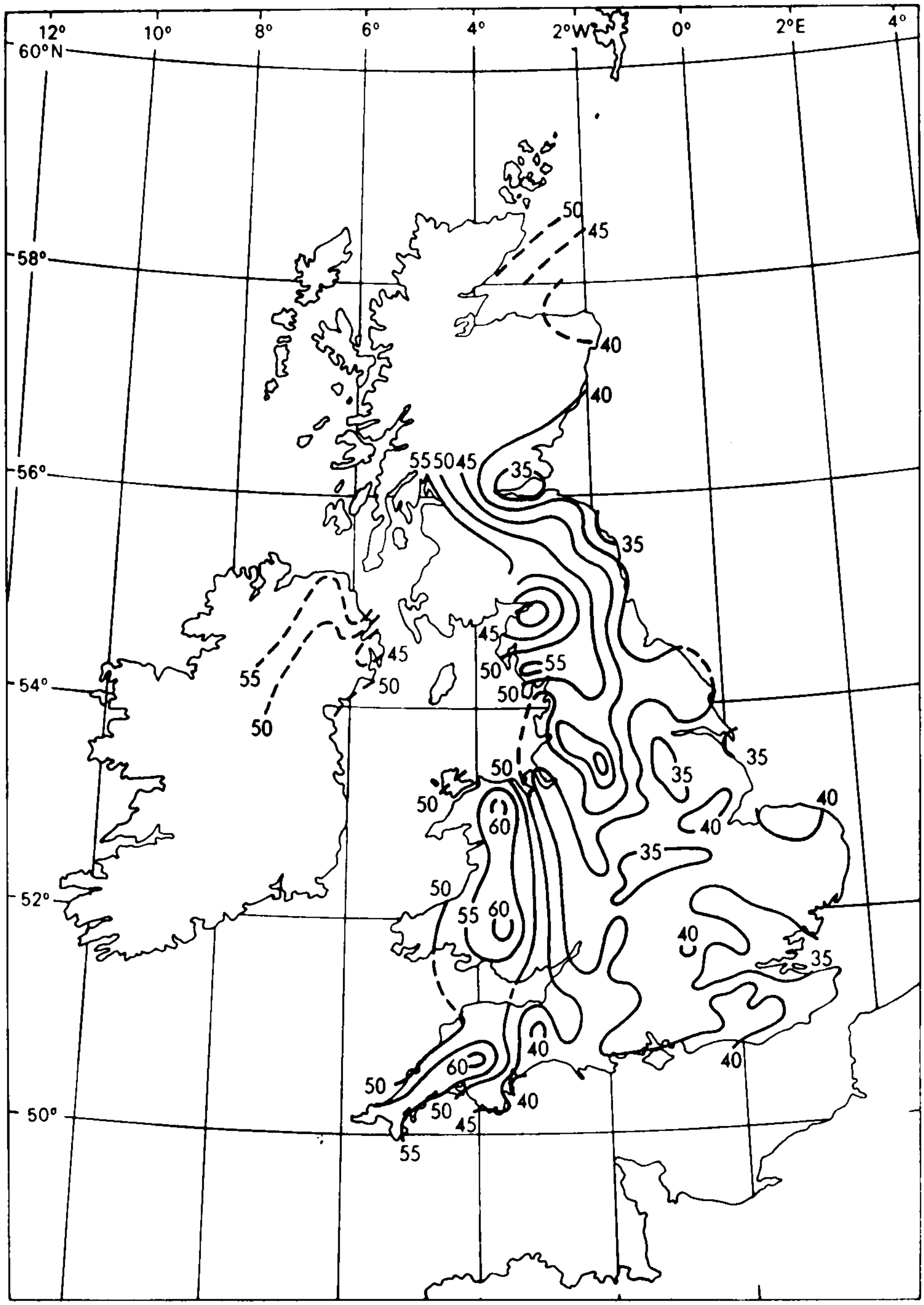

Figure 4. Percentage of wet days to total days in January, 1941–70.

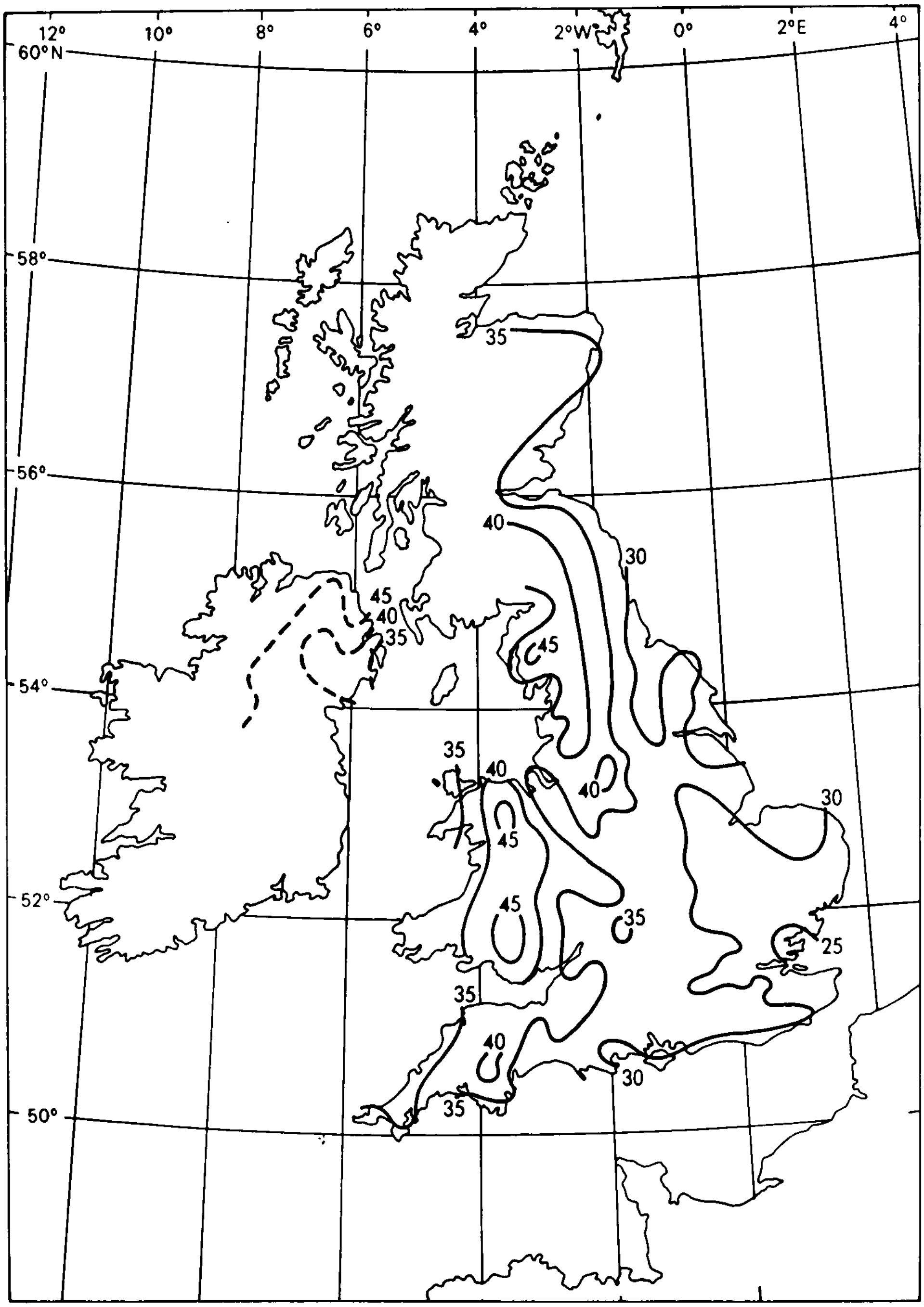

Figure 5. Percentage of wet days to total days in May, 1941–70.

Table III(a). *Monthly estimates of numbers of wet working days (1.0 millimetre or more) and corresponding observed monthly totals for two TSR stations derived from independent data for the years 1977 and 1978*

Station	Mount Batten				Cardington			
Technique (see footnote)	Observed	(a)	(b)	(c)	Observed	(a)	(b)	(c)
Jan. 1977	10	9	9	8	5	5	5	5
Feb.	15	12	11	6	9	9	9	5
Mar.	12	9	9	5	8	7	7	4
Apr.	6	6	7	5	6	5	5	5
May	7	6	6	6	5	5	5	5
June	7	5	5	3	3	4	4	5
July	3	3	3	4	1	1	1	5
Aug.	5	5	5	6	8	7	7	5
Sept.	2	3	3	6	1	2	2	4
Oct.	7	6	5	6	4	3	3	5
Nov.	7	8	8	7	4	6	6	5
Dec.	7	7	8	8	4	5	5	5
Jan. 1978	7	10	9	8	8	6	6	5
Feb.	14	9	9	6	4	6	6	5
Mar.	11	9	9	5	7	5	6	4
Apr.	2	5	5	5	3	4	4	5
May	2	2	2	6	2	3	3	5
June	3	4	4	3	7	5	5	5
July	5	5	5	4	5	5	5	5
Aug.	1	3	2	6	6	6	5	5
Sept.	2	3	3	6	1	3	4	4
Oct.	0	1	1	6	1	1	1	5
Nov.	5	5	5	7	3	3	2	5
Dec.	15	12	12	8	9	9	9	5
Total	155	147	145	140	114	115	115	116

Footnote: The monthly estimates of numbers of wet working days were derived by three methods—(A), (B) and (C). The technique used in each case was as follows:

Method (a): Estimates derived from the observed monthly wet rainfall-day totals and the individual station reduction factors.

Method (b): Estimates derived from the observed monthly wet rainfall-day totals and the areal reduction factors.

Method (c): Estimates derived from the areal reduction factors and the 30-year monthly percentages contained in the wet rainfall-day maps.

● For methods (a) and (b), standard errors of monthly estimates are of the order of 2 days at the 0.1 mm threshold, reducing by the 4 mm level to around 1.2 days at Mount Batten and 0.8 day at Cardington. Mean errors for the 24-month series are of the order of half a day at Mount Batten and somewhat less at Cardington.

Standard errors by method (c) for individual months are materially larger than for the other two methods, being over 4 days for Mount Batten and about 2½ days at Cardington. This result is probably largely due to the natural variability of the monthly incidence of rainfall. Mean errors by method (c) for the 24-month series were, however, only slightly larger than those obtained by the other two methods.

● There is a reasonably high measure of correlation between observed and estimated totals computed by methods (a) and (b).

In general, these tests on independent data suggest that:

(a) Where 24-hour rainfall records are available, useful estimates can be made of the number of working days per month when falls reached selected thresholds.

Table III(b). *Monthly estimates of working days for rainfall thresholds of 0.1 millimetre or more, 2.0 millimetres or more and 4.0 millimetres or more and corresponding observed monthly totals for two TSR stations derived from independent data for 1977 and 1978*

(a)				*Mount Batten*					
Threshold	0·1 millimetre			2·0 millimetres			4·0 millimetres		
Method (note (i))	Obs.	(b)	(c)	Obs.	(b)	(c)	Obs.	(b)	(c)
Jan. 1977	16	14	14	8	6	6	4	3	3
Feb.	21	17	11	10	8	4	6	6	2
Mar.	16	13	10	10	6	4	6	3	2
Apr.	13	13	10	3	3	3	2	1	2
May	8	8	10	7	5	4	3	4	2
June	10	9	6	3	4	3	2	2	1
July	7	8	8	2	2	3	2	2	2
Aug.	9	8	10	4	3	4	3	2	2
Sept.	6	6	10	1	2	4	1	1	3
Oct.	13	12	11	3	3	5	0	1	3
Nov.	12	12	13	5	4	5	2	2	3
Dec.	16	14	14	5	5	5	3	4	3
Jan. 1978	18	15	14	3	7	6	3	5	3
Feb.	18	12	11	10	7	4	7	4	2
Mar.	17	17	10	8	6	4	3	3	2
Apr.	8	10	10	2	2	3	1	1	2
May	4	5	10	1	1	4	0	0	2
June	8	8	6	2	3	3	1	1	1
July	8	9	8	5	3	3	3	2	2
Aug.	9	8	10	1	2	4	1	1	2
Sept.	4	7	10	1	2	4	1	0	3
Oct.	2	3	11	0	0	5	0	0	3
Nov.	10	10	13	4	2	5	1	1	3
Dec.	21	17	14	10	9	5	7	5	3
Total	274	255	254	108	95	100	62	54	56
(b)				*Cardington*					
Jan. 1977	10	11	11	3	3	3	1	1	2
Feb.	12	14	9	5	6	3	2	3	1
Mar.	13	12	8	6	5	2	2	1	1
Apr.	11	12	9	2	2	3	1	1	1
May	6	8	9	3	4	3	1	1	2
June	7	9	8	3	3	3	2	2	2
July	4	4	9	1	0	4	0	0	2
Aug.	13	11	10	5	4	4	4	4	2
Sept.	5	8	8	1	1	3	1	0	2
Oct.	7	8	8	3	2	4	2	1	2
Nov.	9	12	10	2	3	4	2	3	2
Dec.	8	12	11	4	3	4	2	1	2
Jan. 1978	16	14	11	6	4	3	3	2	2
Feb.	11	11	9	4	5	3	1	1	1
Mar.	16	14	8	4	4	2	1	1	1
Apr.	7	10	9	3	2	3	2	2	1
May	5	7	9	2	1	3	1	1	2
June	9	7	8	5	4	3	3	1	2
July	7	10	9	3	4	4	2	2	2
Aug.	9	8	10	4	3	4	0	1	2
Sept.	5	5	8	1	2	3	0	1	2
Oct.	3	5	8	0	0	4	0	0	2
Nov.	5	5	10	2	1	4	2	1	2
Dec.	14	15	11	7	6	4	3	4	2
Total	212	232	220	79	72	80	38	35	42

Note (i): The column marked 'Obs.' is the observed number of working-days per month with a rainfall total equal to or greater than the specified threshold.
Column (b) shows the estimated monthly working-days with rainfall equal to or greater than the specified threshold derived from the observed number of rainfall-days at that threshold and the areal reduction factors.
Column (c) shows corresponding estimates derived from the 30-year monthly percentage maps and the areal reduction factors.

Table IV(a). *Summary of statistical tests made on 24 months (1977/78) of independent data for Mount Batten and Cardington for the wet working day (1.0 millimetre or more)*

Station	Mount Batten			Cardington		
Method (see note (i)	(a)	(b)	(c)	(a)	(b)	(c)
Mean error (days)	0·33	0·42	0·63	—0·04	—0·04	—0·08
Standard deviation (days)	1·95	1·98	4·27	1·20	1·27	2·60
r.m.s. error (days)	1·98	2·02	4·32	1·20	1·27	2·60

Note (i) Details of the methods used to derive estimates of monthly wet working-day totals are given at the foot of Table III(a).

Table IV(b). *Summary of statistical tests made on 24 months (1977/78) of independent data for Mount Batten and Cardington to assess estimates of numbers of working days with thresholds of 0.1 mm or more, 2.0 mm or more and 4.0 mm or more*

Threshold	0·1 mm or more		2·0 mm or more		4·0 mm or more	
Method (see note (i))	(b)	(c)	(b)	(c)	(b)	(c)
Station	Mount Batten					
Mean error (days)	0·79	0·83	0·54	0·87	0·33	0·25
Standard deviation (days)	2·03	4·72	1·69	3·13	1·17	2·23
r.m.s. error (days)	2·24	4·80	1·78	3·26	1·22	2·25
Station	Cardington					
Mean error (days)	—0·83	—0·33	0·29	—0·04	0·13	—0·14
Standard deviation (days)	1·83	3·53	0·91	2·01	0·80	1·13
r.m.s. error (days)	2·02	3·55	0·96	2·01	0·81	1·14

Note (i) Details of the methods used to derive estimates of monthly working-day totals are given at the foot of Table III(b).

(b) At such locations the areal reduction factors can be used without serious loss in the accuracy of the estimation.

(c) For planning purposes estimates of working-day monthly frequencies for specific thresholds can be prepared using the monthly percentage maps and the corresponding areal reduction factors. Owing to the variability in monthly rainfall, however, the quality of estimates is likely to deteriorate for thresholds below 1 mm.

Discussion

Whilst the method goes some way towards filling the gap in rainfall statistics, it does not fully meet the current requirement. No information is provided regarding the duration of the falls. Indeed, although the method follows the historically accepted threshold of 1 mm or more in a rainfall day, this value does not necessarily serve the best interests of all outdoor activities. For example, the threshold for interrupting outdoor painting work will be lower than that for bricklaying, and for this reason the growth factors were introduced. Although growth factors were computed for thresholds up to 10 mm the values provided in Table II were restricted to the 4 mm level, since the higher the threshold considered the greater is the probability that the fall will span 0900 GMT or 1800 GMT.

Perhaps the best solution to this limitation is to extend the work via a study of the duration of the falls during the working day. This aspect is currently under investigation using the returns from the stations with hourly data in machinable form and it is hoped to combine both studies in due course. Other aspects which require investigation include a study of the percentage of days on which rainfall lasts for one hour or more and exceeds selected thresholds, an examination of the likelihood of consecutive wet days and an investigation into the likely timing of rainfall within the working day.

Conclusion

Because of the areal relationships derived, estimates can be made of the average number of wet workings days per month at most locations in England and Wales and some districts in Scotland and Northern Ireland, irrespective of the availability of actual rainfall statistics. Providing there is a 24-hour rainfall station in the vicinity, it is also possible to estimate the number of wet working days for specific months. The degree of association between wet working-day values and other rainfall thresholds also permits estimates to be made of the frequency of rainfall events other than 1 mm or more in the working day.

Acknowledgements

Much of the computer programming and card preparation required to run the various programs was carried out within Met O 9 and in particular by Miss Alison Welham whose assistance was invaluable. The writer is grateful to Mr Hawson (Met O 9 Outstations Investigations Section) for his encouragement throughout the investigation.

References

London, Meteorological Office 1979 Annual Report on the Meteorological Office, 1978 London, HMSO, Table IV, 70.

University of California, Los Angeles, Health Sciences Computing Facility 1977a 1975 Program Manual (revised 1977).

1977b BMDP-77 Biomedical computer programs, P-series. P2M, cluster analysis of cases.

Appendix 1—Summary of the principles of the clustering technique applied to the analysis of rainfall data

This brief summary has been included since the technique may well prove useful in other meteorological investigations where an objective assessment of the degree of association between observing stations and/or areas is required.

The program first sets up a matrix consisting of one row to each station and one column to each station's individual monthly value of R (i.e. the first column for January values, the second column for February values etc. up to the twelfth column for December values). This matrix is then standardized so that the values for all stations in each column scatter about a mean of zero with a standard deviation of unity. The program proceeds to calculate the 'distance' between cases (stations and groups of stations) where the 'distance' is the Euclidean distance d_{kl} between case k and l. This is the square root of the sum of the squares of the difference computed from the standardized matrix for the two cases

$$d_{kl} = \{\sum_{j=1}^{12}(x_{kj} - x_{lj})^2\}^{\frac{1}{2}},$$

where x_{kj} is the value of R from the standardized matrix for station k for month j and x_{lj} is the value of R from the standardized matrix for station l for month j, and the summation is carried out over months j from 1 to 12 (i.e. January to December).

The two cases yielding the shortest Euclidean distance between them are amalgamated and subsequently treated as one case and then in turn clustered with other cases. This algorithm continues until all cases and all clusters are amalgamated into one cluster. A diagram is output using horizontal and sloping lines to indicate clustering of cases. The order of clustering and the relevant Euclidean distances are also indicated, permitting the investigator to determine the number of what he considers to be realistic clusters in the data. Additional facilities allow for the distance matrix, after case clustering, to be printed in a sorted and shaded form with the researcher specifying the maximum distance to be represented by shading. A histogram of the distribution of distances can also be printed.

Appendix 2 –An example of the use of the Figures and Tables to determine the likely number of days per month with working-day rainfall equal to or greater than specified amounts

Problem. The average numbers of January working days with 0.1 mm, 1 mm, 2 mm and 4 mm of rainfall are required for Ringwood (Hampshire).

Method

(1) From Figure 4 compute the average January wet rainfall-day incidence for 1 mm or more at Ringwood. (0.41 × 31) = 12.7 days.

(2) From Table I (area 18) obtain the wet working-day reduction factor (0.52). The average January wet working-day incidence is the product of (1) and (2). (12.7 × 0.52) = 6.6 days.

(3) From Table II(a) (area 18) use the January growth factors to compute the rainfall-day incidence for 0.1 mm, 2 mm and 4 mm. (12.7 × 1.5) = 19 days, (12.7 × 0.8) = 10.2 days and (12.7 × 0.6) = 7.6 days.

(4) From Table II(b) (area 18) use the January values to compute the working-day average incidences for the specified thresholds. (19 × 0.68) = 12.9 days, (10.2 × 0.46) = 4.7 days and (7.6 × 0.36) = 2.7 days.

Solution. The average January working-day frequencies for falls equal to or greater than the required thesholds are:

Threshold	Frequency
0.1 mm or more	12.9 days
1 mm or more	6.6 days
2 mm or more	4.7 days
4 mm or more	2.7 days

Letter to the Editor

Correction to published paper

In Figure 2 of my paper 'Statistical comparison of central England annual and monthly mean air temperature variability, 1660–1977' published in the *Meteorological Magazine*, Vol. 109, 1980, pp. 101–113, the terms 'January' and 'July' have to be exchanged. I am grateful to Dr L. Makkonen, Institute of Marine Research, Helsinki, for discovering this error.

Dr C. D. Schönwiese

Munich
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THE METEOROLOGICAL MAGAZINE

No. 1302 January 1981 Vol. 110

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1.80 monthly
Dd 698260 K15 1/81

Annual subscription £23.80 including postage
ISBN 0 11 726278 1
ISSN 0026-1149

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

February 1981

Met.O. 942 No. 1303 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1303, February 1981, Vol. 110

551.501.81:551.515.43:551.553.6

Estimates of surface gust speeds using radar observations of showers

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Summary
The speed of travel of shallow showers during the 1979 Fastnet Yacht Race, and on other occasions of strong wind, has been found to give a good indication of the peak surface gusts at exposed coastal locations. An objective echo-tracking procedure is capable of determining the speed of travel of the showers provided that the radar data are available with a resolution of at least 5 km and 5 min.

1. Introduction

Small, fast-moving precipitation echoes are sometimes observed by radar. If it were possible to relate such observations to the occurrence and magnitude of strong surface winds this would suggest a useful practical application of weather radar in addition to its more usual role in the measurement of precipitation distribution and intensity. It is now more than 25 years since Ligda and Mayhew (1954) reviewed radar studies of the motion of small precipitation areas (SPAs). They concluded that such radar measurements (so-called spawinds) are not very helpful for estimating winds because of difficulties in determining the steering level of the precipitation areas. Frequently these areas travel at the velocity of the winds far above the surface. Areas of locally heavier rain in frontal regions, for example, are often found to travel at the speed of convective generating cells embedded within the middle-tropospheric flow. The high speed of such areas (sometimes as high as 130 km h^{-1}) does not necessarily bear any relation to the speed of the winds at the surface. Nevertheless, there are occasions when the precipitation echoes can be shown to be due to showers confined to a shallow layer in the lower troposphere, and the purpose of this note is to consider whether the radar echo movements in these circumstances can be used to make worthwhile inferences about the surface winds.

In this paper we present radar observations obtained as part of the Short Period Weather Forecasting Pilot Project (Browning 1980) on the occasion of the 1979 Fastnet Yacht Race (14 August 1979) when storm-force winds occurred in sea areas Fastnet and Lundy. The radar, located at Camborne, Cornwall, observed numbers of short-lived showers over the sea during the period of the gales. The showers were light and only just above the threshold of radar detectability; they were also very shallow with tops

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mostly in the range $2 \pm \frac{1}{2}$ km above sea level. Similar observations were obtained on 7 and 8 December 1979 when once again the South-west Approaches were exposed to strong winds located in the cold air to the south of a depression, although on this occasion the winds were not as strong as on 14 August. Results to be presented in this paper show that, in both cases, the showers travelled rapidly, at speeds similar to those of the peak gusts reported at the surface. A computerized cell-tracking procedure, capable of evaluating these velocities from the radar data almost in real time, has been used, and the results are compared with those derived subjectively.

2. The synoptic setting

A deep depression travelled eastwards across southern Ireland in the early hours of 14 August and behind the cold front a strong, fairly dry west-south-westerly flow covered the South-west Approaches. Reports from competitors indicate that the strongest winds over the area occurred between 0200 and 0600 GMT. Fig. 1 shows the surface analysis superimposed on the pattern of cloud-top height derived from the Meteosat infra-red imagery at 0600; at this time the strongest surface winds were in a narrow zone just to the north-west of the radar at Camborne (C). The cloud tops in the area near Camborne are seen to have been in the range 1·3 to 2·7 km. The locations of individual showers detected by the radar at 0600 are indicated in the figure by triangles. Although operational compromises dictate that only low-elevation radar data are available in real time, data from higher elevations are tape-recorded for off-line analysis and these data confirmed the satellite indications that the showers were confined below 2·7 km.

Fig. 2 is a vertical cross-section along the line VXCBrB in Fig. 1. It shows the 0600 winds at Valentia (V), Camborne (C) and Brest (Br) and also the 1030 ascent at Aberporth displaced to the position in relation to the synoptic system that it would have occupied at 0600 (position X). The strongest surface winds occurred between X and C, at little to the south-east of the main upper tropospheric jet which reached 77 m s^{-1} at 300 mb. The small cumulus turrets drawn in Fig. 2 between X and C indicate the vertical extent of the showers which occurred in this region.

Fig. 3 shows a vertical sounding representative of the airstream generating the showers. It is actually the 09 Larkhill sounding but its position relative to the synoptic pattern at 06 puts it on the boundary of the area of interest (see Z in Fig. 1). The sounding indicates that the showers were within a boundary layer capped by very dry air above 750 mb, the dry air probably having had a recent history of subsidence. Other soundings representative of the same general airstream showed a similar thermodynamic structure; however, those made from stations exposed to a flow coming directly from the sea exhibited a more nearly constant θ_w in the boundary layer, indicating that the boundary layer over the sea was convectively well mixed. Surface temperatures representative of sea-surface conditions have been used to construct the line of parcel ascent on the sounding shown in Fig. 3.

3. Velocities of shower echoes compared with surface gusts

The area over which showers $2\frac{1}{2}$ km deep could be detected by the Camborne radar is indicated by the dashed line in Fig. 1. The average velocity of each of the shower echoes within this area has been evaluated over half-hour periods using data at 5 min intervals. The resulting velocities have been compared with records from anemometers in the vicinity.

The successive half-hourly positions of a line of shower echoes that crossed the Isles of Scilly soon after 0000 GMT on 14 August are shown in Fig. 4. The tracks of the individual shower cells are marked in the diagram together with their velocities, which ranged from 23 ± 3 m s^{-1} to 28 ± 3 m s^{-1}. This line of showers, which could also be tracked as a cloud band on the Meteosat infra-red imagery, produced a well-defined gust at exposed stations in south-west England and Wales. The anemograph

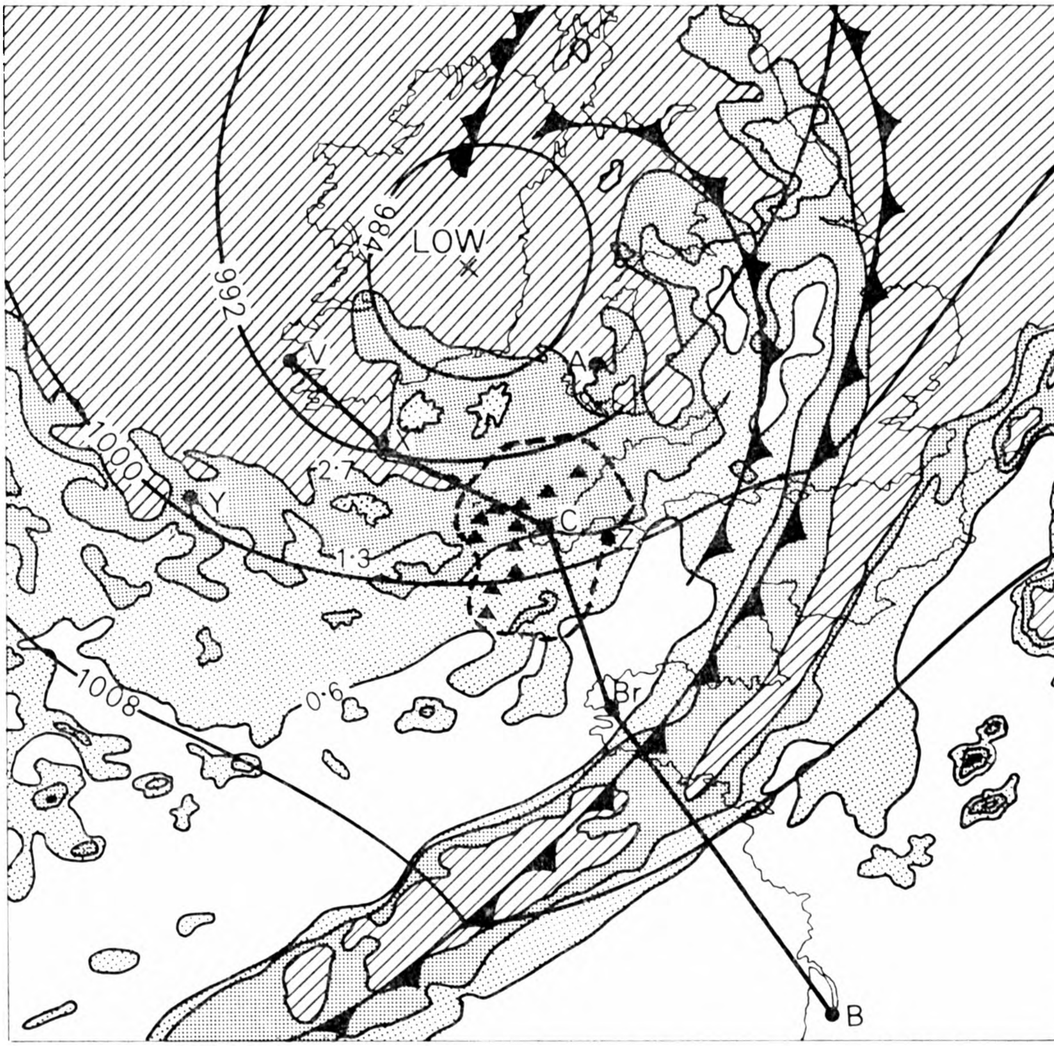

Figure 1. 14 August 1979, 06 GMT: smoothed contours of the height of the cloud tops (km) from Meteosat infra-red imagery with surface isobaric (8 mb intervals) and frontal analysis superimposed. Triangles mark the positions of showers observed on the Camborne radar at 0600 and the heavy dashed line indicates the limit of radar observations. Circles mark the positions of vertical soundings relative to the synoptic system at 0600; Valentia 0600 (V), Aberporth 0600 (A), Aberporth 1030 (X), Camborne 0600 (C), Camborne 1200 (Y), Larkhill 0900 (Z), Brest 0600 (Br) and Bordeaux 0600 (B).

record at Scilly, for example, which is shown in Fig. 5, illustrates a peak gust of 24 m s^{-1} (47 kn) at 0008 GMT. The corresponding peak gusts during the passage of this line of showers through Gwennap Head, Lizard and Hartland Point were 23, 21 and 27 m s^{-1} respectively. These values are plotted in Fig. 4. The peak gusts at these exposed stations were evidently within $\pm$ 5 m s^{-1} of the nearest shower echoes.

The other showers that were observed during the period 0000–0900 were distributed less regularly.

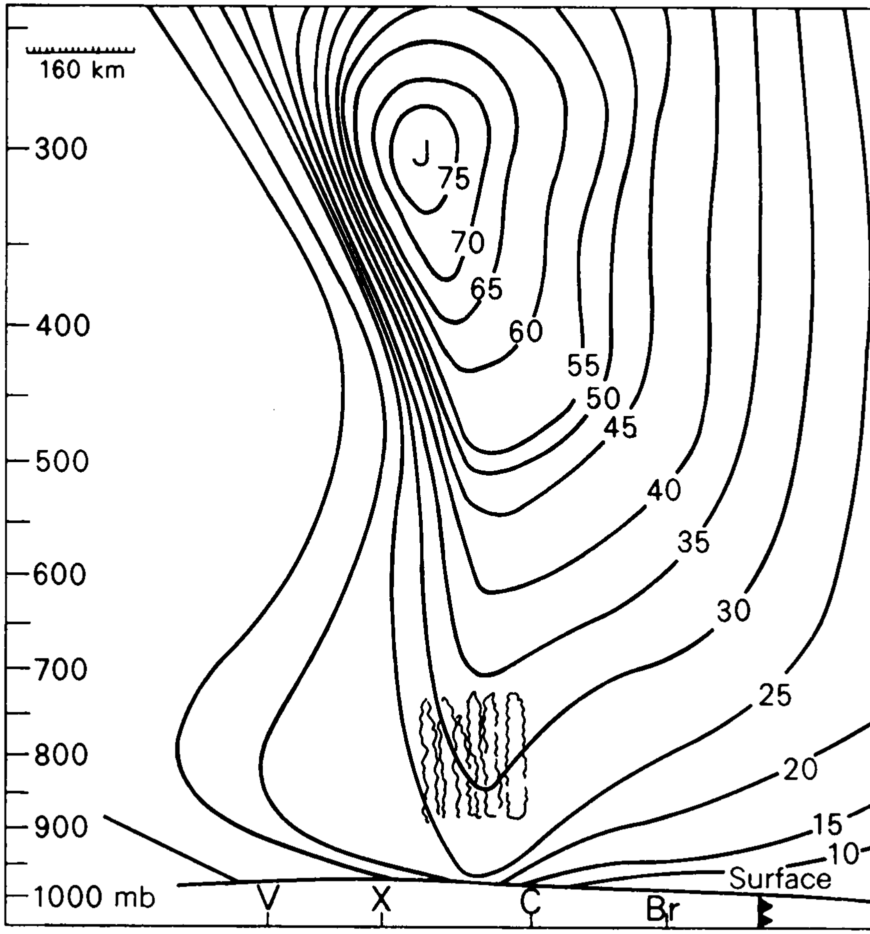

Figure 2. Vertical cross-section of the mean wind speed (m s^{-1}) along the line from Valentia to Bordeaux through X, C and Br as shown in Figure 1. The surface position of the cold front is indicated by the conventional symbol, and the vertical extent of the showers observed between X and C is represented by small cumulus turrets.

Although they could be associated with features on the satellite imagery, the time lapse of ½ h between pictures meant that individual showers could not be tracked by satellite. Individual radar echoes rarely passed directly over a surface-wind recording station and so it was difficult to relate individual showers to surface gusts in a one-to-one manner. Accordingly we have derived average velocities for clusters of showers observed to be moving with similar velocities (50–100 km across) and we have compared these with the maximum surface gusts recorded within one hour of the corresponding time. Figs 6(a) and 6(b) show the results for 0600 $\pm$ 1 h and 0800 $\pm$ 1 h. In these diagrams the velocity vectors for observations within $\pm$ 1 h of the nominal map time are plotted in positions slightly displaced from their true geographical positions so as to be in the correct location relative to the mesoscale wind system at map time. The displacements were made assuming a system velocity equal to the mean shower velocities. Figs 6(a) and 6(b) show that the maximum surface gusts at exposed sites were within $\pm$ 5 m s^{-1} of the velocities of the nearby shower echoes. This agreement is as good as that between the maximum

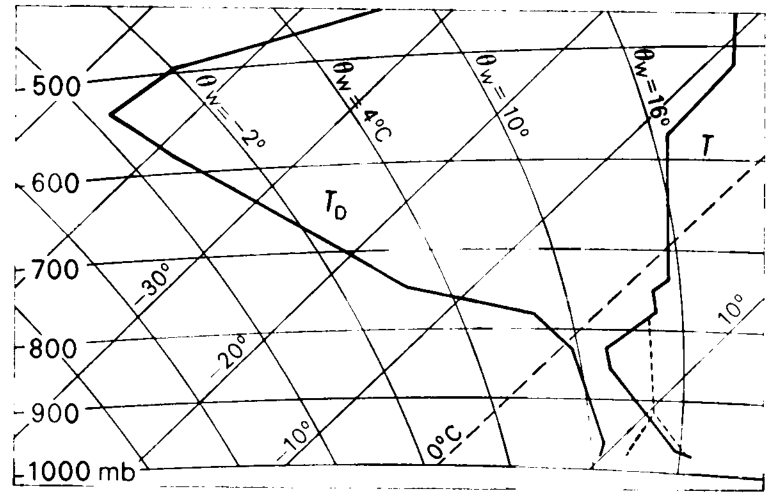

Figure 3. Vertical sounding from Larkhill at 09 GMT on 14 August 1979, representative of the airstream generating the showers. The dashed line shows the path of ascent for a parcel of air rising from the sea surface (T = 16 °C, T_d = 12 °C) through ambient conditions represented by the sounding.

gusts reported by adjacent anemometer stations and so we cannot hope to achieve verification to any greater accuracy. Comparing Fig. 4 with Fig. 6 we further note that the shower velocities reflect the trend shown by the peak surface gusts, which increased over the period 0100–0600 and then began to decrease over the period 0600–0800. Over Scilly, for example, around 0000 GMT the maximum gusts were in the range 23–26 m s^{-1}; they increased to 26–28 m s^{-1} around 0600 and then fell again to 23–26 m s^{-1} around 0800.

The above results are consistent with a model in which eddies confined within the convective boundary layer mix momentum vertically so as to produce downdraughts which over the sea and at exposed coastal locations reach the surface with a horizontal component of velocity similar to that possessed by the convective element as a whole and greater than that of the mean surface wind. The anemograph traces show that the gusts are more numerous than the precipitation echoes observed by the radar, implying that 'dry convection' is equally important and that the weak echoes observed by the radar are simply the tracers of the flow.

It was observed that maximum gusts recorded by anemometers further inland were significantly less than those from exposed coastal stations. The greater effect of friction on the surface layer over land would reduce the strength of the maximum gusts experienced at the surface (but it is also probable that their strength is underestimated owing to the failure of the anemometers to respond fully to sudden, large, short-lived increases in wind speed). Nevertheless, the shower velocities still provide an upper limit to the gusts which might be expected over land.

4. Further examples

In view of the promising results derived from the tracking of small precipitation echoes on the occasion of the Fastnet Race gales, other occasions were sought on which radar observations of shallow showers were obtained during strong winds. One such case occurred on 7 and 8 December 1979 when a depression moved north-north-west along the western coast of Ireland and strong winds occurred to

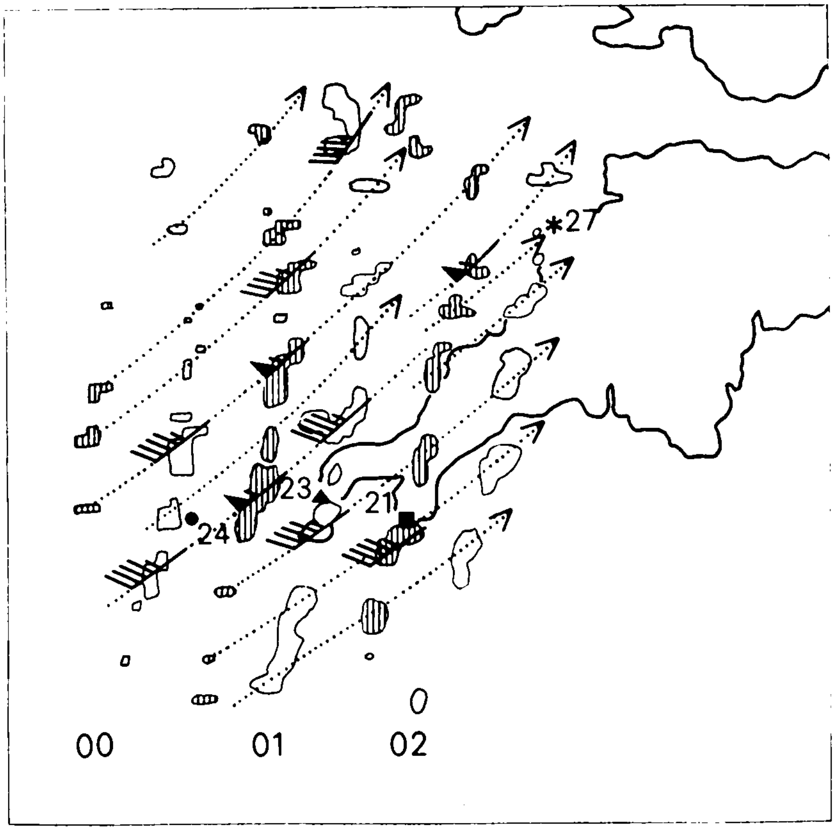

Figure 4. Successive half-hourly positions of a line of showers observed by the Camborne radar; alternate positions are shaded. The tracks of individual showers are marked by dotted lines and their average velocities over periods of half an hour are represented by wind shafts (one full feather = 10 m s^{-1}; one triangle = 25 m s^{-1}). The peak surface gusts (m s^{-1}) experienced at the passage of this line are plotted at Scilly (●), Gwennap Head (▲), Lizard (■) and Hartland Point (*).

the south of it behind the cold front. Fig. 7 shows the surface analysis for 12 GMT on the 7th. Small precipitation echoes were observed by the Camborne radar on the 7th and again on the 8th, and multi-elevation data indicated that they were confined below 3 km except for a few hours around midday on the 7th. Vertical soundings representative of the airstream maintaining the showers showed a well-mixed convective boundary layer with a general cloud-top level around 750 mb (2·4 km).

As in section 3 the shower velocities have been compared with the maximum surface gusts and the results are shown in Fig. 8. Fig. 8(a) is for 1000 $\pm$ 1 h on the 7th and Fig. 8(b) is for 0400 $\pm$ 1 h on the 8th. The maximum gusts at the exposed sites are within $\pm$ 5 m s^{-1} of the velocities of nearby showers. Comparing Figs 8(a) and 8(b), it is evident that the peak surface gusts decreased in the period between 1000 on the 7th and 0400 on the 8th, and the shower velocities manifest the same trend. (On this occasion the peak gusts recorded at Scilly appear low compared with those shown by the other anemometers and the shower velocities, illustrating that there is a problem in verification, probably because of the effect of the exposure to different wind directions of any anemometer situated on land.)

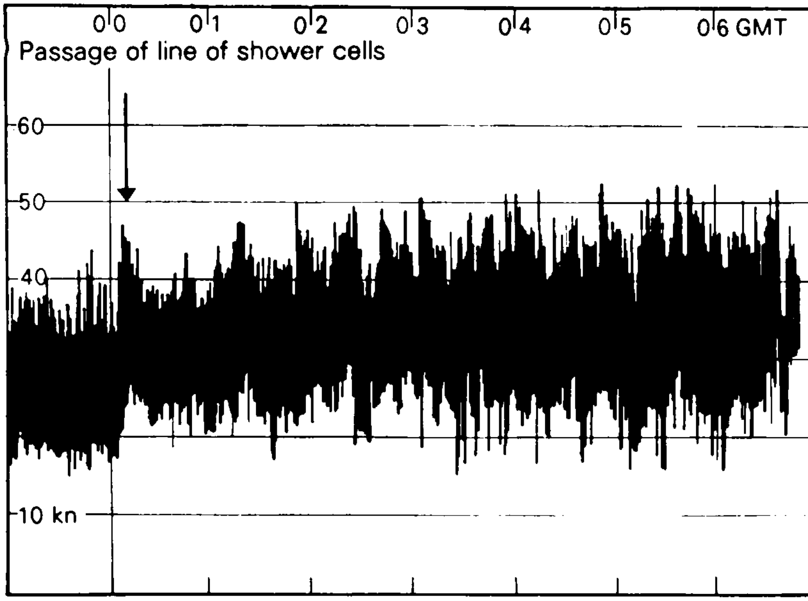

Figure 5. The anemograph record from Scilly on 14 August 1979 between 00 GMT and 06 GMT showing a maximum gust of 24 m s⁻¹ (47 kn) on the passage of the line of showers, and gusts over 26 m s⁻¹ (50 kn) later in the period.

Table I summarizes the results for 14 August, 7 and 8 December and for some other occasions on which radar observations of shallow showers were compared with peak surface gusts. Comparisons between the two sets of velocities are made within two zones, both zones being centred on Gwennap Head, the approximate centre of the set of anemograph locations. (On three occasions the showers were some distance from the set of anemograph locations, in which case a comparison can be made only over the larger of the two zones.) Table I shows that, with the exception of 17 December at 0000, all the cases gave agreement between the sets of velocities to within $\pm$ 5 m s^{-1} in both areas. (At 0000 on the 17th a few small precipitation echoes moving eastwards at 31 m s^{-1} were observed far to the south of the other showers.)

5. Possible operational utility

The velocities of shower echoes presented in sections 3 and 4 were derived off-line by careful subjective analysis. However, in view of the relationship that has emerged between the velocity of shallow shower echoes and the maximum surface gusts at exposed coastal station, it appears that these velocities might, on occasions, be useful in an operational context provided that they could be evaluated virtually in real time. Accordingly, an objective computerized cell-tracking procedure was applied to the Camborne radar data on 14 August 1979 and on 7–8 December 1979.

The procedure used is based upon the radar echo centroid tracking technique described by Barclay and Wilk (1970). Echo areas were defined using a single-linkage cluster technique. This is a simple form of hierarchical clustering (see, for example, Anderberg 1973) which places, in clusters, grid squares with echoes which lie within a specified number of grid squares in the west–east and north–south

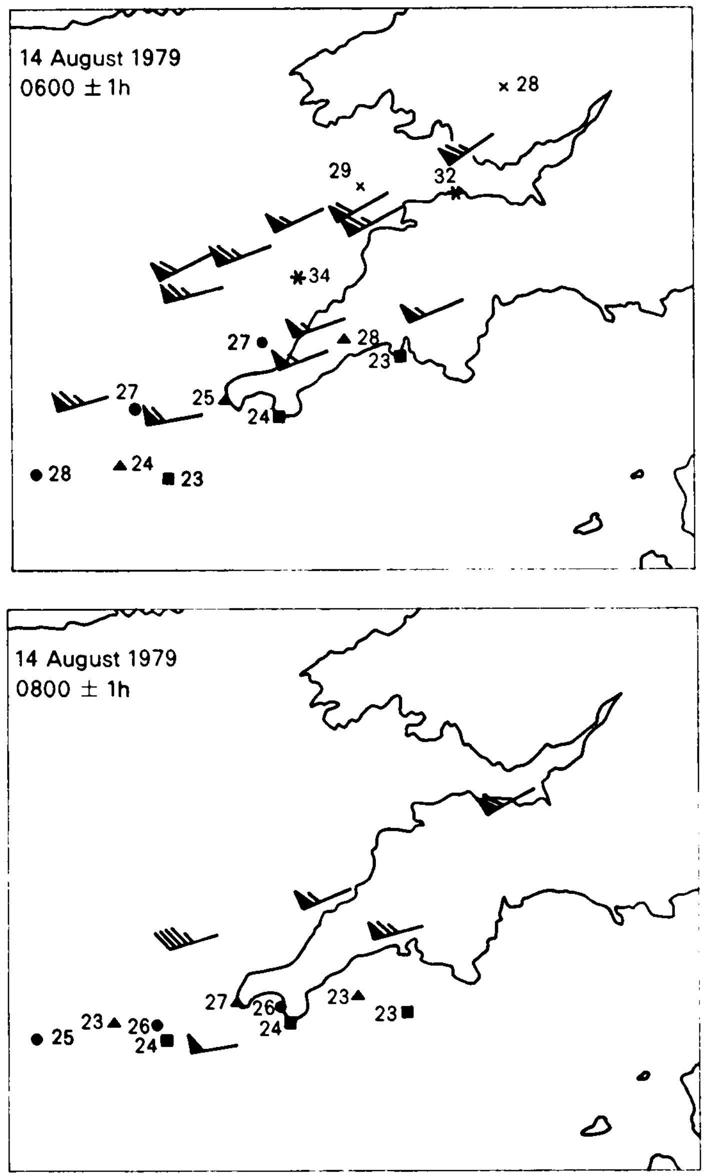

Figure 6. Shower velocity vectors for 14 August 1979 at 0600 ± 1 h and at 0800 ± 1 h. The average velocities were derived over periods of half an hour and are plotted as wind shafts, where one full feather represents 5 m s^{-1}. Peak gusts (m s^{-1}) experienced at the following exposed sites are plotted for comparison: Scilly (●), Gwennap Head (▲), Lizard (■), Hartland Point (*), Mumbles Head (X). All observations within ± 1 h of the nominal map time are plotted in positions displaced from their true geographical positions so as to be in the correct location relative to the wind system at map time.

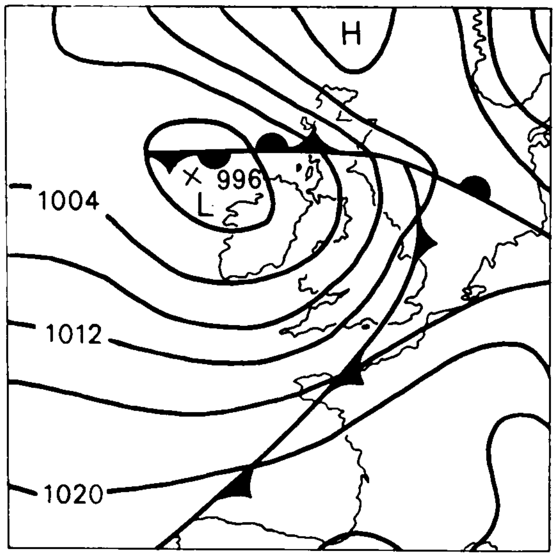

Figure 7. December 1979, 12 GMT: surface isobaric and frontal analysis as published in the *Daily Weather Report* of the Meteorological Office.

directions. (A more detailed description will be given in a paper being prepared by Browning *et al.*, entitled 'On the forecasting of frontal rain using a weather radar network'.) The basic input data used in this study were recorded on a 5 km grid at 5 min intervals.

A comparison of the objectively derived echo velocities with those derived subjectively is shown in Fig. 9. Altogether the computerized procedure recognized 19 clusters of shower echoes on 14 August and 20 on 7–8 December. Most of the objectively derived velocities are seen to be within $\pm$ 5 m s^{-1} of the subjectively derived values, thereby indicating the potential of the objective procedure. An investigation of the individual echo clusters identified objectively showed that all except one of them corresponded to actual groups of showers. The sole exception, identified by brackets in Fig. 9, suffered from confusion with sea clutter. When the objective procedure was rerun using data at 15 min instead of 5 min intervals and on a 20 km instead of 5 km grid, this led to far fewer showers being tracked and it produced erroneous velocities for up to half of the remaining tracks.

Considerably more effort has been put by the meteorological community into the use of sequences of geostationary satellite cloud images for wind determination than has been put into the use of radar sequences. Individual cumulus clouds and stratus elements are normally used for the measurement of low-level winds on the mesoscale. The only clouds which are good tracers of the mesoscale wind field at low levels, however, are very small ($\approx$ 2 km) and short-lived ($\approx$ 10 min) (Fujita *et al.* 1975) and, just as we have found in the present study that 5 min radar data are needed to give reliable velocities, so too it has been found by other workers that 5 min satellite imagery is needed in order to give reliable results (Rodgers *et al.* 1979).

6. Conclusions

The speeds of weak shower echoes observed during the 1979 Fastnet Yacht Race and on other occasions have been shown to be of comparable magnitude to those of the peak surface gusts at exposed coastal locations. Objective procedures can be applied virtually in real time and these have been shown

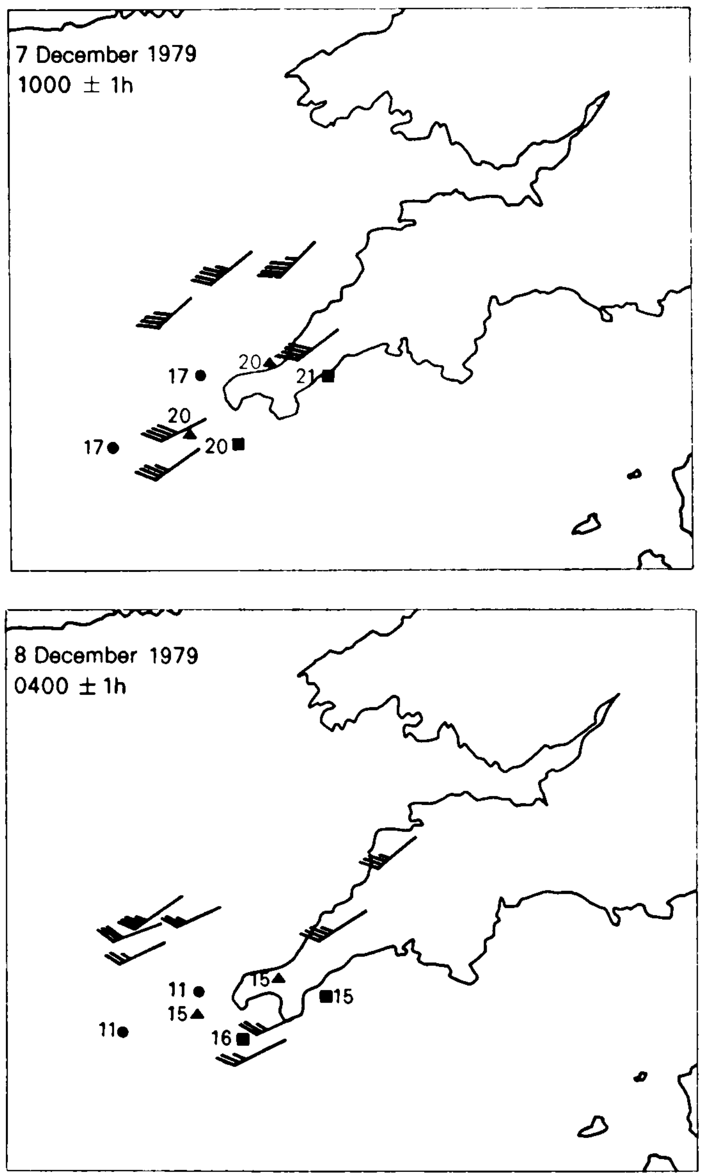

Figure 8. Shower velocity vectors and peak gusts at exposed sites, plotted similarly to Figure 6 for 7 December 1979 at 1000 ± 1 h and 8 December 1979 at 0400 ± 1 h.

Table I. *Comparison between shower velocities and peak surface gusts on* 10 *occasions when shallow showers were observed by the radar.*

Date	Time GMT	Maximum possible height of showers km	Range of shower speeds within 50 km of Gwennap Head m s^{-1}	Range of peak gusts within 50 km of Gwennap Head m s^{-1}	Range of shower speeds within 100 km of Gwennap Head m s^{-1}	Range of peak gusts within 100 km of Gwennap Head m s^{-1}
29 Sept. 1978	0400	3·1	19–20	20–25	19–22	20–25
14 Aug. 1979	0600*	2·7	29	24–28	26–33	24–34
14 Aug. 1979	0800*	2·7	22–25	24–27	22–27	23–27
30 Nov. 1979	1900	2·7	17	15–18	17–21	15–18
30 Nov. 1979	2230	2·7	None	16–20	15–18	14–21
7 Dec. 1979	1000*	2·5	20	17–20	18–22	17–21
7 Dec. 1979	1630	3·1	17	15–17	16–20	15–18
8 Dec. 1979	0200	2·9	None	13–17	14–16	12–17
8 Dec. 1979	0400*	2·9	13–14	11–16	13–16	11–16
8 Dec. 1979	0600	2·9	None	9–14	11–16	9–14
16 Dec. 1979	2200	3·1	19	18–22	19–22	18–22
17 Dec. 1979	0000	3·1	21–24	15–21	19–31	15–21

* These four cases are shown in Figs 6 and 8.

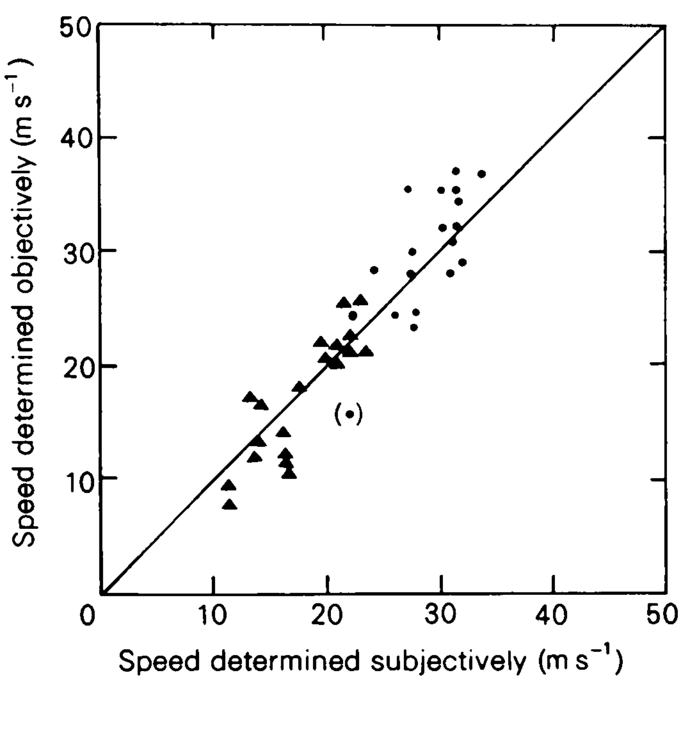

Figure 9. A comparison of shower velocities (m s^{-1}) derived from the computerized cell-tracking procedure with those derived subjectively. Results for 14 August 1979 are shown as circles, and those for 7–8 December as triangles. The bracketed symbol represents an echo cluster which suffered from confusion with sea clutter.

to be capable of measuring the echo velocities provided that the radar data are available in digital format with a resolution of at least 5 km and 5 min. In general, for the showers to provide an indication of the low-level flow, they need to be restricted to a fairly shallow ($\leqslant$ 3 km) well-mixed boundary layer. Therefore it is necessary to investigate the three-dimensional structure of the radar echoes or to combine the radar data with satellite and other information to determine whether the showers are indeed shallow. In operational terms, it is unlikely that the method of determing the upper limit to surface gusts described in this paper will be applicable on large numbers of occasions; however, the possibility is worth keeping in mind since, in an eventual operational system for the short-period forecasting of precipitation patterns, it is likely that an objective cell-tracking procedure will be carried out in any case. Thus, the ability in certain circumstances to assess the maximum likely surface gust and to determine the mesoscale structure of strong low-level winds should be regarded as a useful by-product of a future weather radar network.

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Revised analyses and their effect on the fine-mesh forecast for the Fastnet storm

By A. P. Day
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Summary
A particular combined analysis and forecast computation of the Meteorological Office fine-mesh numerical weather prediction model has been studied to discover why the 'Fastnet low' was not well predicted. The forecast was rerun several times, each run starting with a slightly changed and 'improved' analysis. It was found that a depression was predicted when the analysis was changed, and that this forecast depression could be deepened by increasing the number of analysed levels that were 'improved'. With four levels of the original analysis changed a significant depression was forecast. The position of this depression was, however, some 200 n mile in error.

Introduction

On 13 August 1979 a depression over the North Atlantic deepened quickly and moved to the south-west of Ireland. At 00 GMT on 14 August the depression was situated near Valentia with a central pressure of about 978 mb (Fig. 1). This depression had deepened by about 20 mb in 12 hours, which is very rapid for the time of year, and it was also associated with storm-force winds. It was this weather system that caused the chaos amongst competitors in the Fastnet Race of the Royal Ocean Racing Club, in which many lives were lost.

The Meteorological Office operational 10-level numerical forecast model was unsuccessful in predicting the intensity of the depression: the various operational forecasts based on observations up to 12 GMT on 13 August all failed to indicate the vigour of the system. The fine-mesh (rectangle) version of the numerical forecast starting with data for 00 GMT on 13 August was particularly inaccurate, with the 24-hour forecast of mean-sea-level (m.s.l.) pressure verifying at 00 GMT on 14 August predicting a trough of 1008 mb over Ireland. The actual m.s.l. pressure of the depression centre at this time was about 30 mb lower. An investigation, confined to this worst operational run, was carried out to ascertain whether the forecast model was unable to cope with the development or whether an inaccurate objective analysis was the cause of the poor numerical forecast.

The investigation took the form of a series of experiments.

The experiments

The experiments consisted of a rerunning of the analysis and forecast programs several times. Each run started with data additional to those used by the operational analysis thereby creating a modified analysis. These new data consisted of artificial, or 'bogus', observations of the geopotential of a number of standard levels together with a corresponding wind, for several positions over the North Atlantic. This technique, known as bogusing, is used operationally in the Central Forecasting Office (CFO) by upper-air forecasters to force the objective analysis program to prod uce a more acceptable analysis in data-sparse areas. No bogus observations had been used in the operational rectangle analysis on this occasion.

For the experiments carried out during this investigation the bogus pressure-level geopotential and wind data were obtained from subjectively analysed charts of the pressure levels concerned. Four levels of the objective analysis were changed in this manner in order to bring them closer to the equivalent subjectively analysed levels.

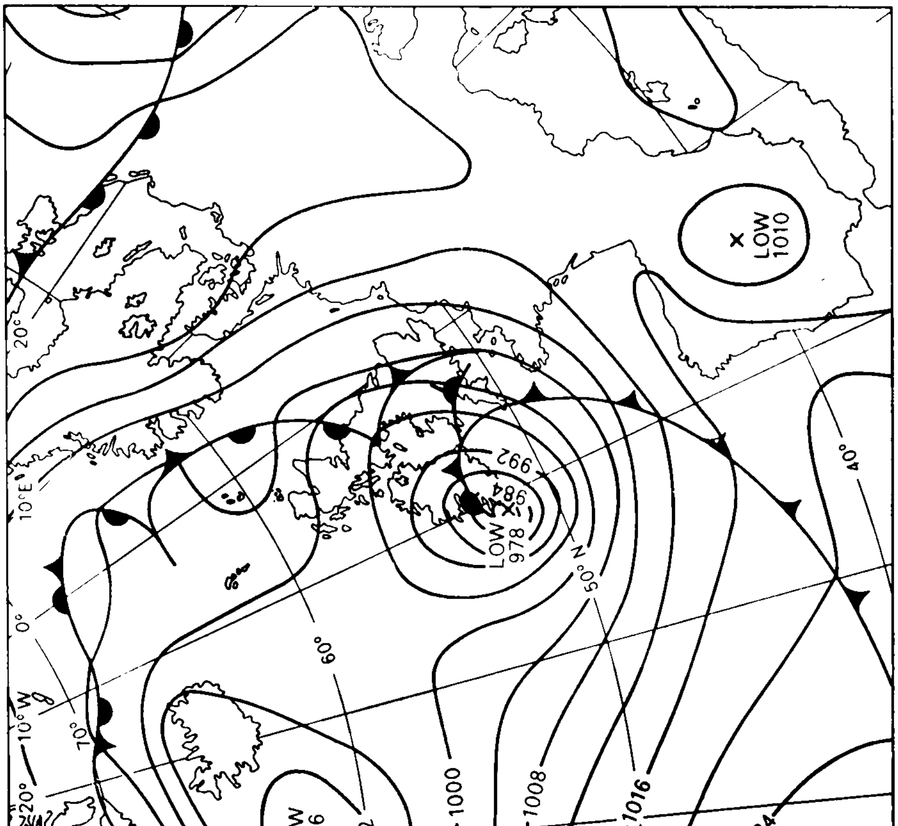


Figure 1. Subjective m.s.l. pressure analysis for 00 GMT on 14 August 1979.

The subjective and original objective analyses

There are four main levels at which the upper-air forecasters in CFO add bogus observations. These are 100 mb, 300 mb, 500 mb and m.s.l. The subjective analyses for these levels for midnight on the 13th were compared with the objective analyses to find where the major differences lay. In addition, the objective and subjective analyses for 850 mb were compared. Particular consideration was given to the region in the central North Atlantic where the depression, which became the Fastnet storm, was situated at that time. Fig. 2 shows the subjective m.s.l. pressure analysis which was drawn after the event. The central pressure of the depression, 1003 mb, is well substantiated by some late reports from ships which were not available to forecasters at the critical time. Forecasters in CFO were analysing the central pressure as about 1006 mb in the early hours of the 13th, using continuity from previous analyses.

The objective analysis scheme uses a method analogous to the continuity technique to produce a 'first-guess' analysis. This analysis is interpolated from a 12-hour coarse-mesh forecast based on data valid 12 hours prior to the current data time and is known as the background field. This background field is transformed into the objective analysis by a computer program that alters it in the light of observations made at the current data time. In regions well away from new data the background field remains as the new analysis. At 00 GMT on the 13th the background field contained a depression of insufficient depth in the area of concern. The operational analysis was made even more inaccurate by a ship correctly reporting light winds and high pressure which gave the only observation in the data-sparse area around the depression. The analysis program then interpreted this observation as representing a greater area than was actually the case, which made the final objective analysis contain a depression less deep than the background field. This depression was objectively analysed as 1014 mb, which is 11 mb higher than was eventually analysed subjectively (Fig. 2).

Fig. 3 shows the objective 300 mb analysis for 00 GMT on the 13th, together with the reports which were used for its production in the Atlantic area. Fig. 4 shows the subjectively and objectively derived isotachs from these reports although it should be pointed out that the subjective analysis used a few more aircraft reports (AIREPs) than the objective analysis; these helped to define the core of the jet stream, but only in the region 15°W to 30°W. It will be noticed that the subjective isotach chart is assigned to 250 mb. However, the same reports were used by the objective scheme at the 300 mb level. The reason for this is that the operational forecast model uses 10 levels spaced at 100 mb intervals, from 1000 to 100 mb (Burridge and Gadd 1977), and therefore it does not require an analysis at 250 mb. To make most use of the AIREPs the objective scheme assigns those within 100 mb of 300 mb to that level and the objective analysis for this level does affect those for adjacent levels (Flood 1977). The objective isotachs in Fig. 4 are those derived from the initialization process. During initialization adjustments are made to the geopotential analysis such that the fields satisfy certain requirements of the forecast model (Golding 1980). One adjustment ensures vertical static stability and may alter the various analysed geopotential fields at adjacent levels. There is also an adjustment to ensure that the wind flow is not more anticyclonic than can be allowed by the balance equation. These adjustments alter the isotachs from those deduced from the geopotential analysis. As the initialized fields are those that the forecast uses as starting data one would like these fields to be as close as possible to the real state of the atmosphere at that time.

A comparison of the two isotach fields in Fig. 4 shows that the objectively produced winds lack the strength shown by the subjective isotach analysis. Two AIREPs of 150 kn are not reflected in the objective scheme which gives speeds of 115 and 95 kn respectively in these positions. Clearly, then, the objective scheme seriously underrated the wind speeds in the jet stream above the depression. One probable reason for this inadequate analysis can be seen in Fig. 4. The grid points to which aircraft

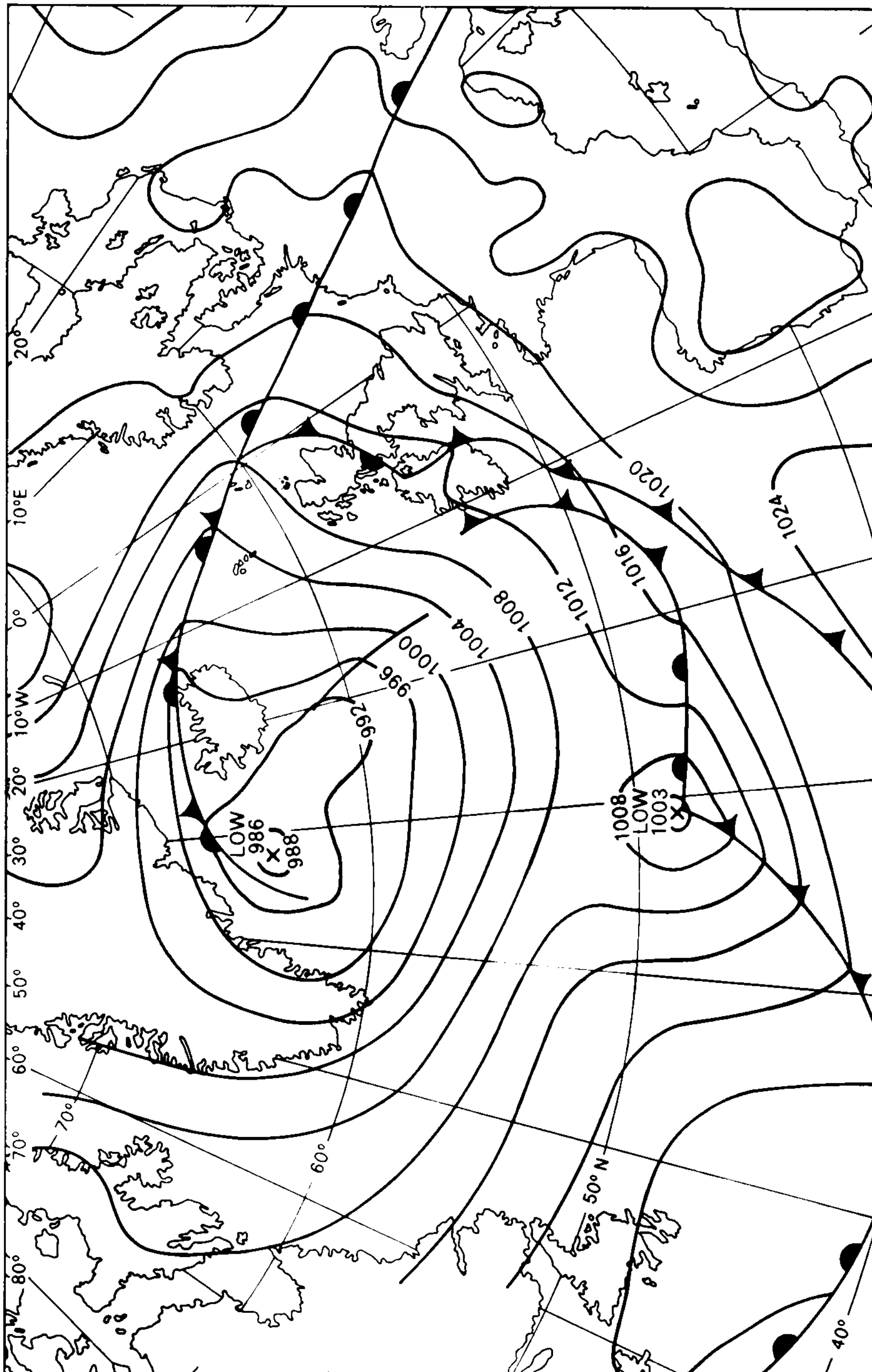


Figure 2. Subjective m.s.l. pressure analysis for 00 GMT on 13 August 1979.

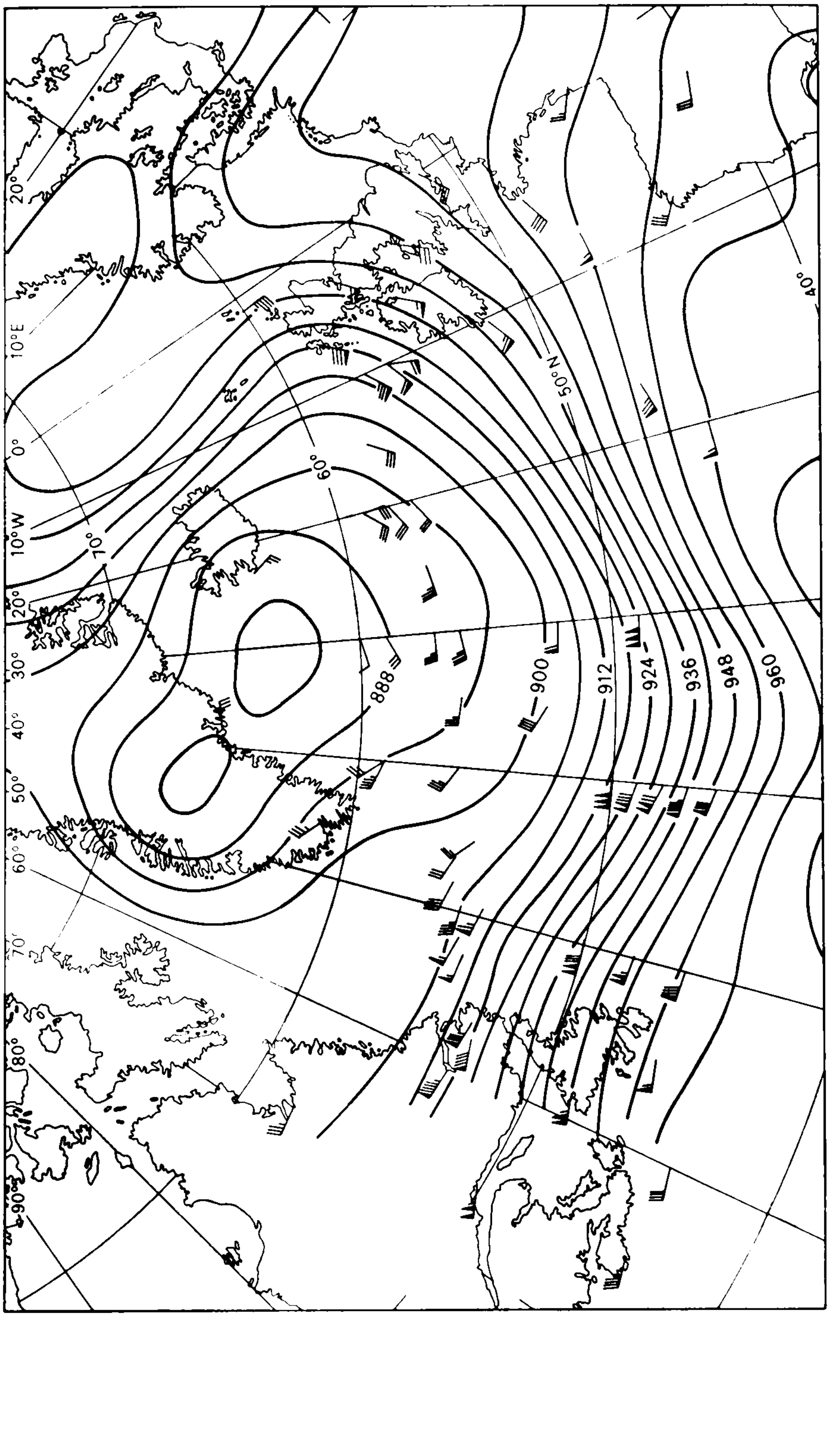


Figure 3. Original objective 300 mb analysis for 00 GMT on 13 August 1979, showing the aircraft and radiosonde reports used.

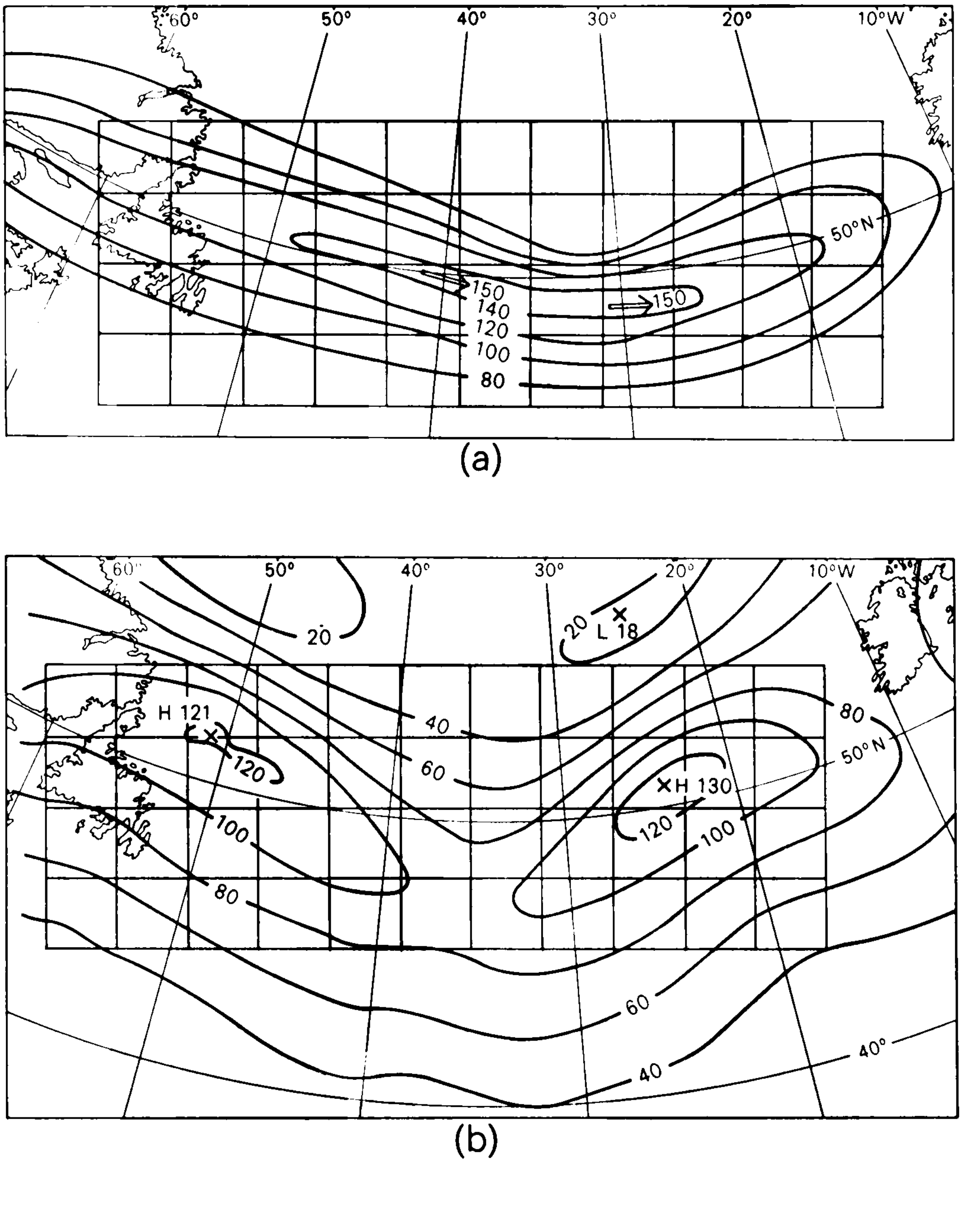


Figure 4. Isotachs for 00 GMT on 13 August 1979, in knots, showing part of the analysis grid: (a) subjectively produced from aircraft and radiosonde reports for approximately 250 mb, and (b) objectively produced from the initialized 300 mb field.

reports are interpolated are 300 km apart; the analysis fits orthogonal polynomials on these grid-point values and evaluates the polynomials on a 100 km grid. The 300 km separation of the analysis grid points clearly cannot represent the strong wind shear associated with this jet stream, most of the core of which lies between grid points. The grid-point spacing used for the objective analysis is 300 km rather than 100 km because although the fine-mesh forecast grid length is 100 km it has not been proved that a finer-mesh analysis would improve the numerical forecast enough to justify the increased computer time.

The objective geopotential analysis at 300 mb (Fig. 3) showed a marked trough at 35°W that was not really indicated by the AIREPs. The subjective analysis was drawn with a much smoother flow and also with a tighter gradient in the region of the stronger wind speeds.

The 500 mb charts were analysed with no data over the central North Atlantic apart from two weather ships. Neither of these ships provided much help in deciding what the state of the atmosphere was above the surface depression.

In the Atlantic area the subjective analysis used the standard gridding technique of adding the analysed thickness to the surface (1000 mb) analysis. The resulting analysis was then refined further, using the 300 mb analysis as a guide. The dubious accuracy of the subjective analysis at this level and, indeed, at other levels away from 1000 mb and 300 mb should be borne in mind. The major differences between the subjective and objective analyses at 500 mb were similar to the differences between the corresponding 300 mb charts. The flow was much weaker in the objective analysis and it also had a much more marked trough at 35°W.

The objective chart for 850 mb was also examined and, although there were no data for the critical area, it was considered likely that a closed circulation would have occurred above the surface depression. This was not present in the objective analysis; indeed, this analysis was probably some 6 decageopotential metres too high in the area of concern, as judged from 1000–850 mb thickness considerations.

Attempts to improve the objective analysis

The analysis programs were rerun several times using the same data that were used operationally plus bogus observations. The bogus data were added for one or more of the levels 1000 mb, 850 mb, 500 mb and 300 mb. Fig. 5 shows the objective m.s.l. pressure analysis after bogusing and Fig. 6 shows the 300 mb isotachs after bogusing. The values chosen for the bogus geopotentials near the centre of the low at 850 mb were estimated by adding thicknesses deduced from Ocean Weather Stations 'C' and 'R' to the 1000 mb geopotential derived from the subjective m.s.l. pressure analysis.

There are two ways in which the upper-air forecasters in CFO can intervene in the objective analysis. The bogusing technique has been described earlier. The second technique is the alteration of the background field via a computer terminal. If the background field does not agree with the forecaster's idea of what the analysis is likely to be at the appropriate time then the contours may be displayed on the screen of the terminal and can be modified with a light-pen. The forecaster can see the direct results of intervening in the background field because the new background field is displayed on the screen. However, this new background field is not the new objective analysis but only the first stage. Unfortunately, on 13 August a problem with the computer program did not permit intervention to be carried out in this way.

Any bogus observations that are introduced are used by the analysis program after the background field has been introduced and carry more weight in the analysis (Flood 1977). Unfortunately, it is not possible operationally to see the results of bogusing before the resulting objective analysis is used by the forecast model, so the field cannot be inspected and refined further. However, during the running of these experiments there was enough time to produce an acceptable analysis by introducing bogus data

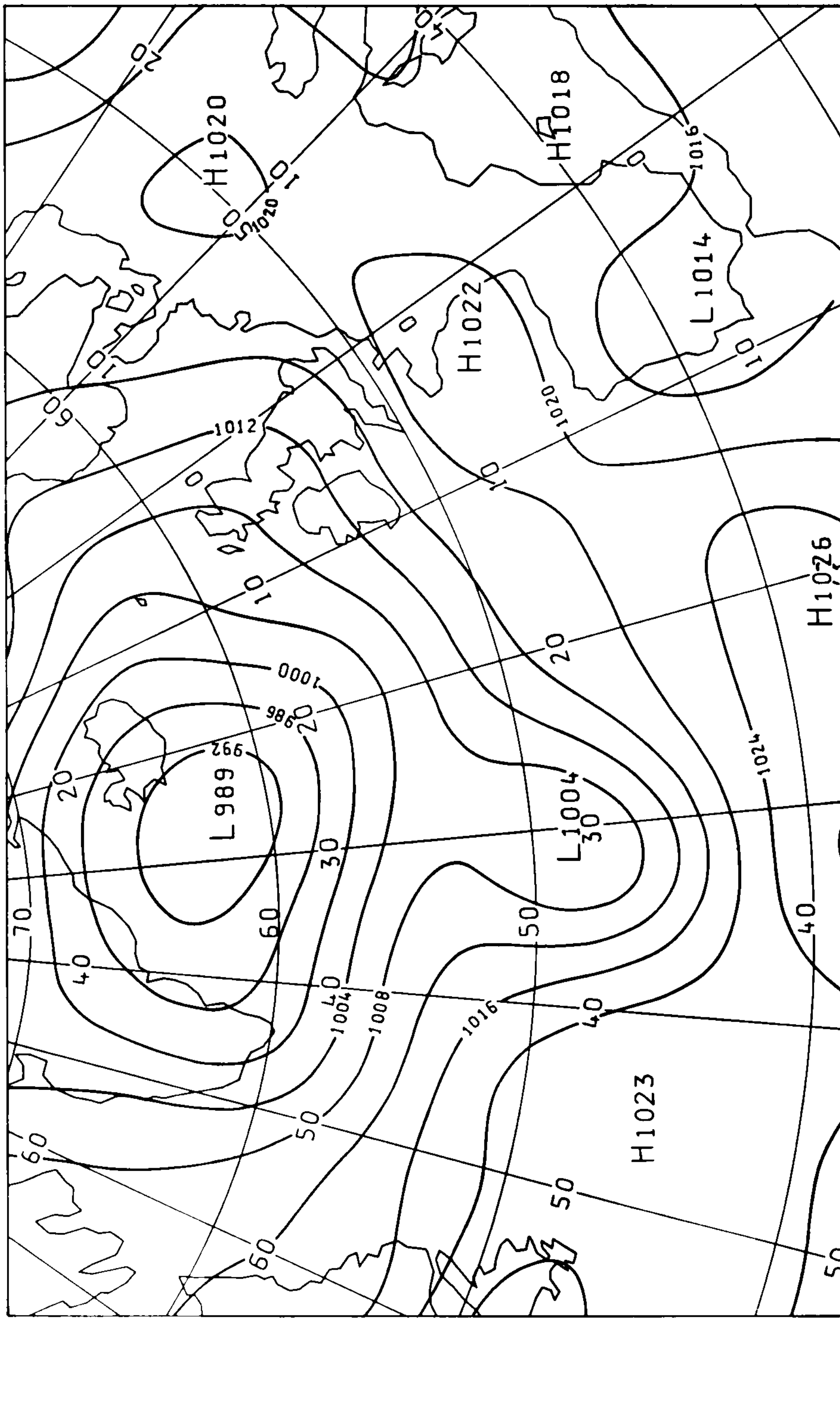


Figure 5. Objective m.s.l. pressure analysis for 00 GMT on 13 August 1979 after bogusing (as used in case 7).

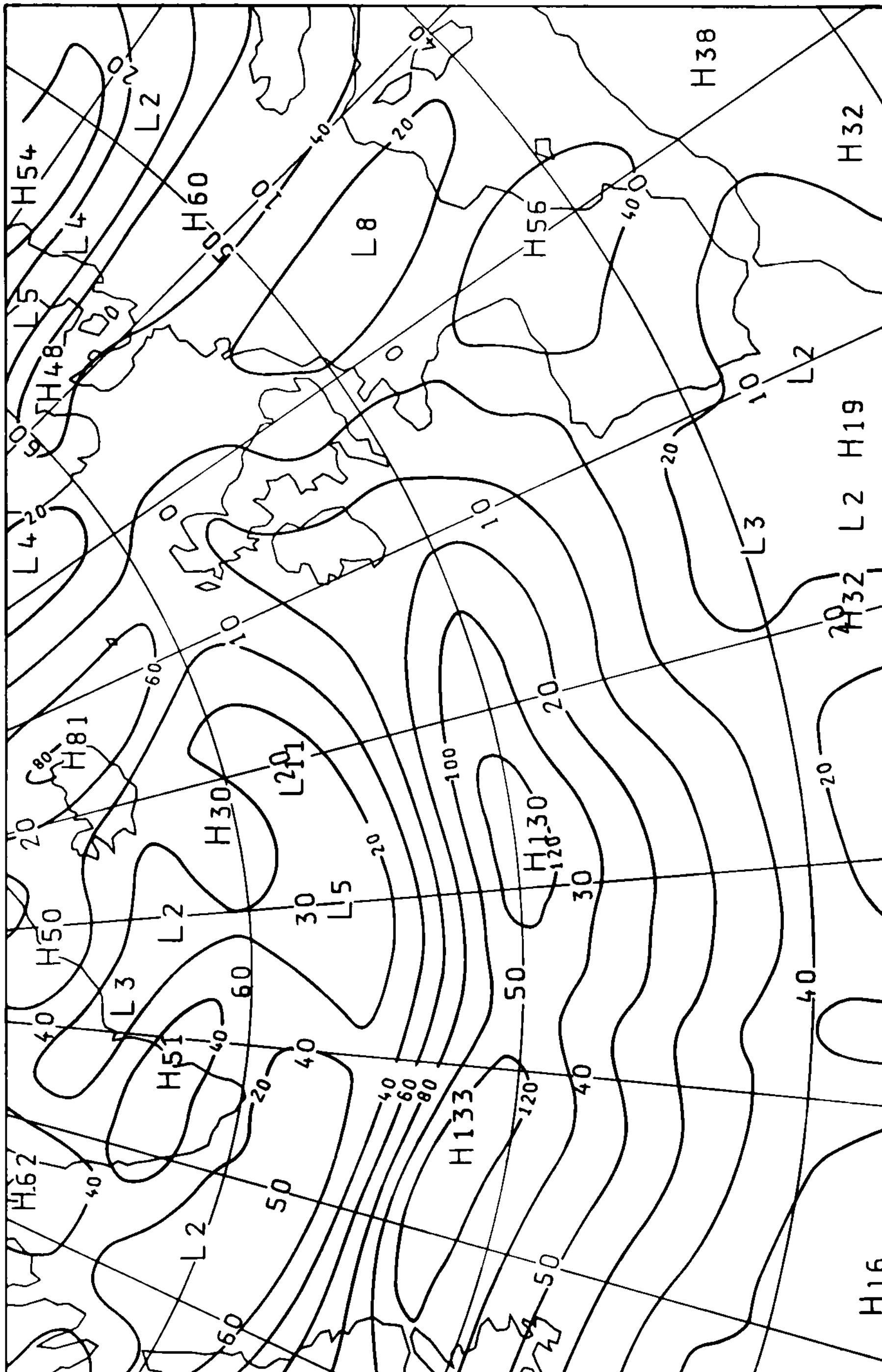


Figure 6. Initialized isotachs for 300 mb at 00 GMT on 13 August 1979 after bogusing (as used in case 7).

on a trial basis and then running the analysis program. If the fields were not acceptable the bogus data were altered and the process was repeated until an acceptable analysis was created. It can be seen that the objective m.s.l. pressure analysis produced in this way (Fig. 5) is a fair representation of the subjective analysis (Fig. 2). This technique was not very successful, however, when an attempt was made to improve the 300 mb analysis. The coarse 300 km grid would not allow the required tight gradient to be created. The isotachs in Fig. 6 show the best field produced for this level, although the wind speeds are still too light. The main improvement made to the original objective 300 mb field was an increase in gradient upstream of the surface-low position. There is still a serious lack of wind strength above the surface low at 31°W. The difficulty encountered in improving the 300 mb analysis is indicated by the fact that 17 bogus observations were used at this level. The 500 mb analysis after bogusing was probably a fair representation of the field at this level. The wind strength was increased successfully in the Atlantic region when compared with the original objective analysis.

The effect of the changed analyses on the forecast depression

The forecast was rerun seven times using a different analysis each time. The results are given in Table I and are presented in order of increasing depth of the forecast depression. Case 1 is the operational forecast. It can be seen that when the objective m.s.l. pressure analysis is acceptable, i.e. in the cases numbered from 2 to 8, bogusing at 850 mb was more effective at producing a deeper depression than bogusing at both 500 mb and 300 mb. As was explained earlier the 300 mb analysis could not be improved satisfactorily because of the coarse grid, so one cannot tell whether a good 300 mb analysis would have resulted in as much improvement in forecasting the depth of the depression as was achieved by modifying the 850 mb field. However, bogusing just the 300 mb field was more effective at producing stronger winds in the Fastnet area, probably a more important consideration for the forecaster. The position of the depression in the 24-hour forecast was most accurate when just the 1000 mb analysis level was modified. For most cases (see Table II) addition of 850 mb bogus data decreased the positional accuracy but increased the accuracy of the central pressure of the forecast depression.

Although cases 5–7 used more surface bogus observations than the other cases it is probably fair to compare all the cases 2–8 as if the surface bogusing was the same. This is supported by comparing cases 7 and 8 which differ only in the number of surface bogus observations and yet produce very similar results.

Cases 5 and 6 differ only in the objective analysis of the 850 mb level. These differences were quite small and yet produced quite a large difference in forecast position of the depression (70 n mile difference). This result indicates the sensitivity of the forecast model to the analysis at this level in the development area. There are, however, no facilities for intervening at 850 mb in CFO.

Also shown in Table II are the geostrophic wind speeds. Any of the forecasts after intervention, particularly cases 3–8, predicted more realistic wind speeds over the Fastnet area. The original operational forecast predicted a geostrophic wind of only 23 kn, whereas the forecasts from the experiments predicted geostrophic winds ranging from 35 kn to 65 kn. The actual geostrophic wind was near 100 kn over a smaller area near the centre of the low and about 60 kn for the area over which the objective wind speed was measured. The winds near the surface over the Fastnet area at this time were up to force 10. The trough that crossed the Fastnet area between midnight and 06 GMT on the 14th was well forecast. It is thought (Watts 1979) that this trough, with the associated change in wind direction and speed, was responsible for the unusually short period, very large waves. Fig. 7 shows that the original forecast gave no indication of a depression or strong winds near the Fastnet sea area. The other three forecasts portrayed indicate that gale-force winds would be likely in the area and that a vigorous depression would have formed. The trough-line mentioned is indicated on all the forecasts.

Table I. *Forecast values of the central pressure of the depression for different analyses. The actual value was 978 mb (see Fig. 1).*

Case number	Number and level of bogus observations 1000 mb	850 mb	500 mb	300 mb	m.s.l. pressure of the depression centre in the 24-hour forecast	m.s.l. pressure of the depression in the analysis at start time
					millibars	
1	—	—	—	—	1007	1015
2	3	—	—	—	1000	1005
3	3	—	—	17	996	1005
4	3	—	10	17	994	1005
5	5	5	—	—	993	1004
6	5	6	—	—	991	1004
7	5	5	10	17	988	1004
8	3	5	10	17	987	1005

Table II. *Positional error of the forecast depression, and the geostrophic wind speed for the 24-hour forecasts shown in Table I.*

Case number	Positional error (n mile)	Geostrophic wind speed over Fastnet area (kn)
1	No depression forecast	23
2	80	35
3	160	55
4	110	45
5	130	40
6	200	45
7	200	65
8	230	60

Conclusions

The following conclusions relate specifically to the combined analysis and forecast run of the fine-mesh forecast model from midnight data on 13 August 1979. However, some generalizations have been tentatively made:

(1) An inadequate analysis was a major reason why the forecast model did not predict the vigorous depression that crossed Ireland on 14 August.

(2) Alteration of the lowest levels of the analysis had a greater effect on the forecast of the depression centre than did alteration of higher levels. Specifically, the greatest effect was achieved by altering the 850 mb analysis.

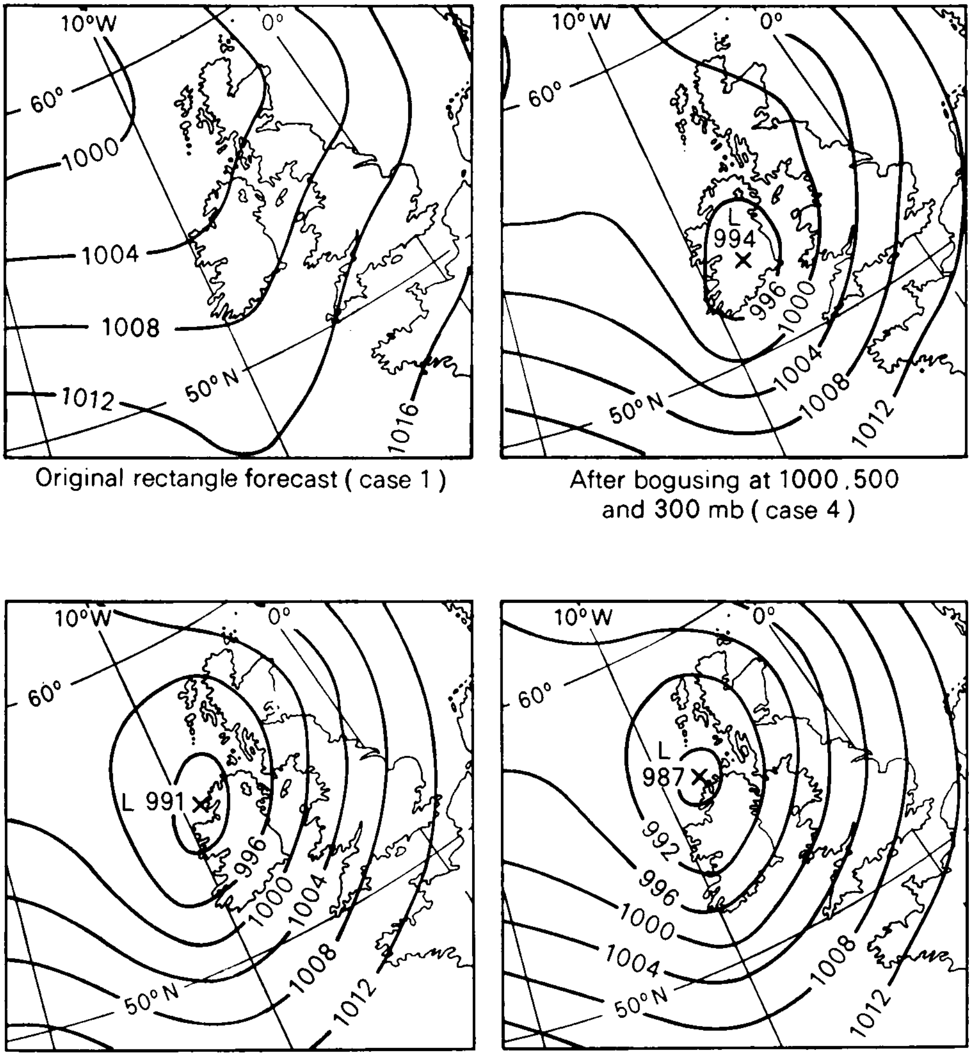
(3) If the forecast started with a good 1000 mb analysis but no other levels were improved there was an unrealistic vertical temperature profile, the 1000–850 mb thickness being too high. However, the forecast was improved if it ran with these initial conditions.

(4) The 850 mb level is not an 'intervention' level in CFO although conclusions (2) and (3) indicate it might usefully be made one, especially if the analysis itself could be modified, as opposed to the background field. However, it is unlikely that the forecasters will have enough time to do anything to this level before the fine-mesh forecast is run at HH + 2 h 20 min.

(5) The jet stream at higher levels could not be adequately analysed because of the large distance (300 km) between the analysis grid points. Thus, the effect of a good 300 mb analysis on the forecast could not be evaluated.

Acknowledgements

Many thanks are due to my colleagues in Met O 2b for their help and advice in running the computer programs and to Bruce Painting of the Central Forecasting Office for his comments on the synoptic details of the case.



Original rectangle forecast (case 1)

After bogusing at 1000, 500 and 300 mb (case 4)

After bogusing at 1000, 850 500 and 300 mb (case 6)

After bogusing at 1000 and 850 mb (case 8)

Figure 7. Some forecasts for verification time 00 GMT on 14 August 1979 (T + 24 h).

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551.5:06(a):551.509.314:061.3

The WMO Symposium on Probabilistic and Statistical Methods in Weather Forecasting, Nice, 8–12 September 1980

By R. H. Maryon

(Meteorological Office, Bracknell)

The Symposium was well attended with around 70 papers being read. It was co-sponsored by the Société Météorologique de France and the program committee was chaired ably and energetically by Dr A. H. Murphy of Oregon State University.

The Symposium coincided with an interesting phase in the relationship between statistical and dynamical methods of weather forecasting. Each method in isolation now has fairly well-defined limitations, so that a rapprochement between the two schools is becoming a matter of some urgency. It was apposite, then, that two of the most distinguished speakers, Professors Lorenz and Leith, should refer respectively to the invocation of assistance from dynamical methods to supplement statistical modelling and to the different ways in which statistics might be used to aid numerical predictions. Lorenz hoped that meteorological statistics would extricate itself from the strait-jacket of linear additive models. Some escape from linearity may be possible either by introducing the results of dynamical prediction into the formulae or by allowing for realization of some of the non-linear processes going on in the atmosphere by means of analogue selection at an early stage of analysis. Brier (USA) recommended research into multiplicative, as opposed to additive, statistical models.

Professor Leith reviewed methods of stochastic–dynamical prediction. He concluded that Monte Carlo techniques, in which forward integrations are made from different members of an ensemble of initial states, have promise. However, model imperfections contribute strongly to error growth, so research should also focus on the statistical properties of model prediction error. The Meteorological Office has been active in this field and R. Dixon gave an introduction to the GMDH (group method of data handling) extrapolation technique and, in particular, its use in modifying systematic numerical forecast error. He pointed out that in a given regression sample a particular combination of predictors may be highly correlated with the predictand even though they are uncorrelated in the population. In the GMDH the regression data are split into two sequences. An algorithm determines best-fitting polynomials from the 'training' set which are evaluated against the 'checking' set. The best are re-combined for further cycling and evaluation. Tests on 72-hour 500 mb grid-point forecasts have yielded encouraging results although problems remain to be solved. A. Hollingsworth (European Centre for Medium Range Weather Forecasts) described an inconclusive experiment in Monte Carlo numerical prediction, where difficulties were encountered at the initialization stage. It must be concluded that at present a practicable combined statistico–dynamical methodology is awaited.

Many papers were devoted to the topic of model output statistics (MOS) and interpretation. Considerable effort has been put into MOS in France and the USA using regression and related techniques. Klein and Dallavalle (USA) compared MOS favourably with the so-called 'perfect prog.' method. These use model output and observed historical data respectively in the regressions. They also concluded that MOS regressions for daily maximum and minimum temperatures based upon 3-month seasons were better than those based upon longer periods and that forecast error increased linearly with time. The average error for a 48-hour forecast is now comparable with the 24-hour error of a decade ago. Woodcock (Australia) suggested that analogues be sought to help in the preparation of forecasts from model output and that regression formulae were best 'stratified' with reference to synoptic type. The choosing and sifting of predictors is a perennial regression problem and Meg Brady Carr (USA) described some new techniques in this field. Ulla Hammarstrand (Sweden) presented some interesting work on the prediction of the probability of convective precipitation from model output. Speculation arose, during discussion, as to what extent the mental processes of the local forecaster might eventually be duplicated by computer—a concept which no doubt prompted one or two wry smiles.

An important topic at the Symposium was that of verification and evaluation of forecasts. Ideas were clarified by Silvert (Canada) who gave mathematical formality to concepts such as the 'effectiveness' and 'strength' of a forecast. Mason (Australia) extended the topic into the cost–loss situation and decision theory. Considerable ingenuity is often devoted to the definition and analysis of skill scores and papers by Rousseau (France) and Preisendorfer (USA) were not lacking in this respect. Murphy strongly advocated probabilistic as opposed to categorical wording, even for routine short-term forecasts for the general public. Certainly the probabilistic format is particularly well suited for input to decision-making machinery. Winkler (USA) gave a useful introduction to the allied subject of Bayesian strategy.

No great optimism surrounded the topic of long-range forecasting although a plea for its interment was rather premature bearing in mind the range of material and methods as yet untried. A number of papers were read in which discriminant analysis and other multivariate techniques featured. Juien (China) reported some success in forecasting monthly mean temperature anomalies using a combination of dynamical parametrization and factor analysis, while good results were obtained by Kung and Sharif (USA) in regressing the onset of the Indian summer monsoon upon upper-air parameters. One or two workers had used ARMA (autoregressive–moving average) models of time series in attempts to project forward time-averaged fields. The Russians Gruza and Rankova submitted a paper on the evaluation of hemispherical analogue methods. They concluded that a combination of several analogues was superior to a single best match, but that the statistical record was insufficient for any noticeable improvement over climatology. Indeed, with underlying irregular long-period oscillations apparent in many meteorological time series and forcing mechanisms, one can only speculate on what might constitute an adequate data base for analogue techniques, even ignoring the additional complications stemming from man's activities. Predictability *per se* and methods in the frequency domain received relatively little airing. The writer presented an unscheduled paper in which a method of compensating for the Slutzky–Yule effect in the autocorrelation of filtered time series was developed and the result applied in investigating atmospheric coherency on certain time scales.

With the advent of statistical computer packages, cluster, canonical and discriminant analysis are becoming increasingly widely used. Discriminant methods have now been applied to the prediction of tropical storm formation and tracking with some success (Lowe, USA; Li and Yao, China). Two non-meteorological statisticians addressed the Symposium: C. W. Granger (USA, formerly UK) discussed new developments in time-series modelling, while I. Jolliffe (University of Kent) gave a review of multivariate methods. In pointing out that the last eigenvector of a joint predictor–predictand domain can be used for forecasting, Jolliffe provided an unexpected topic for discussion.

In a final session it was decided to recommend to the WMO that a standard set of guidelines for the verification of forecasts be prepared and published. It was also considered desirable that further research should be undertaken in specific areas in which statistical methods are most likely to prove useful, for example the quantification of uncertainty in forecasts.

Despite the congestion of papers, most of which cannot be mentioned in this brief synopsis, not all the time was spent in the conference room. The organizers laid on an outing to Monaco along the beautiful coastal corniche and contrived an odoriferous if potentially expensive halt at a perfumery. The Casino visit did not find those statisticians most preoccupied with Monte Carlo methods particularly anxious to test their convictions against the Bank. Memories will linger of the balmy September evenings of the Côte d'Azur.

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Dendroclimatology Workshop

By D. E. Parker
(Meteorological Office, Bracknell)

The Second International Global Dendroclimatology Workshop was held at the Climatic Research Unit, University of East Anglia, Norwich, from 7 to 11 July 1980. The presence of scientists from the Academia Sinica, Peking, along with others from North and South America, Australasia, southern Africa, west and east Europe and the eastern Mediterranean was noteworthy.

Participants discussed two main areas of concern: the availability of adequate data, and the development and global dissemination of satisfactory methods of analysis and interpretation.

The best existing networks of dendroclimatological data are for western North America and for limited areas elsewhere, mainly in America, Europe and Australasia. Serious gaps exist in Europe, Asia and the Arctic and there is an almost total absence of data from the tropics where tree rings may not be annual. The southern hemisphere, being mostly ocean, can never be adequately covered. There are plans to acquire more data for some of the gaps in mid-latitudes, but rapid progress is unlikely owing to the lack of finance, difficulties of access, and the need for representative sampling in locations where climate is a major limiting factor on tree growth. Problems of systematic data archival at Tucson, Arizona, were discussed at length.

The interpretation of dendrochronologies is an even greater problem than the acquisition of data. Difficulties include elimination of poorly understood biological factors which may affect a whole area, such as pests, diseases, human activities and ageing of stands of coeval trees. Statistical methods of removing slow 'biological' trends, even from multi-sample chronologies, may contaminate any record of actual climatic change. Furthermore, the influence of climate on trees may be limited to particular seasons, so that the climatic record is incomplete. Even X-ray densitometry, which appears to isolate a stronger climatic signal than ring-width measurement, appears to show the influence of only certain seasons. The benefits of isotopic studies of tree wood have yet to be proven.

Dendroclimatologists have become more aware of the need for verification of results using independent climatic data, and have urged that more early instrumental meteorological data be made available for this purpose. The need was stressed for adequate testing of the statistical significance of results, and also for a realization of the need for practical appreciation of the meaning of 'significance'. For instance, a correlation of 0·3 is significant at the 5% level for 46 or more pairs of data, but only 9% of the variance is thereby shown to be common between the two sets of values. It is often difficult to assess the statistical significance of results of highly complex operations such as the production of eigenvectors of the surface-pressure field from eigenvectors of the spatial network of tree-growth, and it is here that verification using independent data is vital.

The Workshop was supported by the World Meteorological Organization, the United Nations Environment Programme, the Scientific Affairs Division of NATO and the United States National Science Foundation. The Workshop was organized by Dr M. K. Hughes of Liverpool Polytechnic, Dr P. M. Kelly of the Climatic Research Unit and Dr J. Pilcher of Queen's University, Belfast.

Letter to the Editor

Civil Defence—meteorological advisers to local authorities

Your readers will be aware of the current concern over the very inadequate level of Civil Defence arrangements at present provided in the United Kingdom. The recent statement made by the Home Secretary, the Rt Hon. W. Whitelaw, on the higher priority to be given to county council emergency planning teams, encouraged the use of volunteers.

One category of volunteers that already exists has, for many years, included a number of meteorological officers. I refer to the scientific adviser groups that all county councils maintain. These volunteers, drawn from a wide spectrum of scientific disciplines, can be an important source of expert advice for local authority chief executives in a major civil disaster, or in the event of war as a result of a nuclear strike against this county.

There is an obvious relevance of meteorological conditions to the development of many major civil disasters, e.g. Flixborough and the recent Canadian rail disaster at Missasauga. The prediction of fall-out deposition patterns and the dispersal of toxic gas clouds are of vital importance to local authorities.

Many serving meteorological officers have a war role in the event of an outbreak of hostilities. It is therefore difficult for county emergency planning officers to recruit this important category of volunteer, even if there is a meteorological station in the county.

I would therefore like to appeal through your columns to meteorological officers about to retire, or those who have recently retired, to contact either myself or the county emergency planning officer of their county council. Most counties have a very talented and interesting group of scientific adviser volunteers who undertake training which is jointly sponsored by the Home Office and county councils. The commitment is not a heavy one but one of vital importance.

J. P. Whittaker
(County Emergency Planning Officer)

Royal County of Berkshire,
Department of Emergency Planning,
Shire Hall, Reading.

Obitnary

We record with regret the death on 9 April 1980 of Mr J. C. McDougall, Senior Scientific Officer, of the Synoptic Climatology Branch. Jack McDougall joined the Office in 1964 as an Assistant Experimental Officer in the High Atmosphere Branch. After some forecasting training and experience he was detached from the Office in November 1968 for two years to assist Professor R. C. Sutcliffe (formerly Director of Research in the Meteorological Office) at the University of Reading. In the next ten years he served in a number of posts both at outstations and Headquarters, including Lossiemouth, Meteorological Office College (as an instructor) and Forecasting Research. From 1971 to 1975 he studied for a degree in mathematics with the Open University and was awarded First Class Honours in January 1976—the first member of the Meteorological Office to graduate in the Open University. He and his wife Valerie—who had herself at one time been an Experimental Officer in the Office and who graduated in the Open University at the same time as her husband—were keen members of the Bridge Club and played together as partners in the First Team.

THE METEOROLOGICAL MAGAZINE

No. 1303 February 1981 Vol. 110

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For Meteorological Magazine'.

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1.80 monthly
Dd 698260 K15 2/81

Annual subscription £23.80 including postage
ISBN 0 11 726279 1
ISSN 0026-1149

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

March 1981

Met.O. 942 No. 1304 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1304, March 1981, Vol. 110

551.508:551.509.5:621.3

The work of the Meteorological Office Maintenance Organization

By N. H. Seigne
(Meteorological Office, Bracknell)

Summary

This article describes the origins of the Meteorological Office Maintenance Organization and reviews the scope of its present activities in providing technical support for meteorological offices in the United Kingdom and overseas. It discusses the structure and organization of the network of Maintenance Centres and the team at Headquarters and briefly reviews the more important aspects of maintenance. These include technical training facilities, maintenance policies and the concept of central repair, and the reporting system used to monitor the maintenance function. The article concludes by looking at the future maintenance task and how the Organization may evolve to meet the demand.

Introduction

The Operational Instrumentation Branch (Met O 16) is responsible for the inspection and maintenance of standard Meteorological Office equipment having significant electrical or electronic content. This responsibility is carried out by means of the Meteorological Office Maintenance Organization (Met O M O), which seeks to provide a wide measure of technical support for offices and equipment concerned with the Deputy Directorates of Observational Services, Forecasting Services, and Communications and Computing. The scope of the maintenance task involves regular support for some 1200 meteorological instruments and sets of communications equipment, located at 340 widely scattered installations. To discharge this responsibility effectively, the Maintenance Organization requires suitably trained staff who are properly equipped to carry out their function and located as close as possible to the area of work. The objective of Met O M O is to ensure a satisfactory level of support for local meteorological offices, seeking at all times to achieve a balance between the results obtained and the cost of the effort expended.

History

Before 1939 virtually all Meteorological Office instrumentation in general use was non-electrical in design though the first mark of radiosonde was nearing introduction and the initial Sferics (atmospherics) network was being planned. During the Second World War, regular radiosonde soundings were made and upper-air winds were determined by direction-finding by triangulation techniques, using the 28 MHz carrier frequency of radiosonde transmitters. These apart, most of the meteorological instruments in general use were sensors, linked to mechanisms which provided sufficient mechanical advantage to drive indicators or chart recorders. In 1946, 10 cm radars, previously used for gun-laying, were introduced into the Office for wind-finding purposes and technicians were recruited, mainly from the Services, to maintain them. In this way, isolated pockets of electronic expertise were established at radiosonde stations. In addition, a small group was located at Harrow (Instruments Branch) to provide a specialist 'fire brigade' activity to deal with the more complex maintenance problems, to undertake inspections and installations, and to provide training facilities for new entrants. Later, a group concerned almost exclusively with the installation and maintenance of communication and facsimile equipment was established at Dunstable. With the introduction of Bomber Command Fax network, there arose a need for a further centre at Watnall. The introduction of the National Fax network throughout the United Kingdom showed that installation and maintenance could not be carried out satisfactorily or economically from these two centres alone and the radiosonde stations with their technician complements and geographic spacing were obvious candidates as locations for additional maintenance centres. By 1965, an increasing range of electronic and electrical instruments had come into operational use, notably cloud-base recorders, cathode-ray direction-finders (Sferics), and the ground-station instrumentation associated with the radiosonde network (Cintel). It was important to users of these instruments that they operated reliably and were checked regularly (where possible) to ensure accuracy; also in the event of failure there was need for speedy remedial action. It was against this requirement that a field support group known as the Regional Servicing Organization (RSO) was established, with a Headquarters team located initially in the Observations and Communications Branch but later transferred to Met O 16. This Organization sought to combine the various fragmented groups of technicians engaged in maintenance activities into a single cohesive force, with a structured chain of command carrying out unified maintenance policies and employing common technical practices. Prior to this, the groups of maintainers were wholly administered and locally directed by the Meteorological Office Branches on whose stations they were based. With the formation of the RSO, administrative and techical direction passed to Met O 16 and, in 1974, all staff engaged in maintenance activities both at home and overseas were placed within the Met O 16 staff complement. In 1976, technical support for the Ocean Weather Ship Base was provided for the Observational Requirements and Practices Branch (Met O 1) and by 1977 all equipment used by the Deputy Directorates of Observational Services and Forecasting Services and, to a lesser extent, Communications and Computing, was maintained by the Maintenance Organization. To recognise these expanding activities the RSO was redesignated the Meteorological Office Maintenance Organization (Met O M O).

Functions

The primary functions of the Met O M O fall under the following main headings:

(1) To ensure the operational serviceability and performance of all Meteorological Office meteorological instruments for which maintenance responsibility has been accepted by means of regular maintenance visits and inspections.

(2) To provide a technical advisory service for meteorological officers for all matters concerning the operation and status of their equipment or where an appreciation of technical practices is required.

(3) To act as agents for other sections in Met O 16 by providing support in field trials of prototype or pre-production equipment, field calibration of instruments, evaluation of provisional documentation and the installation of portable types of equipment such as facsimile recorders and wind-measuring systems.

(4) To undertake the collection and dissemination of field maintenance data for design, development, management, and maintenance services.

These varied activities take Met O M O technicians into every corner of the United Kingdom (see Fig. 1). Some of the pieces of equipment are located on exposed coastal sites whilst others are installed on elevated sites or remote moorlands in the northern uplands and Scottish Highlands. Many pieces of equipment are mounted on towers reaching heights of 20 m, whilst others are located on top of multi-storey buildings, lighthouses and bridges. Access to these sites can be very difficult, particularly during the winter months, and the regular servicing of these instruments calls for considerable dedication on the part of the maintainer. Travel to the sites is mainly by road and, collectively, technicians drive over 250 000 miles each year. Access to offshore platforms and islands is by helicopter, whilst a variety of small craft, including inflatables, are used to visit buoys. The magnitude of the task continues to expand. Currently, more than 1200 instruments are maintained, comprising some 30 different types which are installed at 340 widely scattered locations. The major equipment networks include: 330 facsimile recorders, of which more than 20 are used for the reception of satellite imagery, 70 cloud-base recorders, 100 temperature-recording systems, 325 wind-measuring systems, 20 radars (weather and wind-finding), 15 sets of radiation data logging equipment, 12 Mk 3 radiosonde ground-stations, and a diverse range of equipment associated with the Ocean Weather Ship service. Another major area of work is that concerned with providing technical support for the Headquarters communications centre. Here maintenance teams provide a full 24-hour cover for the computer-based message switching system AUTOCOM and the facsimile complex. Within the communications centre a large number of electro-mechanical devices are in use. Some are peripheral to the computer system, such as storage disc drives, line-printers and teletypes, while others form part of the facsimile 'store and forward' system. Satisfactory throughput of meteorological data is heavily dependent upon the reliable operation of this equipment and a comprehensive maintenance program is required to ensure that satisfactory performance is obtained. The Meteorological Office is progressively becoming more involved in equipping oil platforms and buoys in the seas around our coasts with instruments and data acquisition systems, and similar equipment is being installed on small remote islands off the north coast of Scotland. An Automatic Weather Station (AWS) has been successfully installed upon Muckle Holm in the Shetland Isles and plans are well advanced to locate a further AWS on Sule Skerry. The technical aspects of maintaining equipment offshore are not more difficult than those associated with land-based systems, but there are problems and hazards in working and, indeed, travelling to these offshore sites which place them in a different category from maintenance activities normally carried out on the mainland. In consequence, it was decided that the work would be carried out most effectively by staff dedicated to the marine maintenance task who need to be good sailors and have an aptitude for work aboard ships and buoys. Maintenance of the buoy moored in deeper water (DB1) located some 137 miles south-west of the Isles of Scilly is especially challenging, involving as it does a 35-hour trip each way in quite small vessels during which sea swells of typically 5–10 metres are experienced.

To carry out successfully the technical and physical tasks required to keep the buoy serviceable, whilst trying to combat the peculiar motion of the buoy, calls for a high degree of commitment to the job. To undertake this work a Marine Maintenance Centre has been established, forming part of the larger Centre maintaining the Ocean Weather Ships at Greenock. From this Centre, staff carry out a regular program of inspections and maintenance on the Ocean Weather Ships and will shortly extend the work to Automatic Weather Stations on oil platforms located in the Beryl and Piper fields in the northern North Sea. As the marine work expands, staff from the Bracknell Maintenance Centre are becoming involved in the support program for meteorological equipment located on oil and gas platforms in the southern North Sea, and the Royal Sovereign light-tower, as well as ships calling into southern ports. In providing this support program for marine activities, close co-operation is maintained with the Port Meteorological Officers and staff in the Marine Division.

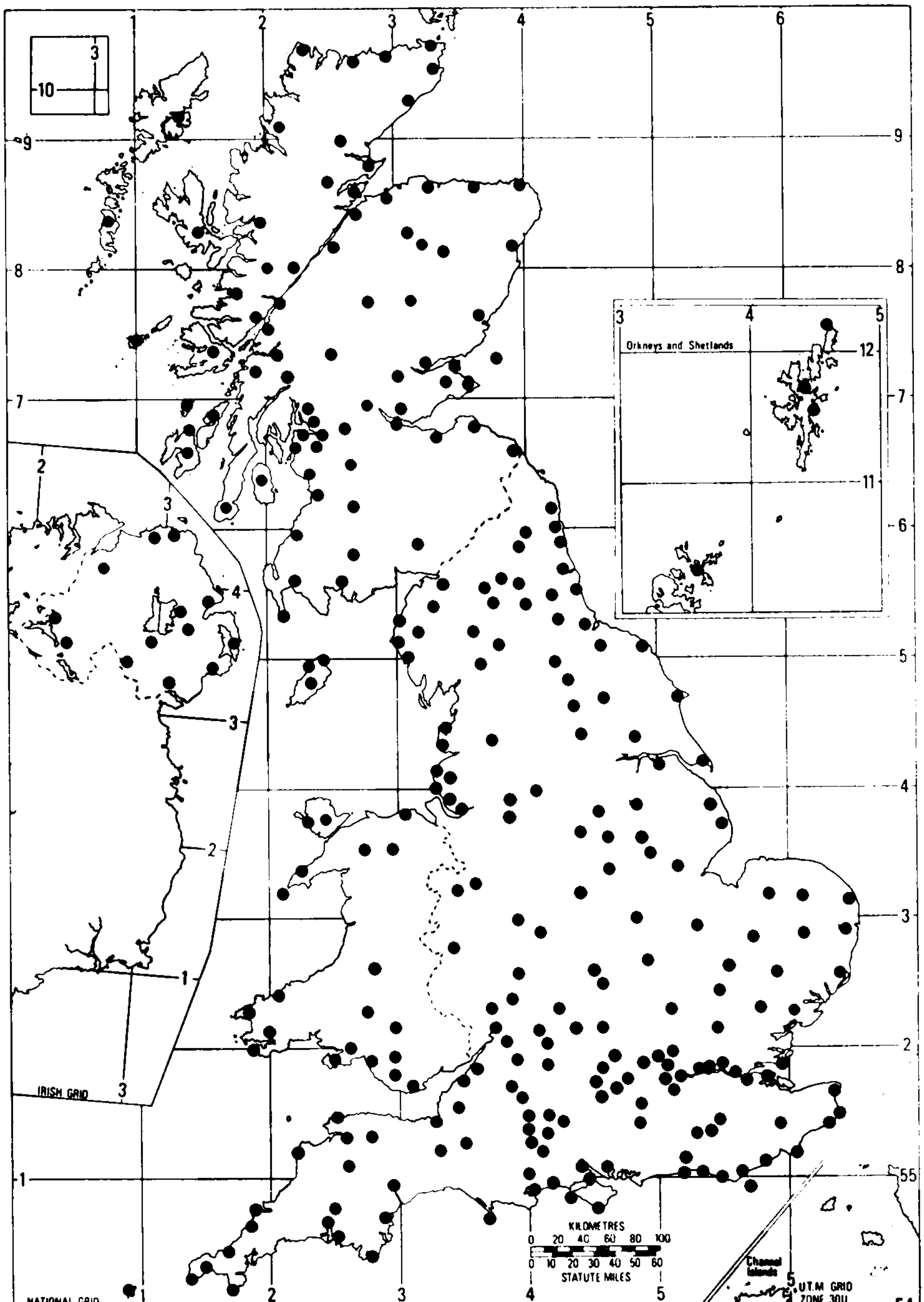

Figure 1. Locations of meteorological offices supported by the Meteorological Office Maintenance Organization.

Organization

Given the widely scattered distribution of meteorological equipment within the United Kingdom and the need to respond quickly to instrument failures, a policy of decentralization has been adopted. At Headquarters a small team comprising a Chief Technical Officer and two Group Technical Officers designated (North) and (South and Overseas) has been established. These control 22 geographically distributed Maintenance Centres, each supervised by an Area Technical Officer and grouped into 5 Regions, each controlled by a Regional Technical Officer. This organization has several advantages:

(a) It allows the Centres to be placed close to the centre of the work-load. This minimizes travel, speeds the time to respond to calls for support and enables the establishment of small but fully employed teams.

(b) It enables close links to be forged between the equipment user and the maintainer with the aim of using the equipment in the most effective manner.

(c) It allows close control of the work to be achieved and improves the efficiency of the maintenance activity.

(d) It increases the maintainer's personal involvement with specific equipment, so that he obtains a deeper insight into local equipment operation and an increased job satisfaction.

The organization chart (Fig. 2) shows the Met O M O infrastructure and the distribution of the 22 Centres in the United Kingdom and the 4 overseas. As stated earlier, there are three levels of direction and responsibility: Headquarters, Regional and Area. At Headquarters, concern is for the overall assessment of the maintenance task and the direction of Met O M O activities. Major functions are:

(a) to partition the work-load and to allocate responsibilities to ensure maximum use of staff and to minimize travel,

(b) to frame maintenance policies for each equipment type (here the appropriate sponsoring Headquarters Branch and the finance branch (Met O 4) are involved closely with the formulation),

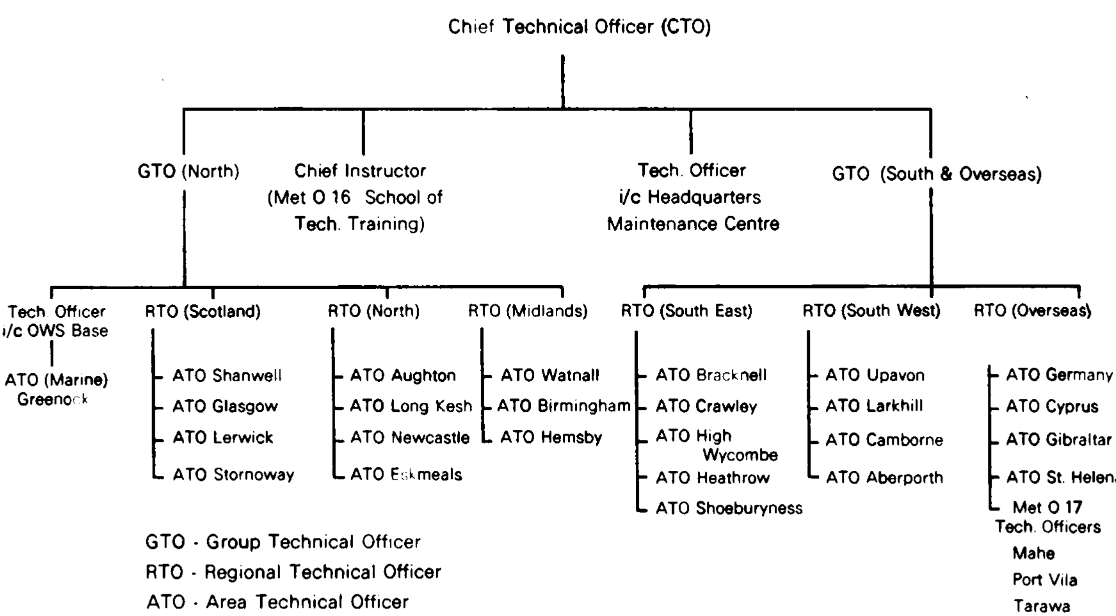

Figure 2. The structure of the Meteorological Office Maintenance Organization.

(c) to co-ordinate the activities of the Area Maintenance Centres (AMCs) by specifying the work to be undertaken through the issue of maintenance instructions and inspection schedules,

(d) to collect servicing data for management, maintenance, development, and logistic purposes,

(e) to make arrangements for servicing at fourth-line level (see Appendix), and

(f) to advise the Personnel Management Branch on technical staff matters and to liaise with other Headquarters Branches on aspects affecting the inspection, calibration, and, where appropriate, the installation of equipment.

In addition, the Headquarters team are called upon to deal with the many elements of work associated with the day-to-day line management, technical, and administrative problems that arise. In particular, close attention is given to all activities concerned with staff reporting, training and career advancement. The Headquarters Maintenance Centre and the 21 AMCs in the United Kingdom are wholly administered and directed by Met O 16 and are located at meteorological offices, radiosonde stations, Weather Centres, and civil airports. This arrangement enables the Centres to take full advantage of local accommodation and communications facilities, and to be sited sensibly, central to the area work-load, this being typically within a radius of 100 miles from the AMC. Locally, each AMC is directed and controlled by an Area Technical Officer (ATO) who leads a small team of technicians, usually not more than three. The distribution of these AMCs and their area of operation is shown in Fig. 3. A substantial amount of responsibility is placed upon the ATO and his technician staff. Staff manning these Centres enjoy a considerable degree of devolved autonomy; each technician has to respond to the varied needs of outstations with the minimum of supervision. Most technicians recognize their job as a challenge and respond positively and, although they are part of a team, there is considerable scope for personal involvement. There is a wide variety of equipment to be maintained and no one technician can expect to gain and retain full comprehension of it all. Specialization amongst members of the teams is encouraged, since this improves the combined performance of the teams and has the added effect of building the individual's confidence in his technical ability. At five of the Centres (Shanwell, Aughton, Watnall, Bracknell, and Upavon), a Regional Technical Officer (RTO) has been established to provide an enhanced level of expertise and experience to enable that Centre to carry out work to third-line level. He also undertakes work of a more exacting nature in the fields of inspection, fault diagnosis and field calibration of equipment employing the newer technology. The RTO is responsible for the direction and control of all AMCs in the Region and also technical control of the entire population of specified instruments. He is expected to establish effective communication with the officers-in-charge of meteorological offices by regular visits and discussion on matters concerning the performance and operation of their equipment and so promote the interchange and feedback of technical information between equipment users and the development and post-design groups in Met O 16 Headquarters.

Overseas

Technical support facilities are provided for overseas stations in a manner similar to that for the United Kingdom. For Royal Air Force Germany, Met O 16 staff are based at Rheindahlen and provide cover for all Meteorological Office equipment in the British Sector of West Germany and also support the facsimile recorders in Gatow (Berlin). Similarly, there are Maintenance Centres at Cyprus, Gibraltar and St Helena. Technical staff overseas are members of the Maintenance Organization and come under the technical direction of Met O 16, but for administrative purposes they are placed under the control of the local Principal Meteorological Officer, since it is for him to decide where local operational equipment priorities lie. Close co-operation on these matters is established between Met O 16 and Met O 6 (Defence Services Branch) as appropriate and no inter-Branch difficulties are experienced in administering these dual responsibilities. The technical activities of these overseas teams are co-ordinated in

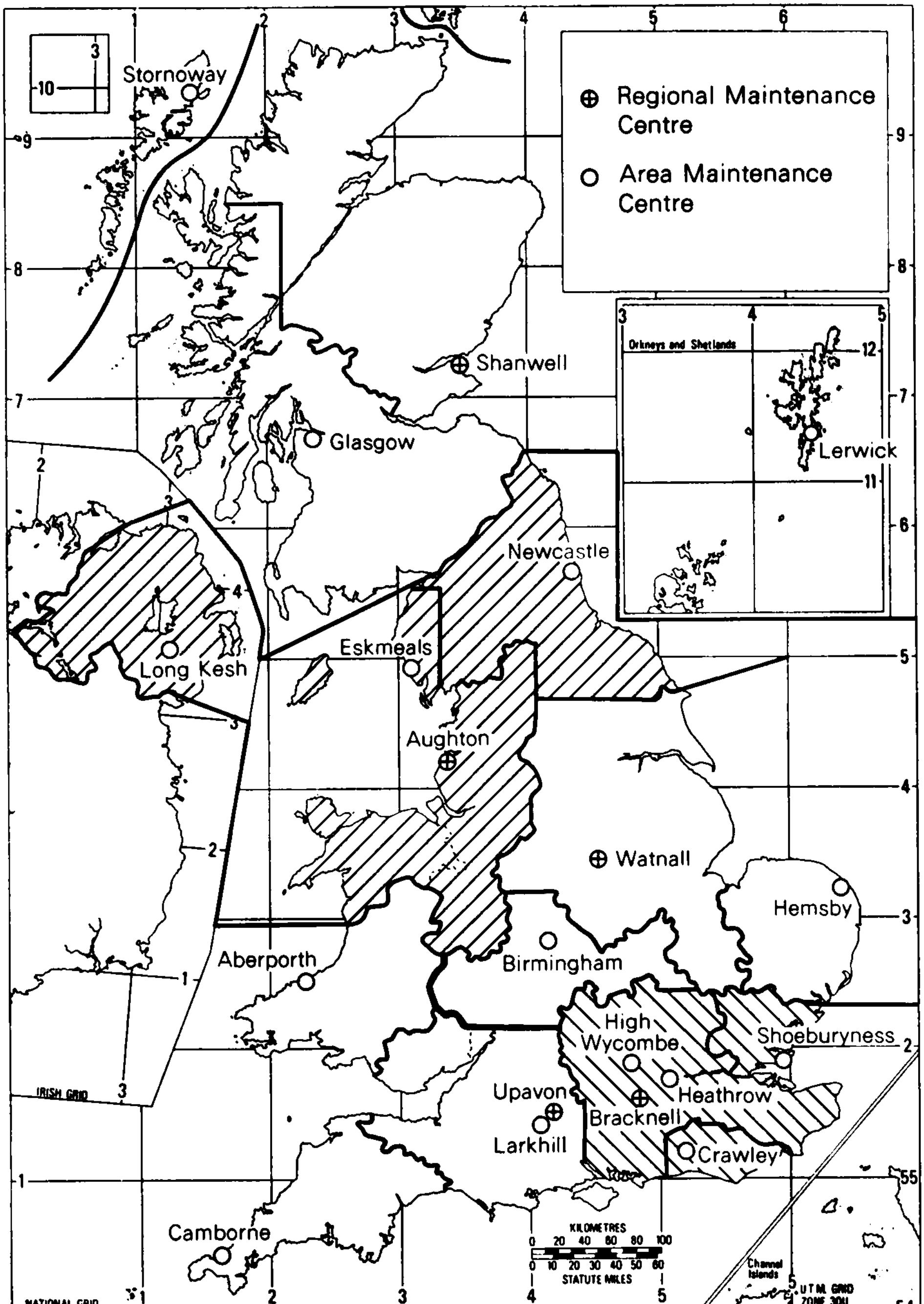

Figure 3. Distribution of Area and Regional Maintenance Centres and their areas of operation.

Met O 16 Headquarters by an Overseas Inspector, RTO(O), who is required to carry out a regular program of inspection and liaison visits. He is also required to provide Headquarters support should an 'emergency' arise and to ensure that the overseas teams are kept fully informed on all technical aspects of the maintenance activity. The Met O M O also acts as an agent for the International and Planning Branch (Met O 17) in providing support for World Weather Watch stations. This service is mainly consultative but, on request, periodical inspections are carried out of radar installations in the Seychelles, Vanuatu, Kiribati and Tuvalu. This latter area of work is being extended to support countries in the continent of Africa.

Maintenance policies

The policy to be adopted for a particular type of equipment is dictated by the operational requirements, its design, construction and complexity, and, to a lesser degree, its location and test requirements. Within the Meteorological Office, equipment falls into three main categories:

(a) Those pieces of equipment which are relatively large, whose construction is non-modular and whose design employs thermionic valves or discrete components not mounted upon printed-circuit boards (PCBs). This category includes wind-finding and weather radars, rotating-beam cloud-base recorders, and Sferics equipment. Most of these are 10–20 years old and for these systems there is no alternative but to maintain and repair them locally down to component level. This demands that a large inventory of spares be held on-site, that the maintainer has a detailed knowledge of the system, has access to a wide range of test equipment, and has been given extensive training. Fortunately, with the advent of PCBs and solid-state devices, many of these problems have been designed out of the new equipment. Nevertheless, these older designs still represent a substantial proportion of the current maintenance work-load.

(b) This category covers all pieces of equipment whose construction is based on modular principles and which use the newer technology. For these more recent designs Met O M O adopts a 'repair by replacement' policy for failed modules and this requires the maintainer only to diagnose the malfunction to one section of the equipment, and to replace the item for subsequent repair at a central workshop. Typical Meteorological Office equipment of this type includes the Mk 3 radiosonde ground-stations, Meteorological Office Weather Observing Stations (MOWOS), Digital Anemograph Logging Equipment (DALE), Continuous Automatic Remote Displays (CARD), and Mk 5 wind-measuring systems.

(c) For small portable instruments such as Magnetic Tape Event Recorders (MTER), Digital Temperature Indicators (DTI) and some wind-measuring systems the policy is to replace the complete instrument when it fails and to return the item to a central repair facility. Here the equipment 'down-time' is limited purely to the response time of the repair team.

The concept of central repair carries with it the commitment to hold locally at AMCs a number of operational 'spares' to support the network of portable equipment and also a full range of modules and PCBs for the more complex systems. Central repair carries with it the following advantages:

(a) The equipment 'mean time to repair' is decreased and hence its availability is much improved.

(b) The level of training and expertise to be acquired by the field maintainer for any one type of equipment is reduced. This enables him to achieve an effective working knowledge of a wider range of instruments.

(c) The local holding of specialized test equipment associated with the more complex equipment such as microprocessors can be reduced, and the inventory of components can be limited at the Maintenance Centres.

On the other hand, there are disadvantages, such as the following:

(a) It may initially prove more costly to support the equipment with spare modules, PCBs, etc.

(b) The central repair time can often be lengthy, particularly if undertaken by an outside agency. Should this be the case then the central base spares would need to be increased to cover the additional turn-round time.

(c) There may be some loss of job satisfaction on the part of the field maintainer.

It is the job of Met O M O to examine the repair policy implications for each type of equipment in conjunction with the equipment sponsor and the finance branch and to attempt to find the most cost-effective option. This mainly involves balancing the cost against the operational requirements. The repair policy is defined at the earliest possible stage so that maintainers and equipment users are well aware of the various implications prior to installation. The successful introduction of equipment into field service depends largely on an adequate logistic support being available.

Various considerations need to be taken into account:

(a) An adequate range of spares must be available where they are most required. If the equipment is remote and 24-hour operation is required, these spares must be held at the parent Maintenance Centre; such items may of course support a number of types of equipment.

(b) The maintainers need to receive an adequate level of training for the work specified and all the relevant documentation must be provided.

(c) Any special-to-type test equipment necessary for the regular maintenance must be made readily available.

(d) Back-up repair facilities have to be organized. These should include:

(1) skilled staff at Headquarters who can travel if necessary to the equipment location at relatively short notice,

(2) a centralized repair facility supplied either 'in-house' or by the manufacturer, perhaps incorporated in a support maintenance contract, and

(3) an adequate pool of main base spares.

When these facilities have been made available (as for systems such as the Cossor wind-finding radar and the Mk 3 radiosonde ground-stations) and the project management has been of a high order, the introduction into field service has been successful.

Maintenance reporting system

If a maintenance activity is to be managed in a realistic way it is necessary that the operation should be monitored effectively so that management decisions can be based on the realities of maintenance, rather than on assumptions. To meet this requirement a fairly comprehensive reporting system has been established based mainly upon equipment servicing reports. These reports detail the equipment worked upon, the number of man-hours expended in both preventive and remedial maintenance, the man-hours expended in travel, and the components used. Such data may be analysed to yield information about the cost-effectiveness of the maintenance system, where the cost reflects the efficient use of resources and the effectiveness of the system is measured by its ability to maintain equipment in working order. The data derived from the reporting system can be used by all management levels for their decision making. The supervisors at Maintenance Centres use the data to schedule and to employ properly the staff assigned to them, whilst at Headquarters these data are used to optimize area work-loads and to identify equipment with poor performance. At a higher management level these data can be used to judge general maintenance effectiveness in relationship to the operational requirements. Additionally, the reports can identify weaknesses in equipment design or the need for intervention by post-design services and the location of maintenance areas where additional training or improved support documentation is required. They can also be used to alert higher management to the need to initiate equipment replacement programs. At present, the use of the reporting system enables effective control of the maintenance activities to be achieved but the effort available for prompt analysis of the reports by manual methods is lacking.

To overcome this problem, work is in hand to try to design an Equipment Information System for Management (EISM) seeking initially to improve the cost-effectiveness of Met O M O. The system will use as source data information culled from the maintenance engineers' report forms which will be processed by automatic means, using 80-character punched cards as input to COSMOS (the main computer system of the Meteorological Office).

Technical training

Technical training is conducted by Met O 16 instructors based at Beaufort Park acting as agents for the Assistant Director (Professional Training). The main source of technician recruitment over the past 10 years has been the Scientific Class under the Assistant Scientific Officer (ASO) to Radio Meteorological Technician (R(M)T) conversion scheme. Selected ASOs are given a sound technical education and this allied to their meteorological background has produced a steady flow of technicians of high calibre. The aim of the ASO/R(M)T course is to provide the minimum technical and practical training to enable the selected trainee to be put to work effectively at the earliest opportunity, leaving him to complete his formal technical education through 'on-the-job' training and external study concessions. This approach enables the technician to gather experience whilst learning his profession and to keep his formal training broadly in line with the requirements of his job specification.

Normally about eight ASOs are selected for training each year and the overall conversion course extends for a period of 15 months. The Electronic Induction Course (seven months) has in the past been held at Royal Air Force Sealand; more recently the training has moved to the REME School of Electronics at Arborfield with the advantage that the facilities (including accommodation) of the Meteorological Office College at Shinfield Park can be fully used. Following successful completion of this first phase, ASOs are promoted to R(M)T (Temp.) and training moves on to the various types of electronic equipment deployed at meteorological offices. Tuition during the remainder of the course is given by instructors from the Met O 16 School of Technical Training and considerable use is made of the equipment located on the trial grounds at Beaufort Park. This second phase, of five months duration, includes a period of eight weeks devoted to practical work in the Met O 16 laboratories and workshops. Finally, a further period of three months is spent at selected Maintenance Centres, where trainees are given 'hands-on' field experience under close supervision, maintaining a wide range of meteorological instrumentation so that they may gain a full appreciation of the duties associated with the technicians' role before taking up their posts as R(M)Ts. The Met O 16 School of Technical Training is not large and has a complement of three full-time instructors. Nevertheless, virtually all the equipment in use within the Deputy Directorates of Observational and Forecasting Services is covered. Additionally, the instructors participate in the instrument maintenance courses for overseas students and special courses have occasionally been mounted abroad under the WMO Voluntary Co-operation Program.

Future services

In the past Met O M O have attempted, whenever possible, to respond to all calls for remedial action within a 24-hour period, whatever the type of equipment involved and wherever it is located, and equipment users have become accustomed to this level of service. With the increasingly tight manning situation that now prevails, and the growing amount of equipment being deployed, staff at Maintenance Centres are becoming fully stretched and this will reflect adversely on their ability to respond to service calls at short notice. It will become necessary to agree with the user Branches the priority to be ascribed to individual equipment types, or even locations, prior to introduction into field service so that an equitable balance may be struck between the operational requirements and the maintenance resources available. For systems which employ suites of sensors, such as the various types of automatic weather stations, some sensors may have less meteorological importance than others, and failures to these may need to await service until a maintenance team is next in the vicinity.

Within the next three or four years the Meteorological Office will be deploying a wide range of new instruments. These will include: synoptic and climatological automatic weather stations, laser-type cloud-base recorders, Digital Anemograph Logging Equipment (DALE), and additional unmanned radars and displays associated with a national weather radar project. Other networks of communication equipment are also scheduled to become operational within the next few years. These include the AUTOPREP systems at Main Meteorological Offices and Speech plus Duplex equipment for the dissemination of teleprinter traffic via facsimile lines to offices receiving MOLFAX. New automatic data processing systems are to be installed at Heathrow and High Wycombe and Met O M O will be much concerned in providing a full range of technical support for these systems. Maintenance policies are being framed for all these networks and consideration is being given to how they may be integrated into the current work-load. Where necessary, new centres may be established and the roles and responsibilities of existing units redefined to determine the most cost-effective combination. Types of equipment employing the newer technology are expected to prove more reliable than many of those currently in service and, where the design is mainly electronic, maintenance activities will be restricted solely to periodic calibrations and remedial work. Some, such as facsimile recorders, are capable of satisfactory operation for periods of up to four months without expert attention, providing a small amount of user maintenance is undertaken. Where this applies, Met O M O technicians will seek the co-operation of meteorological staff to provide this local service, offering such advice and training as may be necessary. Normally, Maintenance Centres have a specified area of operation but working arrangements are quite flexible and Regional and Area boundaries are in no way sacrosanct. To use the available expertise fully, Met O M O will develop specialists for various equipment types who will provide a 'fire brigade' service to deal with the more difficult equipment failures. To provide the same high level of service over the next decade will make considerable demands on the abilities of maintenance staff. There exists at present a high level of commitment to the work and staff have shown a willingness to respond readily to the difficult or dirty jobs that come their way; they are also keen to embrace new technology and to be faced with a generous work-load. To use these qualities to the full, line managers will need to be both flexible and imaginative in directing them, whilst seeking to achieve the most speedy and economic solutions to their problems. I hope that electronic designers can be encouraged to continue to improve the reliability of their equipment so as virtually to eliminate the maintenance activity, but the achievement of this objective seems rather distant at present. Nevertheless, until such time as they are able to make substantial progress towards this goal, I suggest that the future maintenance of Meteorological Office instruments by Met O M O may be viewed with some degree of confidence, and that the Organization will evolve to meet these demands as and when they are made.

Appendix

Ranges of maintenance

The maintenance of equipment is divided into four ranges, first-, second-, third-, and fourth-line, which are defined as follows:

1. *First-line maintenance*

(a) Those tasks which can be carried out by technicians to maintain the equipment in its operational state by means of functional checks, adjustments and servicing by replacement.

(b) The diagnosis of faults and their rectification by replacement units.

2. *Second-line maintenance*

(a) Those tasks which can be carried out within the resources of an Area or Station Maintenance Centre. The actual depth of maintenance carried out at second line will vary widely with different types of equipment. Where large immobile equipment such as radar is installed it will be necessary to carry out a higher level of servicing *in situ*.

(b) The diagnosis of faults in assemblies or sub-assemblies and their rectification by replacement units or replacement of elements within those units.

3. *Third-line maintenance*

(a) Those tasks which are required to maintain equipment in a serviceable condition but which require the resources of a centralized maintenance base. This category of work is appropriate to a Regional Maintenance Centre where more specialized test equipment and a wider range of spares will be accommodated.

(b) The diagnosis of faults in assemblies and sub-assemblies and their rectification by the replacement of elements within these units.

(c) The fabrication or refurbishing of simple mechanical or electrical assemblies.

4. *Fourth-line maintenance*

(a) Those technical processes requiring the use of a main maintenance base with the capacity of undertaking the complete reconditioning of equipment or manufacture of assemblies, or the repair of printed-circuit boards by automatic or manual testing, where the holding of spare components locally is uneconomic.

(b) Testing to an agreed production standard.

(c) Such tasks may be undertaken either at Met O 16 Headquarters or in certain circumstances a contractor may be used.

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Computer story

By Mavis K. Hinds
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Summary
An account is given of the history of electronic computers in the Meteorological Office from 1951 to 1980, with particular reference to numerical weather prediction.

In 1980 so much of the work of the Meteorological Office is inextricably bound up with computers of one sort or another that it is difficult to imagine the Office of only 30 years ago, when pencils, rubbers and 'plonkers'* were by far the most important tools, and slide-rules, desk calculators and Hollerith machines were merely useful adjuncts.

Back in 1948 the Synoptic and Dynamical Research Sub-committee (SC II) of the Meteorological Research Committee discussed the possibilities of using electronic computing machines (as they were then known) in meteorology. Although L. F. Richardson (1922) had put forward his suggestions on numerical weather prediction a quarter of a century earlier, his ideas had not been furthered in the meantime because of lack of computing power. It was now recommended that the Office should recruit one or more mathematicians who were specially qualified in computational methods and also obtain an electric desk-calculator for use in trial computations. Staff of the Forecast Research division spent many a boring hour in later years using the calculator, which did not even have the facility of automatic multiplication.

A big step forward came in the autumn of 1951 when Mr F. H. Bushby (now Director of Services, Meteorological Office) attended a course at Cambridge University on the use of their EDSAC computer, one of the earliest large electronic computers in the country. In a paper published in March 1952 Sawyer gives some of the early history of meteorological computing and also reports that at the colloquium given by Mr Bushby on his return from Cambridge 'there was a lively discussion on the merits of applying the first calculations to the behaviour of a textbook model cyclone rather than to the irregular disturbances of a real synoptic chart; nevertheless all were agreed that numerical methods had a more immediate application to dynamical research than to forecasting'. By the end of 1951, Mr Bushby and I were actively using LEO 1, a copy of EDSAC, which had been built by Messrs J. Lyons, the caterers, at their Cadby Hall headquarters. This machine's storage medium was mercury delay lines, which were housed in large coffin-like wooden boxes covering most of the floor of the computer room. These were very reliable but had very slow access times and were the only form of storage, as there was no backing store. In the early days the only input and output was by paper tape, but later a card reader/punch and a line-printer were installed. Paper tapes were punched on a teleprinter-type hand-perforator with the keys relabelled to the LEO 1 coding and any necessary amendments could be made only with the kind assistance of those with access to a reperforator. All values were stored in the machine in fixed-point binary and careful scaling was necessary if accuracy was not to be lost whilst ensuring that 'overflow' did not lead to wrong answers. There were no counting-registers and movement through the grid of values was done by amending all the relevant instructions after each grid point, and then testing them against the appropriate instruction for the last point in the grid line, or the final point in the grid. The storage was so small that it was essential to overwrite data and intermediate results during the computation. Programming was in a mnemonic assembler-type code.

* See the glossary at the end of this article.

The first project to be attempted on the computer was the production of charts of the Sutcliffe expression for development. The results were reported in the *Meteorological Magazine* (Bushby and Hinds 1953b) and it is interesting to note that 'the machine took 3 min. to read in the programme and data, 1 min. to perform the calculations and 1½ min. to print the results', compared with manual methods taking 4 to 5 hours.

However, the Sawyer–Bushby atmospheric model equations had now been formulated (Sawyer and Bushby 1953) and interest naturally turned to attempts to solve these equations by computer methods. Programming and numerical methods suitable for high-speed computers were still in their infancy, so it was prudent to advance by fairly small steps. The first of these was the computation of 500 mb geopotential tendencies, using the Liebmann iterative process to solve the Poisson-type differential equation. Bushby and Hinds (1953a) give some details of the computations. The program instructions occupied 480 of the 2048 storage locations in the machine and results were produced for a 12 × 8 grid of points in about 12 minutes, including 40 iterations of the Liebmann process. Intermediate results were printed out in order to compare the different terms in the equation, and the equation was solved with both zero and actual boundary conditions to help assessment of the error due to the use of the former.

The next stage was to solve the Helmholtz-type equation for the 1000–500 mb total thickness and thence obtain a representation of vertical velocity. This program was more complicated than the one for 500 mb tendencies and occupied 757 storage locations, almost half the total storage of the machine. It was suggested that we should subtract the thickness tendencies from the 500 mb tendencies in order to obtain 1000 mb rates of change and with some trepidation we did so, to find an encouraging agreement with observed changes. It was natural to extend this work to the production of numerical forecasts, but this led to organizational problems, as the necessary program and data storage would have exceeded the capacity of the machine. Since the time-stepping was by centred differences, the results of each time-step were punched out from the computer on cards and read in again during the following time-step, together with cards of part of the program which had also been overwritten. There was great pleasure the day that the first 12-hour forecast was produced and actually looked like a synoptic chart and, even more, the right chart. Forecasts were made for an 18 × 14 grid (of grid-length approximately 260 km) covering Europe and the north-western Atlantic Ocean, and a 24-hour forecast took about 4 hours' computing time using 1-hour time-steps. Most of the computing was done during evening sessions at Cadby Hall with assistance from the staff of Messrs J. Lyons both in operating the computer and the provision of supper in the managers' mess.

Cases were mostly chosen from those that had been referred to the Forecasting Research division by the Central Forecasting Office because of errors in their own forecasts, and two of the earliest ones are of particular interest. The east coast floods of 31 January 1953 occurred shortly after the computer forecast program was working and data for 15 GMT on 30 January were quickly read from the chart and punched on paper tape. The results of this forecast (Figs 1–6) show an extraordinarily severe north-north-westerly gale across the British Isles. To quote from Bushby and Hinds (1954b), 'there is no doubt that if these charts had been correct the floods would have been even more calamitous than they actually were'. The other case of interest was a forecast starting from initial data for 15 GMT on 8 January 1951 when a small wave-depression deepened considerably and moved into the south-western approaches. No such development was computed, but on this occasion the forecast produced by conventional methods was very similar to the computed forecast. Data were read from the actual charts for 24 hours later and a hindcast was performed by the simple expedient of reversing the signs in certain instructions in the program. The hindcast suggested that the small depression might have been a more intense feature at 15 GMT on the 8th than originally thought and, in fact, late surface ship reports, which would not have been available when the upper-air charts (from which the computer data were

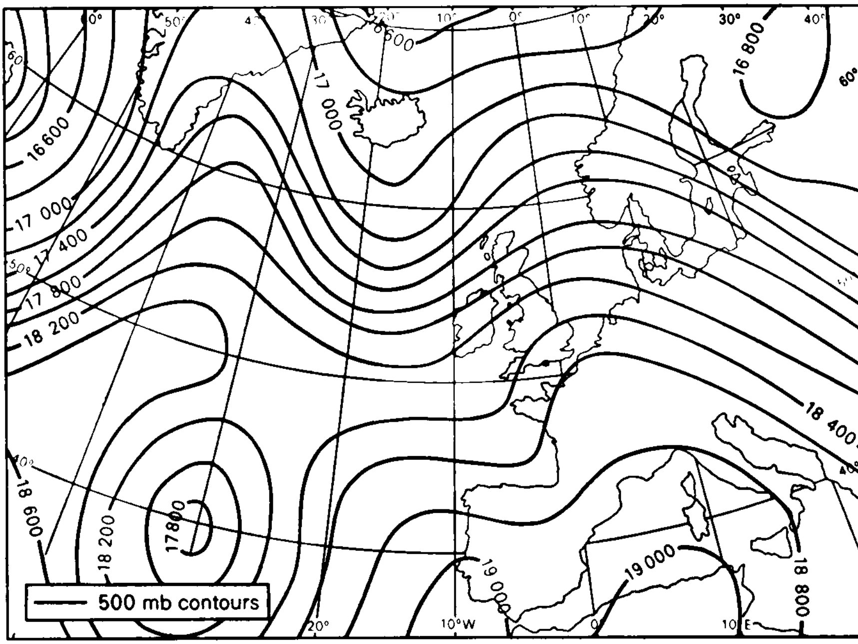

Figure 1. Actual 500 mb chart, 15 GMT, 30 January 1953. (Isopleths in Figs. 1 to 6 are geopotential feet.)

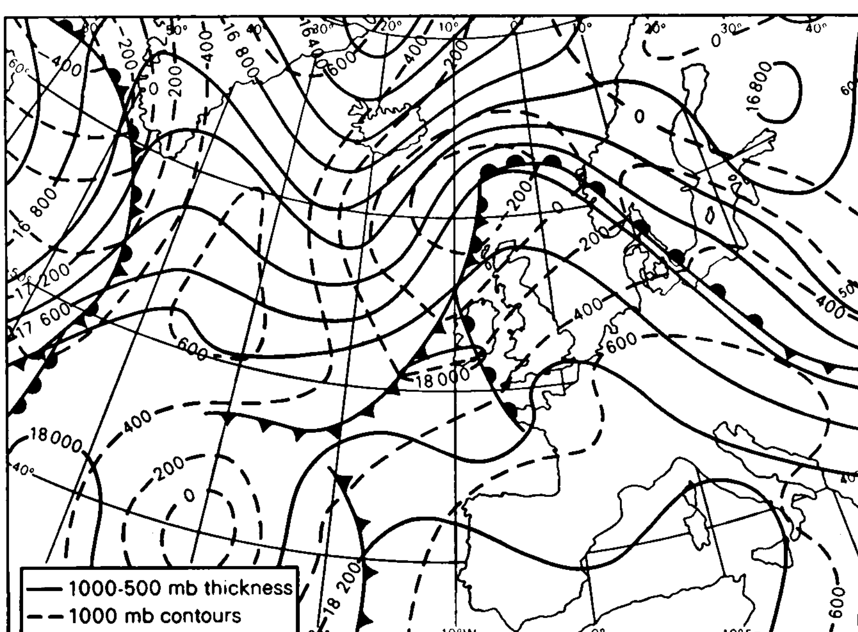

Figure 2. Actual 1000 mb and 1000–500 mb thickness charts, 15 GMT, 30 January 1953.

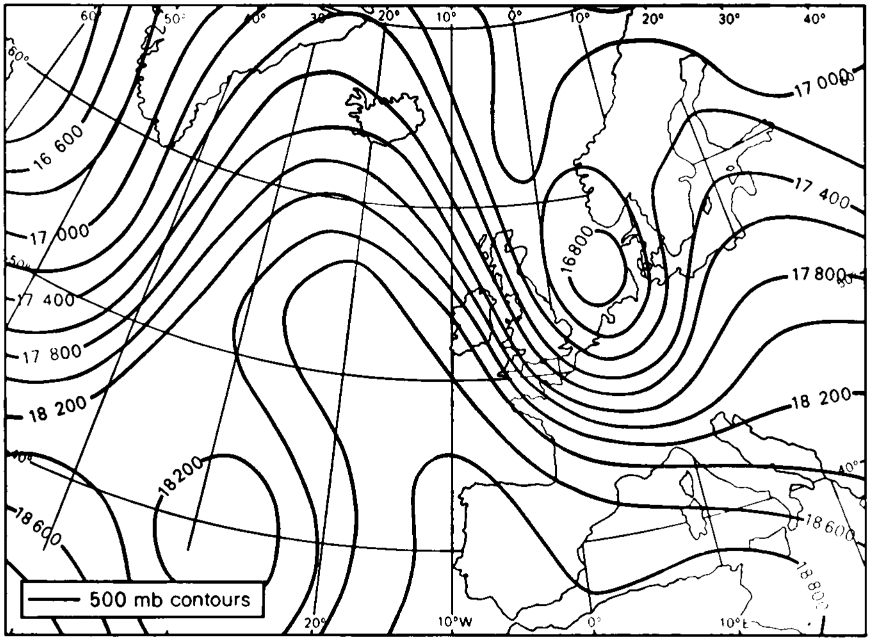

Figure 3. Actual 500 mb chart, 15 GMT, 31 January 1953.

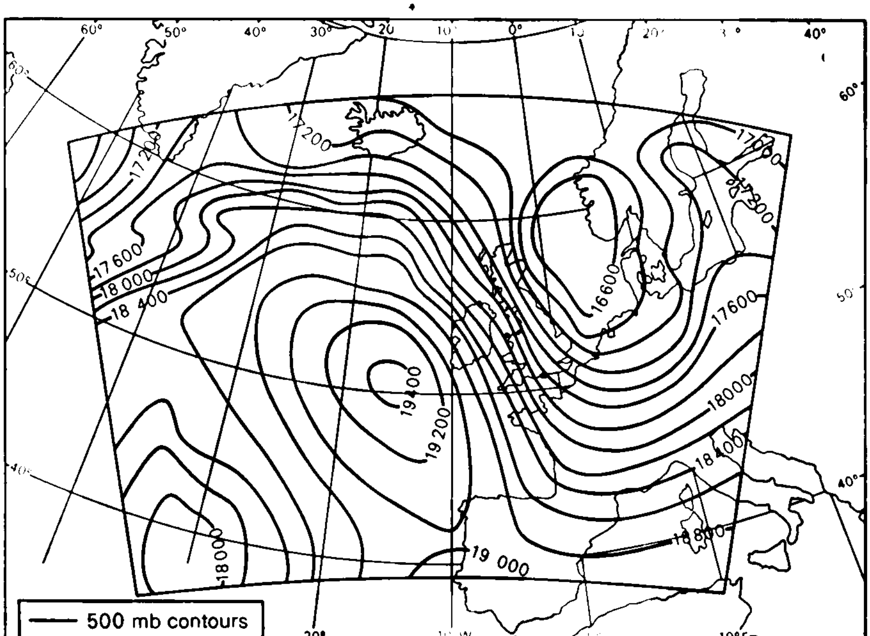

Figure 4. Computed 500 mb chart for 15 GMT, 31 January 1953, using initial data for 15 GMT, 30 January 1953, and the Sawyer–Bushby model.

Plate I. Meteorological Office staff using the Ferranti Mark 1 computer at Manchester in the 1950s.

Plate II. The console of the Ferranti Mark 1 computer at Manchester.

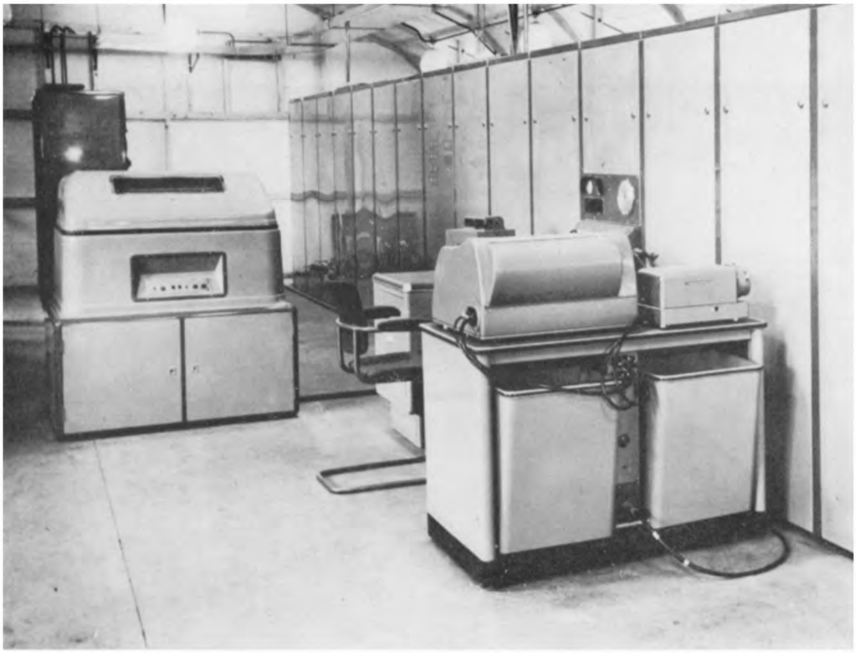

Plate III. Mercury computer at Meteorological Office, Dunstable, showing line-printer.

Plate IV. Mercury computer at Meteorological Office Headquarters, Bracknell, showing console and magnetic drums.

Plate V. KDF9 computer Comet showing console, magnetic tape decks and paper-tape readers.

Plate VI. Mounting a magnetic tape on the Comet computer.

Plate VII. IBM 360/195 computer, Bracknell, 1971.

Plate VIII. Master console and video-screen of IBM 360/195 computer at Bracknell.

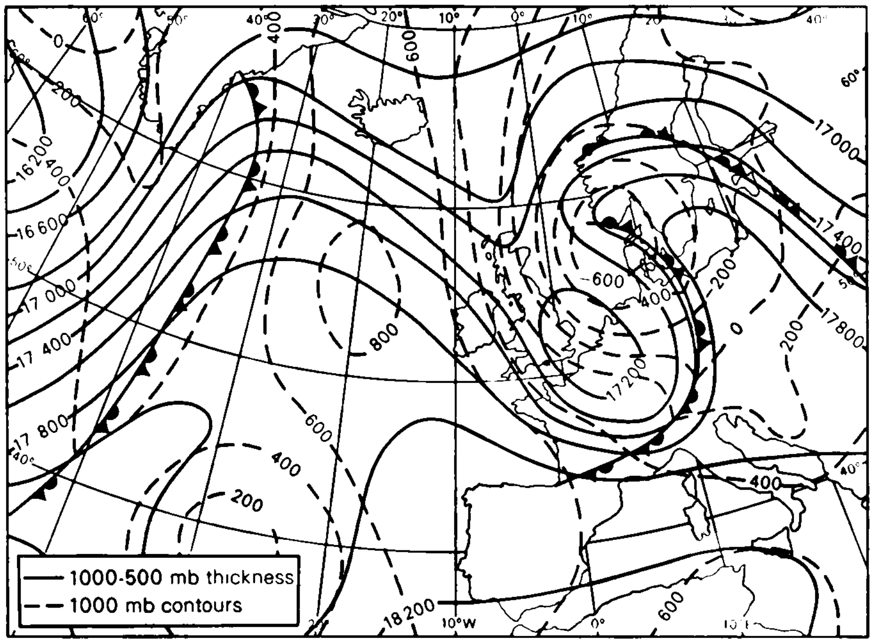

Figure 5. Actual 1000 mb and 1000–500 mb thickness charts, 15 GMT, 31 January 1953.

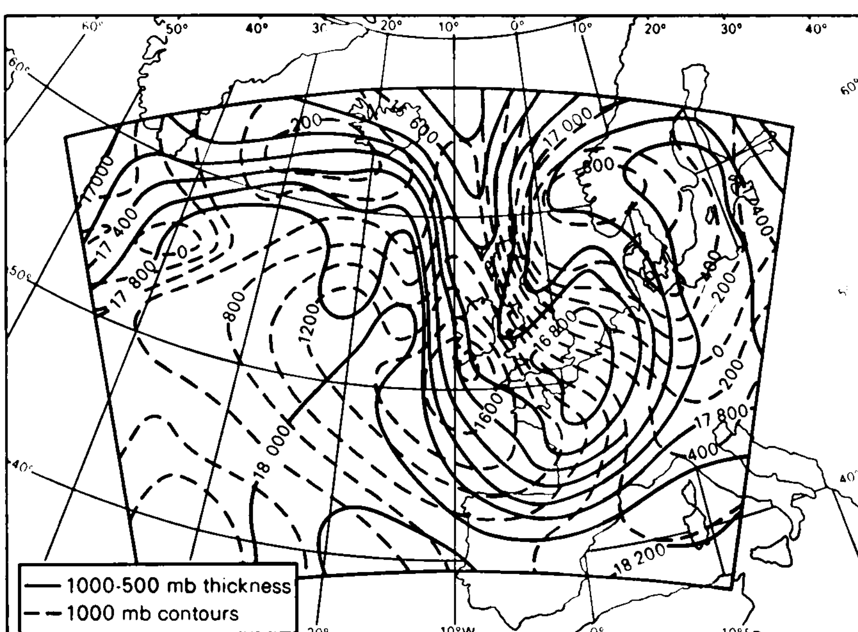

Figure 6. Computed 1000 mb and 1000–500 mb thickness charts for 15 GMT, 31 January 1953, using initial data for 15 GMT, 30 January 1953, and the Sawyer–Bushby model.

extracted) were drawn, indicated that this was probably so. This was a reminder of the importance of a good analysis for producing a reliable forecast.

Another very early computer in this country was the Ferranti Mark 1 machine in the electrical engineering department of Manchester University and, since it seemed likely that more computing would be possible on this machine within the available funds, the decision was made to change over. This machine had cathode-ray-tube storage supplemented by a magnetic-drum backing store. Each binary digit of either program or data was represented by an electrostatic spot on the surface of the cathode-ray tubes and the store could be viewed on monitor tubes on which the 'ones' glowed more brightly than the 'zeros' and the actual data and instructions being currently used glowed more brightly than the rest. Programmers operated the computer themselves (Plates I and II) and with much-used programs they became very familiar with the pattern of 'dancing digits' in each routine of the program. Because of the unreliability of cathode-ray-tube storage each routine was repeated until identical results had been produced twice running. However, since the computer was faster than LEO 1, a 24-hour forecast was still produced in about the same time.

We had no programming course to teach us about this machine and so had to discover everything for ourselves from the large and comprehensive manual without the aid of the team of advisers that was common in later years. The storage of the Ferranti Mark 1 (apart from the backing store) was only 512 words, one-quarter of that of LEO 1, and with our need for large amounts of program and data we had no room for the standard supervisor program, but had to invent our own system. We designated one-quarter of the store (128 words) for program and all routines were arbitrarily made to be of this size, the last instruction obeyed in any routine being the one which overwrote itself with the next routine in the sequence. The remaining 384 words of storage had to suffice, with the aid of backing store, for data, intermediate results and so on. This computer had no compiler, the programs being read in directly from Murray-code teleprinter tape, the holes in the tape corresponding to 'ones' and four rows of holes making up one 20 bit instruction. Tapes were punched on a converted teleprinter/perforator and, since the punching had to be checked from the perforated tapes or from semi-perforated overprinted copy-tapes (because the normal carriage control characters had specific meanings to the computer and could not be used at suitable intervals to produce hard copy), the programmers of that era became expert in Murray code. This had the added bonus of enabling them to recognize the pattern of digits on the cathode-ray tube corresponding to each instruction, a very useful facility for 'debugging'. The paper-tape reader on the Ferranti computer used photoelectric cells in place of the mechanical system of LEO 1 and the coloured self-adhesive tape which was just coming on the market proved to be a boon for last-minute amendments.

Since we needed the computer for several hours at a stretch, most of our usage was at night and for some years we used the machine for two nights each alternate week. We stayed at a nearby commercial hotel, made up of several elderly terraced houses, now happily demolished. Sleeping during the day was made difficult by the shouting of the cleaners and the insistence of the electricity-meter emptier, and if we returned during the night the chorus of snores through the thin walls was unbelievable. Occasionally our time off enabled us to sample the delights of Edale or the Peak, or watch a second-grade film at the local cinema. More readily available treats were the sight of sunrise over Manchester from the roof near the computer room or the exhilaration of coping with an old-fashioned Manchester smog in which the buses were led by a man on foot holding a flare. It was also sometimes necessary to have one member of the party with sufficient athletic prowess to scale the wrought-iron University gate (whilst the others 'kept cave') in order to gain access to the computer building, and several of those who performed this feat have since reached higher directorate level.

The series of forecasts using the Sawyer–Bushby model was continued at Manchester and the encouraging results reported at a 'Monday Discussion' in February 1954 (Meteorological Office 1954) and by

Bushby and Hinds (1954a, 1954b, 1955). By this time the first attempt had been made to include physical processes in the forecasting system by simulating the heating of cold air masses over a warm sea. It had also become clear that with the small grid of 18 × 14 points appreciable errors arose with the use of no-change boundary conditions and in future work with this grid actual boundary changes were incorporated. Preliminary work was now started on objective analysis of data (Johnson 1957) and this was extended to enable the grid-point data required for a numerical forecast to be obtained by least-squares fitting to a quadratic surface at each grid point. Comparison of numerical forecasts based on objectively and subjectively analysed charts (Bushby and Huckle 1957) gave encouragement for the future of automated analyses as well as forecasts.

Meanwhile, in December 1954 SC II of the Meteorological Research Committee had recommended that the Office should have control of an electronic computer for the purpose of continuing research in numerical forecasting. In December 1955 financial approval was given for the purchase of a Ferranti Mercury computer and in the summer of 1956 staff attended the first programming course. The fact that the compiler was being written whilst the course was in progress added some confusion, but also enabled us to influence some of the decisions being taken. Whilst the programmers were busy with their preparations, Mr N. H. Seigne (now of the Operational Instrumentation Branch (Met O 16)) was at the Ferranti factory in Manchester helping to build a Mercury computer as training for his future work as maintenance engineer at Dunstable. The workmen were also busy extending the building and making rainproof that part which would house the computer (a job which had defeated them whilst it was my desk rather than a computer that was at risk). Finally, in the autumn of 1958, pieces of computer started to arrive and in January 1959 it was handed over. In those days the administration of computers was in its infancy and on the Branch inventory 'One Mercury Computer' was entered amongst the slide-rules and desk calculators.

The Mercury computer (named Meteor by the Office) was still a valve machine and input was still 5-hole paper tape, though now in Ferranti code, but in other respects it seemed to be a great leap forward. Floating-point numbers were available, so the old days of careful scaling of all values were at last over. The compiler allowed for 'floating addresses' or labels so that the chore of having to change a great many addresses every time an instruction had to be inserted was also finished with. The instructions were written in a numerical code and translated by the compiler into machine instructions on a one-for-one basis except for 'quickies' which were replaced by in-line routines to perform such functions as sine, square root and reciprocal (there being no hardware division instruction). There was a backing store on magnetic drums and the high-speed store of magnetic cores contained 1024 40-digit floating-point numbers. The first half of the store could also be used for 20-digit instructions or 10-digit fixed-point integers. Output was by paper tape or line-printer. There was also an instruction which sent a pulse to a loudspeaker and, by careful counting of time-wasting instructions between pulses to give the desired frequency, music reminiscent of the bagpipes could be produced. In honour of visiting Soviet meteorologists a data tape for 'The Volga Boatman' was punched. It was fortunate that it was tested before the visitors' arrival, as a punching error led the computer to produce some very embarrassing noises.

By the time that Meteor was available, programs had been written and developed not only for numerical forecasting and objective analysis, but also for the automatic extraction from teleprinter tapes of some upper-air information and the surface synoptic reports from ships. Therefore, two parallel experiments were run using current data, one in which as much of the procedure was automated as possible and one in which only the numerical forecast was done by computer. At 0830 GMT each morning the Frankfurt teleprinter tape was read into the computer and midnight data for 500 mb and 1000–500 mb total thickness were extracted. Missing data were then noted, searched for and manually punched, and at 0945 objective analyses of the 500 mb and 1000–500 mb charts were performed. Just after 1000 the surface data from ships were extracted by the computer from a collective tape produced in the teleprinter room. Following this, the 1000 mb chart was objectively analysed and the results used to amend the 500 mb and total thickness values. The numerical forecast program was then run to produce a 36-hour forecast by 1100 GMT. In parallel with all this activity grid-point data were manually extracted from Central Forecasting Office 500 mb and total thickness charts and punched on paper tape. The forecast based on these data was run at 0845 the following morning whilst the computer was available during the manual search for missing upper-air data. Forecasts by these two methods were then assessed against conventional forecasts and actual events. It was concluded that although numerical and conventional 24-hour forecasts were of similar standard over the British Isles, over a wider area the numerical forecasts were mostly of lower value, for a variety of different reasons.

During the next few years effort was concentrated on research and the production of better methods of numerical forecasting and objective analysis, the results being tested from time to time in real-time experiments. In the first experiment in early 1959 a great deal of manual effort had been found to be necessary for scrutiny of suspected observations and their deletion or correction. Therefore, in the second experiment, from late July to mid-November 1959, an attempt was made to automate this procedure. After an initial objective analysis of all available data, the individual observations (except those from Ocean Weather Ships) were tested in the computer against this first analysis and a second analysis was performed using only those observations which were not suspect. Despite the extra computer time involved, this was found to be a much more satisfactory procedure. The results of these first two experiments are reported by Knighting *et al.* (1961), who concluded that the main errors in the numerical forecasts arose from (a) spurious anticyclogenesis as a result of the geostrophic assumption, (b) boundary conditions, and (c) neglect of the effect of topography.

By early 1960 the two-level Sawyer–Bushby model had been extended to the three-level Bushby–Whitelam model and a version of the two-level numerical forecast program had been developed incorporating a stream function at 600 mb. Therefore, during the spring of that year an extended series of forecasts was run to compare the different available models. The results are reported by Wallington (1962) and Knighting (1961) and the conclusion drawn was that the three-level model was superior to either of the two-level models. As a result of these tests it was decided to mount a full-scale real-time experiment in operational numerical weather prediction in the winter and spring of 1960–61 using the three-level model. The aim was to provide the forecasting staff by 0930 GMT with a forecast for 06 GMT the next day. This necessitated an earlier start than in the previous experiments and the high-quality Frankfurt broadcast that had been used for data extraction was not received in time. Data were therefore extracted and punched manually as they arrived. It was planned to run a 6-hour forecast from 00 GMT data, and then to reanalyse the charts using any available 06 GMT data and continue the forecast for a further 24 hours. In order to obtain as many 06 GMT data as possible, a very close time schedule was planned, and in fact it was only possible to produce the forecast by 0930 GMT on about 35% of occasions. However, it was ready by 0945 GMT on a further 20% of occasions. On about 30% of occasions computer faults caused the delay or abandonment of the forecast, but many of these faults were quickly located and corrected. The results are reported by Knighting *et al.* (1962). The writers concluded that a larger, faster and more reliable computer than Meteor was needed if numerical prediction was to be used operationally. A number of improvements were also needed in the methods used, of which the most important was an increase in accuracy of data-handling.

In June 1961 it was necessary for Meteor to be dismantled so that it could be transported to Bracknell and reassembled on the fifth floor of the Napier Shaw Building (Plates III and IV). Opportunity was taken, with this break in computational facilities, to reorganize and rewrite the experimental operational programs. The biggest change was the production of a comprehensive data-extraction program to obtain the upper-air and surface synoptic observations from paper tapes of the main international teleprinter broadcasts. The three-level forecast program was changed to include the effects of topography and later changed to incorporate a stream function at 600 mb. Arrangements were also made to allow for the use of additional 'bogus' data. Analysis of 06 GMT data was temporarily abandoned so that an earlier start was possible at 0530 GMT and the schedule made it easier to produce the forecast by the appropriate deadline. Real-time testing of numerical forecasting began again in the late summer of 1962 and continued for much of 1963. The extremely cold weather of January 1963 was a considerable trial for the hardware of Meteor and it was found necessary to keep the computer working all night if it was to produce satisfactory results in the early morning. The programmers of the Dynamical Research Branch (Met O 11) took it in turns to 'machine-mind' on those nights when the computer had not been booked for use by another Branch of the Office.

With the acquisition of a computer for the Office in 1958–59 it was obvious that a larger number of staff needed training in computer programming. A small number of courses in Mercury machine code were provided by Met O 11 staff at Dunstable for those who needed a low-level language. However, it was felt to be important to spread a knowledge and understanding of computers much more widely through the Office and, with this in mind, courses were held twice a year in Mercury Autocode, a simple high-level language developed by Dr R. A. Brooker at Manchester University. These courses lasted for three days and by the end of the first day students had written a complete small program, punched it on paper tape, and operated the computer themselves to test it. One course each year was timed to coincide with the end of the Scientific Officer course, so that all new scientists entering the Office received computer training.

Use of the computer spread quickly to spheres other than numerical forecasting and as early as 1961 we find upper-air statistics being routinely computed on Meteor (Dewar 1961). Since Meteor was operated by the programmers themselves and only one program could be in it at a time, a complicated timetable for computer usage had to be drawn up each week in Met O 11. There were several 'development' periods each day when staff could queue up for very short test runs of their programs, but mostly it was necessary for them to book the computer for periods of a quarter of an hour or longer. Those needing several hours of computer time would be expected to use the machine during the late evening or even overnight.

The time was now rapidly approaching for numerical forecasts to become fully operational. For this to be practicable it was necessary for them to cover a much wider area of the globe in an appreciably shorter computing time and for the computer to be more reliable than was possible with a valve machine like Meteor. The decision was therefore taken to purchase an English Electric Leo KDF9. Staff training was started in the summer of 1963 and the computer was in use in an enlarged computer room on the fifth floor in the summer of 1965. Meteor was dismantled by our own engineers and reinstalled at Porton Down, where its useful life extended till 1971.

The KDF9 computer, known in the Office as Comet (Plates V and VI) and, like its predecessor, designed and made in Britain, included quite a number of considerably more advanced features than those of machines of the previous generation. Thermionic valves had gone, and transistors and plug-in circuits had come, and the designers were ahead of their time with the concept of a very fast access 'nesting store'. This consisted of 16 words used on a 'first in, last out' basis. All the arithmetic was actually performed on the top few words of the nesting store, the transfers to and from the store being done in separate instructions. With careful thought it was therefore possible to perform some functions, for instance evaluating a polynomial, at extremely high speeds and in many circumstances it was possible to cut the number of store accesses quite considerably by leaving values in the nesting store.

Fetching and storing could also take place in parallel with arithmetic, so a careful arrangement of instructions could cut the total time taken by the program. Up to four programs could reside in the store at the same time, the one with highest priority having control till it was held up, for instance by the need for input/output. As each program was completed, those remaining would move to either end of the store, leaving all the available space in one block in the centre for a further program to be read in. Control of the store and arrangement of program-switching was performed by the Time-sharing Director. Because of the multi-programming system, for the first time in the Office separate staff (from Met O 18c (Support Services), later Met O 12 (Data Processing)) were set aside to operate the machine on a shift-working basis, in 1965 from 0530 to 2200 GMT seven days a week and from autumn 1966 covering 24 hours a day.

The low-level language was the very simple and easily remembered Usercode in which, for instance, $+$; $\times$; were fixed-point addition and multiplication and $+$F; $\times$F; their floating-point counterparts. Algol was available as a high-level language. Table I (from Sumner 1964) gives some idea of the size, speed and input/output facilities of Comet compared with Meteor. In almost every way it was appreciably larger, faster and more reliable than Meteor and, in particular, had the additional facility of magnetic-tape storage.

Between 1963 and 1965 all the operational programs were rewritten in Usercode. Most of the testing was done at Kidsgrove, near Stoke-on-Trent, either on personal visits or by courtesy of British Railways, paper tapes and computer output being conveyed overnight via Reading in specially adapted tool-boxes. Soon after Comet was handed over, real-time tests were started and the numerical forecast officially became operational on 2 November 1965. There was much publicity for this event in the local and national Press, with photographs of the Director-General looking at output charts and headlines like '£500 000 computer speeds up weather forecasting. Comet feeds on isobars'. From then on the forecast suite of programs was run twice a day, starting at 0530 and 1730 GMT. The use of the computer for climatological and research purposes increased rapidly and before long there was a backlog of jobs waiting to be run which was cleared only at weekends.

Meanwhile, Met O 11 were already using the larger and faster Atlas computer, first at Manchester and later at the Rutherford Laboratory, for developing the Bushby–Timpson 10-level model. Atlas again was a British-designed and British-built machine and was far ahead of its time in incorporating such features as virtual storage (a system in which parts of the main store not in current use are parked temporarily in the backing store). This computer was also used by the Dynamical Climatology Branch (Met O 20) for research into the general circulation, work which had been started in a very tentative manner at Manchester in the 1950s.

However, by the time that it was appropriate for Comet to be replaced, the IBM 360/195 had become available and this computer was estimated on numerical forecasting work to be 20 times faster than Atlas and 80 times faster than Comet. Programmer training for the IBM 360 started in early 1970 and later that year and for much of 1971 program-testing took place at Croydon and at Poughkeepsie (New York State). Late in 1971 the present IBM 360/195 was installed in the COSMOS computing laboratory in the new Richardson Wing (Plates VII and VIII). KDF9 programs could be run on the IBM machine using a 'KDF9 simulator' and, in fact, the operational three-level model was run in this manner for a while, but Comet continued to operate in the fifth-floor computing room until March 1973.

As would be expected, the IBM 360/195 included a number of new features, apart from the fact that the basic machine cycle was much faster than that of Comet. There was a small, very high-speed buffer store which saved considerably on access times to the main store and the central processing unit was organized so that it could look ahead through the instructions and be decoding and obeying a number of them at the same time. Input/output was improved by the addition of discs for backing store and

Table I. *KDF9 and Meteor compared*

Item	KDF9		Meteor	
Internal storage				
Main store		12 288 48-bit words		1 024 40-bit words
Magnetic drum		40 960 48-bit words		16 384 40-bit words
Operating speeds		*microseconds*		*microseconds*
Access to main store		2–12 (average 7)		120
Addition and subtraction—fixed-point		1		–
—floating-point		7–12		180*
Multiplication—fixed-point		15		–
—floating-point		15–19		300*
Division—fixed- and floating-point		35–40		3800
Input/output equipment	Number	Speed	Number	Speed
Paper-tape readers	3	1000 characters per second	1	300 characters per second
Paper-tape punches	3	110 characters per second	1	33 characters per second
Card readers	1	600 cards per minute	0	
Line printers	1	1000 lines per minute (160 characters per line)	1	150 lines per minute (92 characters per line)
Magnetic tape units	6	40 000 characters per second	0	

*Note: Arithmetic times on Meteor include the time of one transfer from the main store to the arithmetic unit, whereas those for KDF9 do not.

Calcomp microfilm plotters (to replace the flat-bed line-drawer used on KDF9), and by the input/output channels being independent of the main processor. There was an increase in the number of programs operating at the same time and further programs could be read in to await their turn in a job queue. The programs in the queue were classified into different types, thus enabling the computer itself to choose the next job according to the facilities available.

The work which had previously been done on the Atlas computer was transferred to the IBM 360/195 and with the extra computing power available the general circulation and climate modelling by Met O 20 were considerably expanded. Other work also increased, and at the end of 1974 an IBM 370/158 was installed in the COSMOS laboratory to provide facilities for those programs which did not require the computing speed of the 195 and to act as a 'front end', organizing the input, output and job-scheduling for both machines. Still the work-load continued to increase. With parallel automation of telecommunications, synoptic data were able to flow directly from the twin Marconi Myriad computers in the Telecommunications Branch via an IBM System 7 computer directly into COSMOS without the use of teleprinter paper tapes. Charts could be plotted automatically by the computer using the data so received. Climatological data, which used to be punched on cards and processed by Hollerith machines, were keyed directly and processed by computer. Interactive visual display units (Time-sharing Option terminals) were available in different parts of Headquarters to give programmers more direct access to the computers. Data for flight-planning could be sent directly from COSMOS to the British Airways computer. COSMOS not only schedules its own work in a sophisticated fashion, it also provides management statistics for those in authority over it. By 1979 over 1000 jobs a day were being run and 4400 million bytes (or characters) of on-line data were available on COSMOS.

By early 1979 some Branches were already making use of the vector facilities of the CRAY-1 at the European Centre for Medium Range Weather Forecasts at Shinfield Park. Now, as this is being written in late 1980, preparations are in full swing for the installation of the 'number-crunching' Cyber 203E in COSMOS early in 1981.

Gone are the days when it was possible, as in 1966, for a small enthusiastic group of staff to film in the computer room in off-duty hours a computer-age fantasy based on the medieval fable of the Sorcerer's Apprentice. (It failed to win an award because the judges felt that insufficient chaos was depicted.) Now, in the 1980s, the operation of the much more powerful COSMOS computing facilities 24 hours a day requires first-class organization and the co-operation of hundreds of staff—a very far cry from the single electrical desk-calculator with which it all started in about 1950.

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Glossary

Compiler. A computer program whose purpose is to read in to the computer a program written in one of a number of appropriate codes by a user, and to translate that program into machine instructions of the form required by the hardware of the computer.

Fixed-point binary. The representation of a number to the base 2, that is, as a series of noughts and ones. Often this refers to integers only—in other words, the binary point is usually after the last digit.

Floating-point binary. The representation of a number as $a \times b^c$, where b is frequently 2 or 16, c is an integer, and a is in fixed-point binary, sometimes an integer, but more often a fraction. Usually the exponent c is represented by about one-quarter of the digits in a computer word and the other three-quarters represent the mantissa a. The value of b is fixed for any particular computer. The use of floating-point enables a wide range of numbers to be represented in a computer to the same number of significant digits.

High-level language. A code for writing computer programs which is very similar to normal algebra, but far removed from the machine instructions required by the hardware of the computer. Normally a sophisticated compiler is required to translate such a code.

LEO. LEO computers were originally produced by Messrs J. Lyons, the caterers, but this section of their enterprise was later acquired by English Electric.

Low-level language. A code for writing computer programs, which is very closely related to the machine instructions required by the hardware of the computer. The compiler is normally much simpler than for a high-level language, and the programmer has a closer control of the processes inside the computer and therefore can often use the computer more efficiently.

Mercury delay-line. This is a device in which electrical signals are converted into an acoustic wave (piezo-electrical effect), this being delayed by circulation through mercury before being reconstituted into an electrical signal. The speed of sound in mercury is very much slower than the speed of electrical signals in a conductor.

Murray code. Teleprinters can be operated automatically by punched paper tape and Murray code is the code connecting each row of holes on the paper tape with the appropriate character. Trained teleprinter operators can frequently read from Murray code tape as effectively as from a printed text.

'Plonker'. A small plastic scale, usually for measuring geostrophic wind strengths from a chart, which could be placed or 'plonked' on the chart.

Total thickness. The difference between the geopotentials of the 1000 mb and 500 mb surfaces. The total thickness chart was a very useful forecasting tool.

Valve. A thermionic valve (or vacuum tube) was a basic part of the hardware of most radios and computers till the invention of the transistor to perform a similar function.

Correspondence

The heat balance of wet snow

We have received the following letter from Dr Lasse Makkonen:

In the article by A. K. Kemp in the March 1980 *Meteorological Magazine* a mechanism of snow accretion on wires was suggested. According to it the cooling of the snow deposit due to evaporation causes refreezing of wet snowflakes after impact, the wet-bulb temperature thus being an important factor in the occurrence of accretion.

This hypothesis has been tested by Wakahama, Kuroiwa and Gotō (1977) by measuring the temperature changes in the snow deposit in wind-tunnel experiments. They found, however, no evidence indicating the freezing of water in the snow deposit during accretion. On the contrary, the free-water content of the deposit increased considerably during accretion, even in the tests with only 70% relative humidity, and in addition some free water was removed from the leeward side of the snow deposit, just as in the case of rime formation in the wet-growth regime (e.g. Makkonen 1980). Thus, it is concluded that the heat transfer from the moving air to the snow-mass by convection exceeds by far the heat lost by evaporation, at least in the temperature range from +1 °C to +2 °C of the wind-tunnel tests. However, intensive snow accretion on wires has been observed at these temperatures (Shoda 1953, Wakahama, Kuroiwa and Gotō 1977).

Lasse Makkonen

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References

Kemp, A. K.	1980	The formation of ice on electrical conductors during heavy falls of wet snow. *Meteorol Mag*, **109**, 69–74.
Makkonen, L.	1980	Theoretical estimates of ice accretion intensity on structures. 12th Meeting of Nordic Meteorologists, May 1980, Espoo, Finland.
Shoda, M.	1953	Studies on snow accretion. *Res Snow Ice*, **1**, 50–72.
Wakahama, G., Kuroiwa, D. and Gotō, K.	1977	Snow accretion on electric wires and its prevention. *J. Glaciol*, **19**, 479–487.

Dr Makkonen's letter was referred to Dr P. Ryder of the Meteorological Office, Assistant Director (Cloud Physics), who has sent us these comments:

Kemp (1980) has attempted to explain the formation of ice on electrical conductors during heavy falls of wet snow. Makkonen (above) asserts that this is not in keeping with some wind-tunnel experiments reported by Wakahama, Kuroiwa and Gotō (1977).

It is very difficult to evaluate the heat balance of a mixture of ice and water, on or off a substrate, when sensible heat exchange and transfers of vapour, liquid and solid to and from the mixture are possible. For example, some, but not all, of the terms which should be considered in the accretion of ice on a helicopter rotor blade have been described in Ryder (1978) and references therein.

If, for the moment, accretion, splashing and bouncing phenomena are neglected, the role of wet-bulb temperature can be readily understood as a balance condition between convective heat and water vapour transfer between the mixture and ambient air. If the surface of the mixture is at a temperature T_s, the air temperature is T_a and ambient vapour pressure is e_a, then the rate of convective heat transfer per unit area is $q_c = h(T_a - T_s)$. Here h is the convective heat-transfer coefficient, in general a function of Reynolds number. The equivalent rate of evaporation heat loss is

$$q_c = \frac{0{\cdot}622Lh}{c_p}\left(\frac{e_a - e_s}{p}\right),$$

where the symbols have their usual meanings and e_s is the saturation vapour pressure at temperature T. Note that the convective heat-transfer coefficient enters both equations. Formally, this implies that the Sherwood number is equal to the Nusselt number, a commonly accepted assumption at atmospheric pressure. Qualitatively, both the convective and evaporative heat-transfer rates are expected to be sensitive to the ventilation rate. At equilibrium,

$$\frac{e_s - e_a}{p} = 6{\cdot}46 \times 10^{-4}(T_a - T_s).$$

The psychrometric equation (see *Smithsonian meteorological tables*, page 365, for example) which links the wet-bulb temperature empirically to the appropriate saturation vapour pressure is

$$\frac{e_w - e_a}{p} = A(T_a - T_w), \text{ where } A = 6{\cdot}6 \times 10^{-4}(1 + 1{\cdot}15 \times 10^{-2}\, T_a).$$

As might be expected, the surface temperature is effectively the wet-bulb temperature under these circumstances. It has been derived in this way to emphasize the balance and assumptions that are implied by the concept.

I turn now to Kemp's arguments; his assertion that an increased ventilation rate can increase evaporative cooling but not convective heating is unconvincing for the reasons identified above. He may be correct in drawing attention to ventilation but only in so far as this influences the joint magnitude of the terms. At low ventilation rates these become small and less likely to dominate the heat-balance equation. Snowflakes falling through air of gradually varying wet-bulb temperature may exhibit a discernable temperature lag, for example. Kemp is almost certainly incorrect in suggesting that a train moving into a strong wind is more liable to icing than a train moving with the wind, all other influences being equal. He neglects the effect of dynamic heating which provides a net heat transfer to the exposed surface. An object moving at velocity v will achieve an equilibrium temperature $\triangle T$ °C than when it is at rest, where $\triangle T \simeq v^2/2c_p$. $\triangle T = 0{\cdot}05$ °C at 10 m s^{-1}, 1·2 °C at 50 m s^{-1} and 2·8 °C at 75 m s^{-1}.

Makkonen quotes wind-tunnel experiments in which no signs of refreezing were evident in a mixture of water and ice accreted by a wire. The air temperature was held between +1 °C and +2 °C and ambient relative humidity was stated to be 70%. The wet-bulb temperature under these circumstances varies between −0·8 °C and +0·2 °C. Superficially, some ice growth might have been expected, at least at air temperatures close to 1 °C. However, both he and Kemp neglect the contribution of terms associated with accretion, bouncing, conduction, etc. The wind-tunnel experiments showed that almost 80% of colliding particles rebounded. These must be expected to play a part in the heat-balance equation. If rebounding particles have a higher fractional ice content on average than those impacting, then there is a net transfer of heat to the wire in addition to that implied by the local wet-bulb balance. If fragments being shed by the wire are slightly warmer than those impacting, then there will be a net transfer of heat away from the wire. Similarly, the equilibrium temperature of dry parts of the structure is likely to be controlled by the air temperature. Conduction of heat from there to the cooler, wet regions on which ice is accreting also represents a net warming there. Ohmic heating of a wire carrying an electric current may not be negligible.

It is difficult to disagree with Kemp in his suggestion that a wet-bulb temperature at or just below 0 °C is a necessary condition for the accretion of ice on electrical conductors during heavy falls of wet snow. However, it is not a sufficient condition. The practical balance between significant and no icing is expected to be sensitive also to the processes involved in the collection and shedding of water substance, these being in turn a function of wind velocity, snowfall rate and the variation of wet-bulb and air temperature with height. It is suggested that the empirical results of Kemp, and earlier of Foot (1972), reflect this sensitivity.

P. Ryder

Meteorological Office, Bracknell.

References

Foot, J. S.	1972	Snow accretion on overhead powerlines. *London Weather Centre Memorandum*, No. 23.
Kemp, A. K.	1980	The formation of ice on electrical conductors during heavy falls of wet snow. *Meteorol Mag*, **109**, 69–74.
Ryder, P.	1978	The role of meteorology in helicopter icing problems. *Meteorol Mag*, **107**, 140–147.
Wakahama, G., Kuroiwa, D. and Gotō, K.	1977	Snow accretion on electric wires and its prevention. *J Glaciol*, **19**, 479–487.

The author of the original paper, Mr A. K. Kemp, makes the following additional comments:

Makkonen and Ryder make the valid point that convective heating must have an important bearing on the heat balance of wet snow on a conductor. Ryder asserts that other terms are likely to be important also.

In the equation for convective heat transfer given by Ryder, $q_c = h(T_a - T_s)$, increasing the value of T_a will increase q_c, but as $T_a \rightarrow T_s$, $q_c \rightarrow 0$. In the experiment described by Makkonen, T_a was between +1 °C and +2 °C and, therefore, for a mixture of ice and water and assuming equivalent ventilation rates, the convective heating term must have been greater than in the Anglesey storm where T_a at the level of most of the conductors was estimated to have been from 0·5 °C to 0·0 °C.

It would be interesting to see the results of wind-tunnel experiments carried out with wet snow where the air temperature and wet-bulb temperature were controlled at and close to 0 °C.

A. K. Kemp

Meteorological Office, Royal Air Force Valley.

Reviews

Atmospheric physics, by J. V. Iribarne and H.-R. Cho. 240 mm × 160 mm, pp. xii + 212, *illus.* D. Reidel Publishing Company, Dordrecht, Holland. Price Dfl 40.00, US £15.95.

Any attempt to describe the physics of the atmosphere in about 200 pages is certain to be a compromise. The virtue of this book is that its specific, restricted purpose is pursued intelligently and faithfully.

The authors assert that they have produced 'an elementary but comprehensive survey of the terrestrial atmosphere'. Their potential market is clearly identified as second- or third-year university students engaged in a course which is preparing them for a career in atmospheric, geophysical or environmental sciences. The students are presumed to have only elementary mathematical skills 'and such knowledge of physics as should be acquired in most first year general physics courses'. A working knowledge of chemistry, to rather better than 'O' level GCE standard, is also necessary to understand some parts of the syllabus. Curiously, this point is not identified by the book's title or in its preamble.

There are seven chapters in all. Five of these deal with the general structure of the atmosphere and its chemical, radiative, thermodynamic and large-scale dynamical processes. The remaining sections describe the physics of clouds, at least in so far as they are producers of precipitation, and atmospheric electricity. The chapter on atmospheric dynamics is about 40 pages in length; the others occupy between 20 and 30 pages each. Within this framework the authors adopt a distinctive style of presentation to attain their objective. There is little space for the analysis of individual problems in terms of established physical principles so the text is a predominantly factual rather than a reasoned exposition. However, this compromise is not as brutal as it might appear at first sight because each chapter ends with a number of questions and problems for the student. Answers and hints for solutions are provided at the end of the book. It is these problems which should exercise the reasoning powers of the reader. The problems are chosen with some skill and, where possible, emphasize the application of atmospheric physics and chemistry to a number of contemporary concerns. In the end, and despite some misgivings, I believe that this arrangement could be very successful. Obviously, it is essential that full use be made of the questions, perhaps augmented by a tutorial system, if maximum benefit is to be obtained from the book.

The scientific material is quite well presented, although the choice of diagrams is somewhat uninspiring. Even for a cloud physicist, three separate graphical representations of the Clausius–Clapeyron equation in different parts of the book is carrying a good thing too far! Most features of modern atmospheric science are introduced but their treatment is often very superficial. Tropospheric processes receive most attention, but the role of the upper atmosphere as an absorber of short-wave radiation is discussed in the production of the ionosphere and stratospheric ozone. The section on dynamics is exclusively concerned with the troposphere and it stops short of the concept of vorticity. As expected from someone with Dr Iribarne's research background the sections on cloud physics and atmospheric electricity are up to date. A short general bibliography is provided for each chapter but no other guidance is given to the student who seeks more of the red meat which is not available in this *ragoût*.

As suggested at the outset, the book is consistent with its stated objectives as a teaching aid. It is recommended to those setting up or taking part in the described courses. It is not so well suited to the enquiring reader who has an informal interest in the atmosphere and seeks a worthwhile understanding of its fascinating physical and chemical processes.

P. Ryder

The middle atmosphere as observed from balloons, rockets and satellites (A Royal Society discussion arranged by the British National Committee on Space Research and Solar–terrestrial Physics, under the leadership of Sir Harrie Massey, F.R.S., Sir Granville Beynon, F.R.S., J. T. Houghton, F.R.S., and L. Thomas, held on 12 *and* 13 *December* 1978), The Royal Society of London. 290 mm × 200 mm, pp. v + 268, *illus.* The Royal Society, 6 Carlton House Terrace, London SW1Y 5AG, 1980. Price £24.50 (United Kingdom addresses, including packing and postage) and £25.75 (overseas addresses, including packing and postage).

This is a collection of the invited papers presented at a discussion meeting of the Royal Society in December 1978, covering the structure, dynamics and observation techniques of the layer 10–100 km.

The description of the climatology makes full use of satellite data, enabling useful spectral analyses of the large-scale temperature waves to be made, though the description is spoiled a little because zonal-mean winds are plotted only up to 30 km. Diurnal variations are derived from rocket and meteor wind data. As one author succinctly puts it: a sun-synchronous orbit is not a good one for the study of diurnal changes.

A second group of papers is concerned with models of the interaction between photochemistry and dynamics, transfer between troposphere and stratosphere and with a theoretical and philosophical discussion of the propagation of waves of small amplitude. Finally, there are papers concerned with the chemistry of the layer, spectroscopic *in situ* and satellite observation of ozone, other trace gases and temperature. There is no discussion nor, presumably, any uninvited papers.

The papers are quite informative and the reader will find much to enjoy and much that is stimulating. However, I do not think he will find anything that has not already been published elsewhere, nor will he find a comprehensive review. There is not enough continuity or background, and too much jargon for the browser. Unfamiliar topics will need the references for background; familiar topics will need the references for clarification. According to the flyleaf, the volume is intended to help planners. Perhaps that is why it is published expensively, in hard covers. I suspect that the planners will be as baffled as I am by the statement that 'many experimenters have underestimated the precision of their data', astonished to read that spectrometers may be large, heavy and expensive, and cheered by the implication throughout the text that there is now a great deal of undigested data on magnetic tape.

I cannot wholeheartedly recommend this volume to individuals or libraries except for the useful list of references, and suspect that its reading by those 'planners' will not do the subject much good. Anyone who has £25 to spare might care to note that Ludlam's monumental work on clouds and storms costs just this much.

J. S. A. Green

Corrections

In the Letter to the Editor, *Meteorol Mag*, **109**, 1980, 362–363, the date of the hailstorm at Sevenoaks should be 25 June 1980, not 26 June 1980.

In the article by N. Thompson, *Meteorol Mag*, **110**, 1981, page 2, the symbol printed in equation (2) as 'R_a' should be 'r_a'.

THE METEOROLOGICAL MAGAZINE

No. 1304 March 1981 Vol. 110

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NOTICES

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Issues in Microfiche starting with Volume 58 may be obtained from Johnson Associates Inc., P.O. Box 1017, Greenwich, Conn. 06830, U.S.A.

Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1.80 monthly
Dd 698260 K15 3/81

Annual subscription £23.80 including postage
ISBN 0 11 726280 3
ISSN 0026–1149

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

April 1981

Met.O. 942 No. 1305 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1305, April 1981, Vol. 110

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On the maximum wind in tropical cyclones

By I. Subbaramayya
(Andhra University, Waltair, India)
and S. Fujiwhara
(Hakodate Marine Observatory, Hokkaido, Japan)

Summary

The maximum wind, central pressure and radius of maximum wind in cyclonic storms and typhoons of the western North Pacific in the year 1978 as observed by US reconnaissance aircraft are analysed by regression and correlation techniques and an equation relating the three parameters is derived.

Introduction

The maximum wind in tropical cyclones is of great importance and interest to the meteorologist. Takahasi (1948) attempted to obtain an expression for the maximum surface wind in terms of the central pressure depth using the pressure profile equation

$$p = p_0 - \{c/(r + r_0)\} \qquad (1)$$

given by Horiguti (1926). In the above equation, p is pressure, r is radial distance; p_0, r_0, and c are constants. Takahasi used the peripheral pressure for p_0 and the radial distance of 'half pressure depth' as r_0, and from the cyclostrophic wind relationship he obtained

$$v_m^2 = (p_0 - p_1)/4\rho \qquad \textbf{(2a)}$$

where, v_m is the maximum wind, p_1 is the central pressure and ρ is the density of the air. If v_m is expressed in knots and p_0 and p_1 in millibars, and ρ is taken as $1{\cdot}29 \times 10^{-3}$ g cm^{-3}, equation (2a) would reduce to

$$v_m = 8{\cdot}8(p_0 - p_1)^{\frac{1}{2}} \qquad (2b)$$

He himself felt that the above equation may give underestimates and suggested a value of 11·7 for the coefficient on the basis of direct, though meagre, wind observations. Further, it can be shown that the radius of maximum wind, r_m, is equal to r_0 in the above model. But experience shows that r_m is much smaller than r_0.

The Hydrometeorological Section of the US Weather Bureau (1954) had been using the equation

$$(p - p_1)/(p_n - p_1) = e^{r/r_m} \qquad (3)$$

for the pressure profile in tropical cyclones, where e is the base of natural logarithms and p_n is the peripheral pressure. Using this equation and the cyclostrophic wind relationship, Myers (1957) showed that

$$v_m^2 = (p_n - p_i)/e\rho \quad \text{(4a)}$$

This equation is equivalent to

$$v_m = 10{\cdot}68(p_n - p_i)^{\frac{1}{2}} \quad \text{(4b)}$$

when the wind is expressed in knots and the pressure in millibars.

Fletcher (1955) obtained the following empirical equation for the maximum wind

$$v_m = 16(p_n - p_i)^{\frac{1}{2}} \quad \text{(5)}$$

This equation was reported to be giving high values for v_m (Dunn and Miller 1960).

Subbaramayya and Fujiwhara (1979) used the reconnaissance aircraft data obtained by the US Air Force in typhoons of the western North Pacific and obtained the following empirical relationships:

$$v_m = 12{\cdot}4(1010 - p_i)^{\frac{1}{2}} - 8{\cdot}8 \quad \text{(6a)}$$

and

$$v_m = (1010 - p_i) + 25 \quad \text{(6b)}$$

The standard deviations of the errors of estimation for the two equations were practically the same and hence they laid stress on the usefulness of the latter equation in operational analysis because of its simplicity, but it was not clear what 'power law' relates maximum wind and central pressure depth. In fact, Shea and Gray (1973) indicated a relationship, graphically, which shows a power greater than unity for $(1010 - p_i)$.

Theoretical considerations

According to the generally accepted model of a tropical cyclone, air converges from the surroundings in the lower levels to the centre of the cyclone where it ascends and diverges outward at higher levels. The air-parcels at low levels gain kinetic energy while running down the pressure gradient and hence the maximum wind can approximately be written as

$$v_m^2 = (2/\rho)(p_n - p_i) \quad \text{(7a)}$$

or

$$v_m = 24{\cdot}9(p_n - p_i)^{\frac{1}{2}} \quad \text{(7b)}$$

where v_m, p_n and p_i are expressed in the same units as in the earlier equations. The coefficient on the right-hand side is quite large compared to those obtained in the empirical investigations. This is because, in the above calculations, loss of energy due to frictional forces was not taken into account.

Riehl (1963) took the frictional force into consideration and, assuming the conservation of potential vorticity to hold good, showed that in a steady state hurricane

$$v_\theta^2 r = K \quad \text{(8)}$$

in the low-level inflow layer, where v_θ is the tangential velocity and K is constant. Further, assuming the cyclostrophic wind relationship to hold good as a first approximation, we may write

$$K/r^2 = (1/\rho)(\partial p/\partial r)$$

Integrating the above equation from the periphery to the point of maximum wind and substituting the central pressure value for the pressure at the radius of maximum wind, which is reasonable because the maximum winds are observed practically near the eye-wall, we get

$$K(r_n - r_m)/r_n r_m = (p_n - p_l)/\rho$$

Since r_m is very small compared to r_n, the radius of the cyclone,

$$K/r_m \approx (p_n - p_l)/\rho$$

and

$$v_{\theta,m}^2 \approx (p_n - p_l)/\rho \qquad \text{(9a)}$$

Hence,

$$v_{\theta,m} \approx 17{\cdot}6(p_n - p_l)^{\frac{1}{2}} \qquad \text{(9b)}$$

It is easy to see that the above equation over-estimates $v_{\theta,m}$ because of the assumption of the cyclostrophic wind relationship over the entire area of the cyclone and the other approximations made in deriving the relationship.

Further, Riehl (1963) in his model showed that

$$v_{\theta,m} = f r_o^2/2r_m \qquad \text{(10)}$$

where r_o is the radius at which the cyclonic flow changes to anticyclonic in the upper outward layer and f is the Coriolis parameter. Equation (10) shows that $v_{\theta,m}$ and r_m are inversely related and for the same r_o and r_m values, $v_{\theta,m}$ should be more at higher latitudes because the Coriolis parameter is in the numerator.

The authors in this paper have attempted to study the nature of the functional relationship between maximum wind and the central pressure depth and the dependence of the maximum wind on the radius of maximum wind and the latitude.

Data

Central pressure, maximum wind and location of maximum wind in cyclonic disturbances and typhoons in the north-west Pacific are being observed through US reconnaissance aircraft flights.

The observations are disseminated by the Joint Typhoon Warning Center, Guam, for the use of the littoral and island countries in the area. These observations are available in the data archives at the Japan Meteorological Agency, Tokyo, for quite a considerable period. However, observations of the radius of maximum wind are available since 1978 only. The authors have therefore used data on the typhoons for the year 1978 in the present study.

There were 28 cyclonic storms of different intensities in the western North Pacific during the period June to November 1978. Some of them became major typhoons. There were about 130 reconnaissance reports with simultaneous observations of all the parameters necessary for the present study. The lowest pressure report in the sample of observations is 878 mb and the maximum wind is 150 kn. Only cases with maximum wind greater than 30 kn have been considered for the study.

Analysis and results

The peripheral pressure in all the cases was assumed to be 1010 mb in determining the central pressure depth. Logarithmic regressions between v_m, $(1010 - p_l)$, r_m and $\sin\theta$, where θ is the inflow angle, with $\lg v_m$ as the dependent variable were first obtained. The regression coefficients so obtained are given in Table I. Using these regression coefficients as the exponent values of the different independent variables, their total correlations with v_m as well as the partial correlations were then calculated and are presented in Table II.

Table I. *Regression coefficients*

	$\lg(1010 - p_1)$	$\lg r_m$	$\lg \sin \theta$
$\lg v_m$	0·591	−0·319	−0·412

Table II. *Correlation coefficients*

	$(1010 - p_1)^{0.591}$	$r_m^{-0.319}$	$(\sin \theta)^{-0.412}$
Total correlation	0·856	0·671	0·361
Partial correlation	0·805	0·512	0·193

It can be seen that the total and partial correlations of maximum wind with central pressure depth and the radius of maximum wind are quite significant while those with sin θ are low. The corresponding simple and multiple regression equations for v_m involving $(1010 - p_1)$ and r_m are

$$v_m = 8{\cdot}3(1010 - p_1)^{0.591} - 3{\cdot}358 \qquad (11)$$

and

$$v_m = 6{\cdot}7(1010 - p_1)^{0.591} + 87{\cdot}7 r_m^{-0.319} - 24 \qquad (12)$$

The coefficients of determination (i.e. squares of the correlation coefficient) of the two equations are 0·73 and 0·81 respectively.

The best possible exponent values for $(1010 - p_1)$ and r_m, when they are used in the product form, also were determined, and the corresponding regression equation for v_m is

$$v_m = \frac{20{\cdot}6(1010 - p_1)^{0.172}}{r_m^{0.168}} - 2{\cdot}13 \qquad (13)$$

The coefficient of determination of this equation is found to be 0·812.

Similar analysis was done with v_m^2 as the dependent variable. The regression coefficients and the correlation coefficients so obtained are presented in Tables III and IV.

Table III. *Regression coefficients*

	$\lg(1010 - p_1)$	$\lg r_m$	$\lg \sin \theta$
$\lg v_m^2$	1·182	−0·638	−0·824

Table IV. *Correlation coefficients*

	$(1010 - p_1)^{1.182}$	$r_m^{-0.638}$	$(\sin \theta)^{-0.824}$
Total correlation	0·8799	0·6614	0·4245
Partial correlation	0·8365	0·5068	0·1921

The regression coefficients are approximately twice as large as those in Table I but in this case the correlations with $(1010 - p_1)$ are slightly better than in the earlier case. The simple and multiple regression equations for v_m^2 involving $(1010 - p_1)$ and r_m are

$$v_m^2 = 65{\cdot}5(1010 - p_1)^{1.182} - 57{\cdot}4 \qquad (14)$$

$$v_m^2 = 54{\cdot}5(1010 - p_1)^{1.182} + 15\,348 r_m^{-0.638} - 1631 \qquad (15)$$

The coefficients of determination of these equations are 0·77 and 0·84. These values are higher than the corresponding values of equations (11) and (12).

The best regression equation for v_m^2 with $(1010 - p_1)$ and r_m in the product form is obtained as

$$v_m^2 = \frac{400(1010 - p_1)^{0.943}}{r_m^{0.336}} + 65 \qquad (16)$$

and the coefficient of determination of this equation is 0·85. This is again not only higher than that of the corresponding regression equation for v_m (13), but also greater than those of equations (14) and (15). Therefore, equation (16) can be considered as the best regression equation. However, it may be noted that the exponent values of $(1010 - p_1)$ and r_m in this equation are nearly equal to 1 and $-1/3$ respectively. The authors, hence, assumed these simple power values and evaluated another regression equation for v_m^2 by keeping the peripheral pressure as an unknown constant. The resulting regression equation is

$$v_m^2 = 302(1012{\cdot}6 - p_1)/r_m^{1/3} \qquad \ldots \ldots \ldots \ldots \qquad (17)$$

The coefficient of determination of this regression equation is 0·85 and is surprisingly greater than that of equation (16). The authors, therefore, suggest that equation (17) can be used to give best possible estimates of maximum wind in typhoons from the central pressure and the radius of maximum wind. A similar attempt, with the central pressure alone as the independent variable, gave the regression equation

$$v_m^2 = 161(1003 - p_1) \qquad \ldots \ldots \ldots \ldots \qquad (18)$$

whose coefficient of determination is 0·78.

The values for the peripheral pressure obtained in the above two regressions are quite different. The value in the former equation is close to the actual and it therefore suggests that r_m is also an important factor in the estimation of the maximum winds as well as the central pressure depth.

The work relates only to tropical cyclones in the western North Pacific and those in other parts of the world may differ somewhat in their characteristics (see for example Gray 1979), and therefore caution is required in applying the equation in other areas.

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551.508.77:556.025

Rain-gauge network rationalization and its advantages

By C. A. Nicholass (Meteorological Office), P. E. O'Connell (Institute of Hydrology)
and M. R. Senior (Wessex Water Authority)

Summary

The purpose and methods of rain-gauge network rationalization are described and the ways in which users of rainfall data can benefit from improved rain-gauge network design are discussed; the rationalization of the networks in the Wessex Water Authority area is used as an example.

Introduction

The Meteorological Office provides archiving and validation facilities for daily, weekly and monthly data and, in conjunction with Water Authorities, inspects rainfall stations to ensure a continuing high standard of siting and observational practice. However, although there is no national standard system for archiving automatically recorded data in machinable form, hourly totals from an increasing number of stations are being archived by the Meteorological Office and some quality control is applied.

The costs of operating these networks and of collecting, processing and disseminating the data have increased in recent years (the purchase price of a standard rain-gauge is now about £80) and it is necessary to consider whether the data requirements of users could be met in a more cost-effective manner. This is the main purpose of the Rain-gauge Network Rationalization Project, described by O'Connell *et al.* (1977, 1978, 1979) and Jones *et al.* (1979) in which objectively based methods of network design have been evolved and tested in a case-study. For this evolutionary process the main stages were:

(a) a determination, in numerical terms, of the users' requirements for data,

(b) evaluation of the existing networks in the case-study area, using (1) network operation considerations and (2) statistical methods, and

(c) redesign of the networks, where necessary, to satisfy the users' requirements more effectively.

The reasons why an objectively based rationalization exercise might be expected to be superior to a purely subjective approach based on experience will be discussed, and each of the stages of the rationalization process will be described, with particular reference to the rationalization exercise carried out in the Wessex Water Authority area (O'Connell *et al.* 1978). Additionally, it will be shown how the Water Authority, the Meteorological Office and the other users of rainfall data may benefit (in a qualitative sense) from network rationalization.

Network design considerations

More than one approach to network design is possible. A subjective approach can be adopted in which the new network is evolved from an existing network by consideration of various practical factors and empirical criteria, such as the desired inter-gauge spacing; alternatively, an objectively based method involving statistical analysis of the rainfall field defined by the network may be coupled with elements of the simpler pragmatic approach.

Before adopting either approach it is necessary to consider the factors which influence the ability of a network to provide an adequate representation of the rainfall in time and space. These include:

(a) the type of rainfall,
(b) the density and configuration of the gauge network,
(c) the time resolution of the measuring equipment,
(d) the observational procedures used, and
(e) the accuracy of individual point measurements of rainfall.

The question of how best theoretically to distribute gauges within an area is a *network design* problem, but whether or not the gauges provide reliable measurements of point rainfall is a problem of *network operation.* Because of the interaction of the five factors, a complete approach to the redesign of an existing network will require both the use of statistical techniques for identifying the optimal configuration of gauges and practical consideration of the quality and reliability of the observations.

Using a subjective approach, an apparently satisfactory network can be evolved, but the complexity and interaction of the above factors will preclude any scientific evaluation of the adequacy of such a network, and quantitative comparison with users' requirements is not possible. However, using the objective methods described by O'Connell *et al.* (1978), it is possible to compare the accuracy of estimation at points in the rainfall field between gauges at any stage of the evolution of the design network with that required by users. Another advantage of the objectively based technique is that it is repeatable and is thus not dependent on individual preferences. The same methods should be applicable in different areas, resulting in a uniform standard of network design. Additionally, the assessment of potential networks can be carried out swiftly by computer.

An important fact demonstrated later is that even in areas of apparently uniform topography, a uniform inter-gauge spacing does not necessarily achieve a consistent level of accuracy across the area. The identification of the areas where denser networks are required and the estimation of the numbers of gauges needed in these areas are difficult problems to solve, except by objective techniques.

The stages of a network rationalization exercise

(a) *Evaluation of the users' requirements for rainfall data*

The principal users of rainfall data are the regional Water Authorities, the Ministry of Agriculture, Fisheries and Food (MAFF) and the Meteorological Office, which through its hydrometeorological enquiries section provides data to a variety of commercial and other users, including insurance companies, research organizations and engineers. Table I lists the major uses of rainfall data, the types of data required (usually daily, or shorter period totals), and whether these are required in 'real time'.

In the rationalization exercise, it is necessary to quantify the accuracies required by the users of rainfall data, at points or over areas, so that the accuracy of estimation which can be achieved by interpolating from the existing or proposed gauges can be compared with these requirements. This, too, is not an easy task as many users have never quantified the accuracy required for their activities. However, since most users accept that the present networks are accurate enough for their purposes, the accuracy of estimation which can be achieved using the existing network can form the reference point for a redesigned network. Ideally, rationalized networks should provide at least the same average estimation accuracy as existing networks.

Special network requirements need to be defined so that the redesigned networks can incorporate as many of these as is practicable. For example, some users require a uniform background network of gauges, some require long records, whilst others need denser networks in particular areas. Although it may not be explicitly stated, the requirement for the data to be of a uniformly high standard implies

Table I. *Some uses of rainfall data in the United Kingdom, with types of network required.*

User	Purpose	Network required: Gauges read daily	Recording gauges	Gauges transmitting data in real time
Water Authority	Design of flood alleviation works	X		
Water Authority	Evaluation of yields of reservoirs	X		
Water Authority	River regulation schemes	X (design)		X (operation)
Water Authority	Aquifer recharge calculation	X		
Water Authority	Leaching of waste tips	X	X	
Water Authority, Met. Office	Storm analysis	X	X	
Water Authority, Met. Office	Urban drainage design	X	X	
Water Authority	Flood forecasting/warning			X
Met. Office	Rainfall forecasting			X
Met. Office	Research and development	X	X	X
Met. Office	Soil moisture deficit maps	X		X
Met. Office	General enquiries	X	X	X
Met. Office	Climatic change	X		
Met. Office	Radar–rainfall research	X	X	X
MAFF*	Irrigation requirements	X		
MAFF	Field drainage design	X		
MAFF	Forecasts for crop diseases			X
MAFF	Crop development and husbandry studies	X		

* Ministry of Agriculture, Fisheries and Food.

that the known 'good' sites in the existing network should be retained in the new network, and that other sites should be improved.

(b) *Evaluation of the existing network*

(1) *Operational considerations.* It is necessary to classify the sites to identify those which it is desirable to retain in a redesigned network, and those which must be improved if they are to be included in the new network. The quality of the exposure of a site can be judged by inspection and the reliability of the observer and the observations can be evaluated by considering the numbers of apparent errors which are identified during the routine, computer-assisted quality control procedures over a period of time.

Using these assessments and other information, such as the length of record, a classification of a site can be made. As an example of this, Table II shows the classification of the sites in the Wessex Water Authority area, taken from O'Connell *et al.* (1978). Only those sites registered by the Meteorological Office in 1978, when the study took place, are included.

Table II. *Classification of registered rain-gauge sites in the Wessex Water Authority area in* 1978.

Classification	Number of sites: Daily	Monthly
Class A: should be retained	92	3
Class B: should be retained or removed	116	24
Class C: should be removed	23	4
Totals	231	31

(2) *Statistical methods.* Statistical methods for evaluating the performance of networks can be applied in two ways. Where a measured or estimated rainfall quantity forms the basis of some decision, this is deemed a direct use of rainfall data. Where rainfall data represent only one input to a decision-making process involving a number of variables, perhaps represented by a model, this is classified as an

indirect use. The corresponding statistical techniques, which can be referred to as direct and indirect methods, are described fully in O'Connell *et al.* (1977, 1978).

The direct methods of network evaluation used in this case involve the calculation of errors to be expected from optimal interpolation of gauged rainfall values to ungauged points or areas, followed by a comparison of these errors with those which are acceptable to users. As an example, optimal point interpolation errors for daily and monthly totals were estimated and mapped over the Wessex Water Authority area using the following procedure:

(i) Divide the region into a uniform square grid with elementary grid squares of side 5 km.

(ii) For each square of the grid:

(a) Obtain historical rainfall data for all gauges sited within a surrounding square of side 35 km centred on the given square.

(b) Calculate for this sample the correlations and variances of the rainfall data for pairs of stations lying within 35 km of each other.

(c) Fit a correlation function to the sample correlations and obtain an average variance for the region. This determines a fitted covariance function.

(d) Obtain the locations of gauges in the existing or proposed network which are within the outer square of side 35 km. Let this be the interpolation set for the given (5 km × 5 km) inner square.

(e) Using the gauges in the interpolation set, calculate the mean-square error of interpolation to each point on a 1 km square grid within the inner square.

(iii) The procedure is repeated for all 5 km × 5 km squares. The surrounding squares of size 35 km × 35 km used for adjacent 5 km × 5 km squares overlap each other to a considerable extent providing smoothing, firstly of the correlation parameters and secondly of the interpolation accuracy.

(iv) Using the 1 km grid values ((ii)(e) above) of point interpolation error, produce a contour map of the interpolation error for the whole region.

This technique is illustrated in Fig. 1.

Various categories of daily data can be analysed in order to show the differences in correlation structure (and the resulting effects on interpolation accuracy) between 'wet' days only, 'very wet' days only, or a mixture of 'dry' and 'wet' days chosen essentially at random. Monthly or annual correlation functions can also be calculated. Once correlation functions have been fitted for the chosen areas and categories of rainfall data, the estimation errors (expressed, for example, as root-mean-square errors) can be derived for optimal estimation procedures which use existing (or proposed) rain-gauge networks to interpolate to grid points, thus allowing maps of interpolation error to be drawn. Using the maps it is possible to identify the areas of deficient or superfluous accuracy with respect to the users' requirements. Similarly, the accuracy of areal estimates can be calculated and compared with the requirements of users. Examples of the use of these direct methods of network evaluation are given in a later section.

The use of indirect methods of network evaluation is limited by the difficulty of modelling some of the decision-making processes to which rainfall is an input. Two possible approaches would be (a) to study the effects of daily rain-gauge density on the accuracy of streamflow simulation using a daily rainfall run-off model and (b) to study the effects of telemetering gauge network density and configuration on the accuracy of short-term flow forecasts. Since, however, deterministic models of actual streamflow tend to give misleading results, their extension to provide guidance on the relative performance of redesigned rainfall networks does not entirely recommend itself and possible procedures will not be discussed further here.

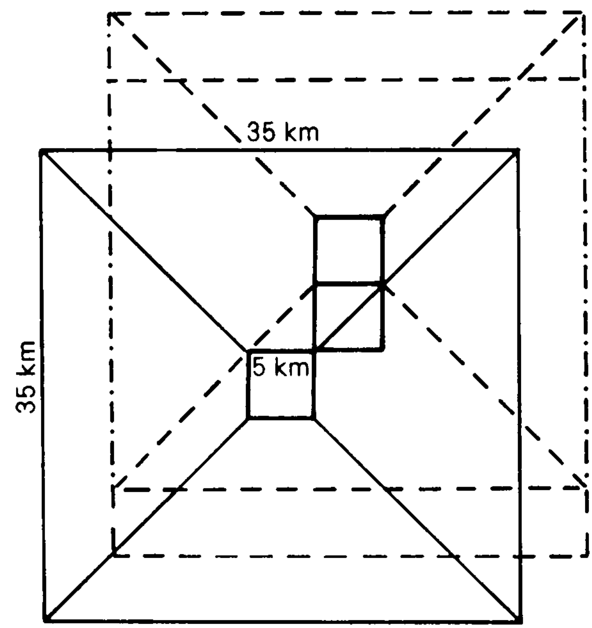

Figure 1. Square regions used for interpolating to points within each adjacent 5 km square.

(c) *Redesigning rain-gauge networks*

Having evaluated users' data requirements and the performance of the existing daily and monthly gauge networks, a set of design criteria can be determined for the rationalized networks. From a consideration of these criteria and by using a step-by-step design procedure the most appropriate distribution of rain-gauges within the network results. This procedure will include the use of the direct methods to evaluate the design network at various stages. By specifying alternative criteria, for example a different inter-gauge spacing, a selection of possible rationalized networks can be produced before the final choice is made.

The procedure used to redesign the Wessex Water Authority daily and monthly networks may be summarized in seven steps as follows:

Step 1. Set up a basic network with a chosen uniform gauge spacing, using existing registered or unregistered daily or monthly sites where possible, but otherwise specifying the locations of new gauges in centres of population only.

Step 2. Add any sites operated by or for the Meteorological Office but not included in Step 1, as these may be expected to continue to operate, irrespective of the rationalization exercise.

Step 3. Add any sites with records over a chosen length not included in Steps 1 or 2.

Step 4. Consider replacing any sites proposed in Step 1 by adjacent sites added in Steps 2 or 3.

Step 5. Add any remaining 'Class A' sites (see Table II), to provide as many reliable data as possible as a basis for the Meteorological Office computerized quality control routines, and to provide a measure of redundancy in the event of unexpected closures.

The network so far may be called a Preliminary Design Network.

Step 6. Evaluate this Preliminary Design Network in terms of its capacity to meet users' requirements by mapping point interpolation errors and calculating areal rainfall estimation errors. Adjust the density of gauges in the areas of deficient or superfluous accuracy.

Step 7. Repeat Step 6 until the desired level of accuracy is achieved in all important areas.

Three networks of daily and monthly gauges were designed for the Wessex Water Authority area using the step-by-step approach, each designed to meet different levels of users' requirements. The network adopted for implementation comprises 220 gauges compared with the existing networks of 333 daily (232 of them Meteorological Office registered) and an additional 46 monthly (30 registered) gauges. This network was designed to be at least as accurate on average as the existing networks and satisfied the design criteria of (a) a basic inter-gauge spacing of 10 km and (b) inclusion of all sites with a record length of at least 50 years. The evolution of this network is shown in Table III.

Table III. *Number of gauges added at each step of design procedure for the Wessex Water Authority Design Network.*

Step	Number of gauges added	Notes
1	133	Basic Network: gauge spacing approx. 10 km
2	13	Sites operated by or for the Meteorological Office
3	25	Criterion for record length: 50 years
4	−2	Two gauges replaced
5	12	Remaining 'Class A' sites
Preliminary Design Network total	181	
6	20	After comparison with users' requirements for data
7 (iteration)	19	
Design Network total	220	

A comparison of the accuracies of the existing and design networks in Table IV shows, for point interpolation, the percentage of the area which has a root-mean-square error of estimation less than specified values. These values were selected, depending on the category of data, so that the existing networks achieved these levels over some 90 per cent of the area. The four categories of data used were: (a) every fifth day's rainfall, irrespective of the amount, (b) days with an average areal rainfall greater than 1 mm, (c) days with an average areal rainfall greater than 5 mm, and (d) monthly rainfall. In the case of (b) and (c) a gap of five days was left after each day chosen, in order to minimize serial correlations between rainfall days.

Table IV. *Evaluation of network accuracy. Percentage of Wessex Water Authority area with root-mean-square errors of interpolation (RMSE) less than stated amounts.*

Network	Number of gauges	RMSE ≤1·0 mm every 5th day	RMSE ≤1·5 mm on days with areal rain ≥1 mm	RMSE ≤2·0 mm on days with areal rain ≥5 mm	RMSE ≤6·5 mm monthly totals
Existing daily	333	90·3%	88·2%	89·4%	
Existing monthly	379				92·9%
Design	220	91·0%	94·4%	90·6%	90·2%

Although a similar step-by-step method could be used to redesign recording-gauge networks, a shortage of recording-gauge data in computer format precluded the use of an objective method in this case, so a more empirical technique was used. Three recording-gauge networks were designed for the Wessex Water Authority area using, where possible, sites from the design daily networks which already have recording gauges. The users' requirements for recording-gauge data were considered at the design stage; for example, extra gauges were proposed in specified urban areas. The recording-gauge network which was adopted for implementation and which was intended to complement the design daily network of 220 gauges, comprised 77 gauges and had a basic inter-gauge spacing of 20 km.

A qualitative assessment of the benefits of rain-gauge network rationalization

The regional Water Authorities and the Meteorological Office, as major users of rainfall data, maintain the rain-gauge networks and collect, process and disseminate the data. Thus it is reasonable that all these organizations and also the customers of the Meteorological Office should be seen as the principal beneficiaries of a rationalization that leads to spatially uniform data of a higher standard, although from fewer gauges.

Whilst it is not a simple matter to quantify the real costs of running a rain-gauge network, or the savings to be made by rationalization, the reasonable expectation is that a reduction in the number of gauges will mean a reduction in operating costs. As regional Water Authorities carry the main burden of operating the networks, they see advantages in reducing the number of gauges. There is also a spin-off to the Meteorological Office which, apart from operating a number of gauges, also provides inspectors to ensure that sites and observational practices are maintained at a uniformly high national standard.

The major costs arising from data processing can be divided into two parts. These are, firstly those associated with the collection and initial visual checking of the data, which have costs proportional to the number of gauges, and secondly the computer-based quality control and archiving procedures which have a relatively stable cost, not significantly dependent on gauge numbers. Regional Water Authorities mostly undertake the first part and the Meteorological Office undertakes the second part. The evidence presented by O'Connell *et al.* (1978) is that the sophisticated but crucial quality control procedures are the most costly step in the data-gathering exercise.

The advantages of the rationalization of the Wessex Water Authority network (O'Connell *et al.* 1978) can be illustrated as follows:

(a) *Reduction in gauge numbers*

(1) From the Wessex Water Authority point of view:

—Before rationalization 333 daily and 46 monthly gauges (including 117 gauges not registered by the Meteorological Office).

—After rationalization 220 daily gauges (all of which would be registered).

—A net reduction of 42 per cent.

(2) From the Meteorological Office point of view (that is, considering only registered sites):

—Before rationalization 232 daily and 30 monthly gauges.

—After rationalization 220 daily gauges.

—A net reduction of 16 per cent.

The Wessex Water Authority clearly has the most to gain (in reduced running costs) from implementing the rationalized network. However, it should be pointed out that in order to achieve the more uniform reduced network, a number of new sites have had to be found and gauges installed, at some capital cost. Offsetting this is the improved standard of records provided by the new network. Such improvement also argues against the need to build significant station redundancy into the network.

(b) *Quality of the network*

All users should benefit from the Wessex design network of 220 gauges which, as well as achieving approximately the same general level of accuracy as the existing (larger) network, has other virtues. For example, the more uniform design network has a background inter-gauge spacing of 10 km (which helps to meet enquiries, particularly legal ones, for information at or near specific locations), all sites which have provided good quality data and those with very long records are included, and the sites which are maintained by or for the Meteorological Office are also retained. In addition, the rationalization exercise has highlighted shortcomings in the operation of some sites, which should be corrected before the sites are included in the design network. All of these features should encourage confidence in the data and allow better use to be made of them.

(c) *A demonstration of the advantages of the objectively based technique*

Fig. 2 shows for the Wessex Water Authority how the average level of accuracy of point estimation varies according to the number of gauges in the networks. This level of accuracy is expressed in terms of the percentage of the Wessex Water Authority area which has a root-mean-square error for point interpolation greater than 1·5 mm on days with an average rainfall over the area of 1 mm or more. The line marked 'Existing (or reduced) networks' demonstrates the effects of simple reductions in gauge densities. Apart from the points for all daily gauges (333) and all registered gauges (232), points are shown for one-half, one-quarter and one-eighth of all registered gauges, with each derivative being achieved by removing every second gauge from the previous network. The four points on the

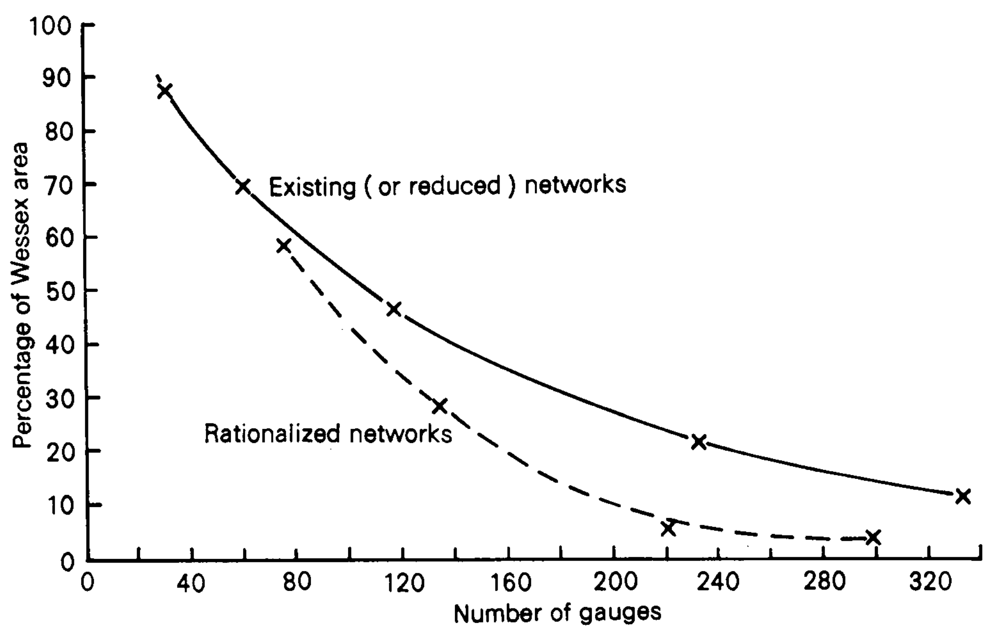

Figure 2. Percentage of the Wessex Water Authority area having a root-mean-square error of interpolation greater than 1·5 mm (for point interpolation on days with more than 1 mm of rainfall) for the different networks considered in this paper.

'Rationalized networks' line represent the networks designed for the Wessex Water Authority area:

75 gauges—that is, one gauge every 15 km
133 gauges—that is, one gauge every 10 km
220 gauges—that is, one gauge every 10 km, plus additions
297 gauges—that is, one gauge every 7 km, plus additions.

It can be seen that, for a given number of gauges, the rationalized networks always achieve a greater level of accuracy, and thus it follows that the rationalized networks require fewer gauges to achieve a chosen level of accuracy. For example, for a network of 200 gauges in the Wessex Water Authority area, a rationalized network would achieve the chosen level of accuracy (that is a root-mean-square error of interpolation less than 1·5 mm on days with average rainfall over 1 mm) over 90 per cent of the area, whilst a network derived by simple reductions of the existing network would achieve the chosen standard over only 67 per cent of the area.

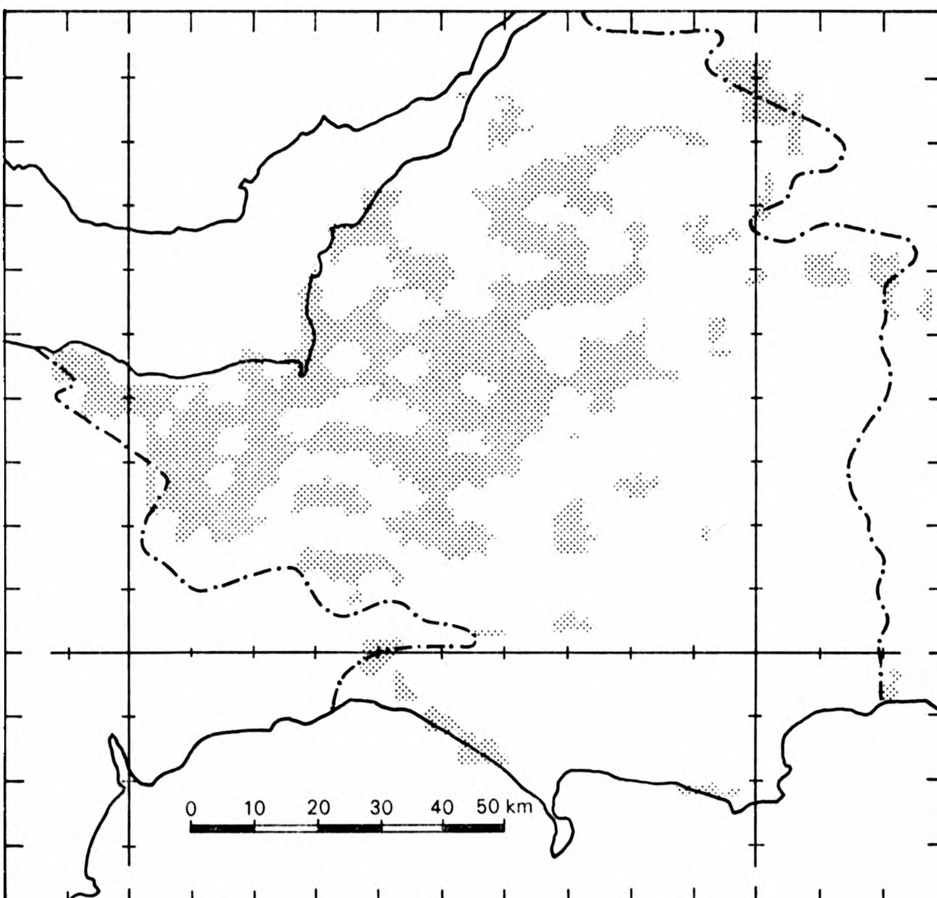

Figure 3. Regions (shaded) for which the root-mean-square error of optimal interpolation is greater than 1·5 mm for days with widespread rainfall of over 1 mm.
Basic Design Network of 133 gauges (one gauge every 10 km).
·—·—· Wessex Water Authority area boundaries.

Plate I. L. G. Groves Memorial Prize and Award winners with Mr Nicholas Abbott and Air Marshal D. B. Craig. Left to right: Squadron Leader M. J. Bibby, Mr Nicholas Abbott, Air Marshal D. B. Craig, C.B., O.B.E., M.A., Mr T. Denholm, Dr P. J. Mason, and Flight Lieutenant J. G. Ticehurst. (See page 112.)

Plate II. Air Marshal D. B. Craig congratulates Flight Lieutenant J. G. Ticehurst, winner of the Aircraft Safety Prize.

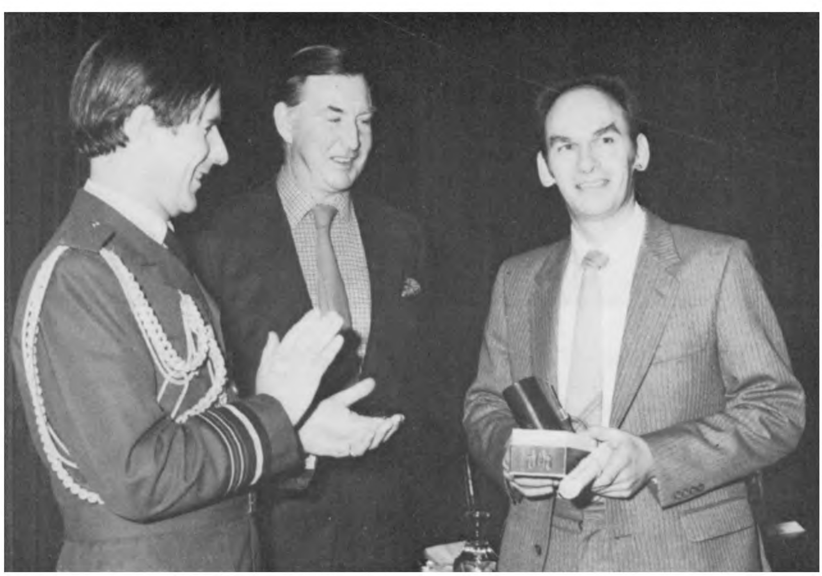

Plate III. Dr P. J. Mason, winner of the Meteorology Prize, being congratulated by Air Marshal D. B. Craig and Mr Nicholas Abbott.

Plate IV. Squadron Leader M. J. Bibby receiving the Meteorological Observer's Award.

Plate V. Congratulations to Mr T. Denholm after being presented with the Second Memorial Award.

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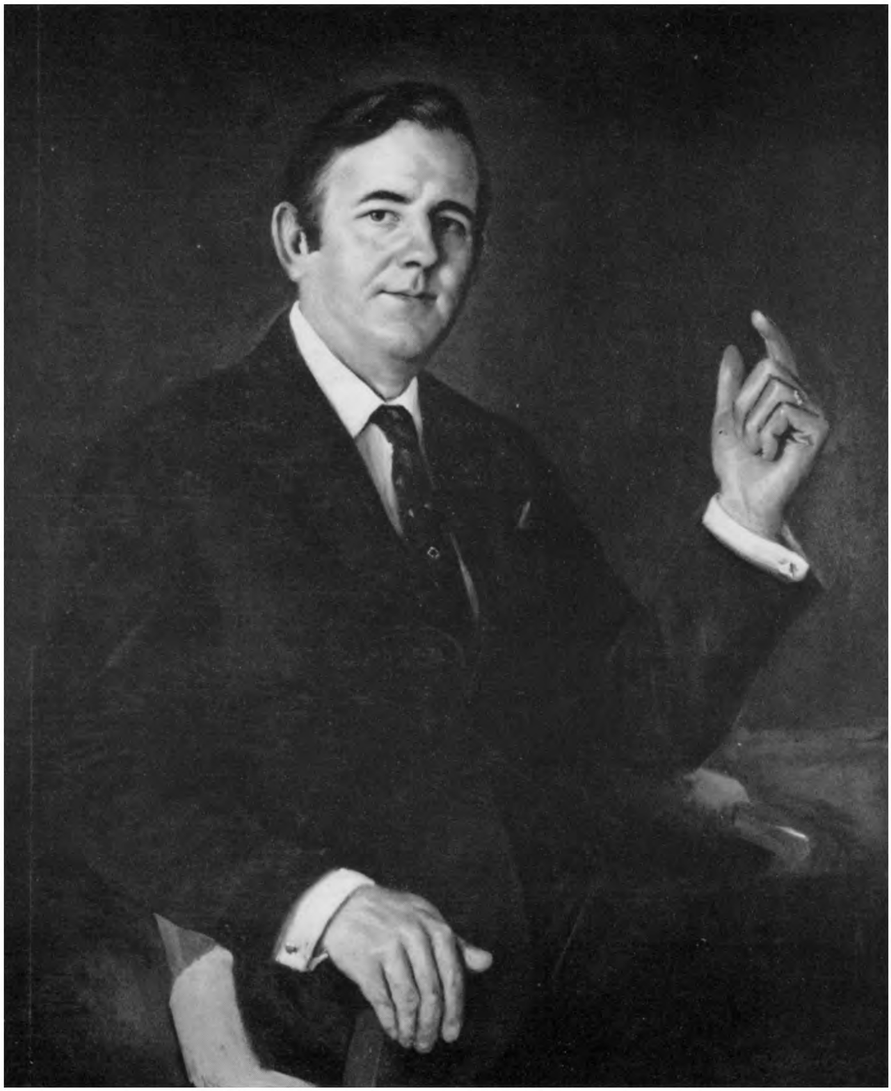

Plate VI. Photograph of an oil painting of the Director-General, Sir John Mason, by Roy Barley. The original portrait was presented to Sir John by his senior colleagues on 18 December 1979 to mark the conferment of his knighthood.

Fig. 3 shows the parts of the Wessex Water Authority area which have a root-mean-square error of point interpolation of over 1·5 mm on days with average rainfall of over 1 mm for the rationalized network of 133 gauges—that is, one gauge every 10 km. It is clear from this that, despite a uniform spacing, the accuracy of estimation is less in the west than in the east of the area, even though this is a region of relatively uniform topography. Fig. 4 shows how the final design network of 220 gauges has overcome this difficulty, thus demonstrating how the objective approach is superior to empirical procedures.

Conclusions

The rationalization exercise carried out in the Wessex Water Authority area has shown that it is possible to use the methods developed by O'Connell *et al.* (1977) to redesign rain-gauge networks so that the users' requirements for data are satisfied in a more cost-effective way that results in considerable advantages to the organizations which manage the networks and the data.

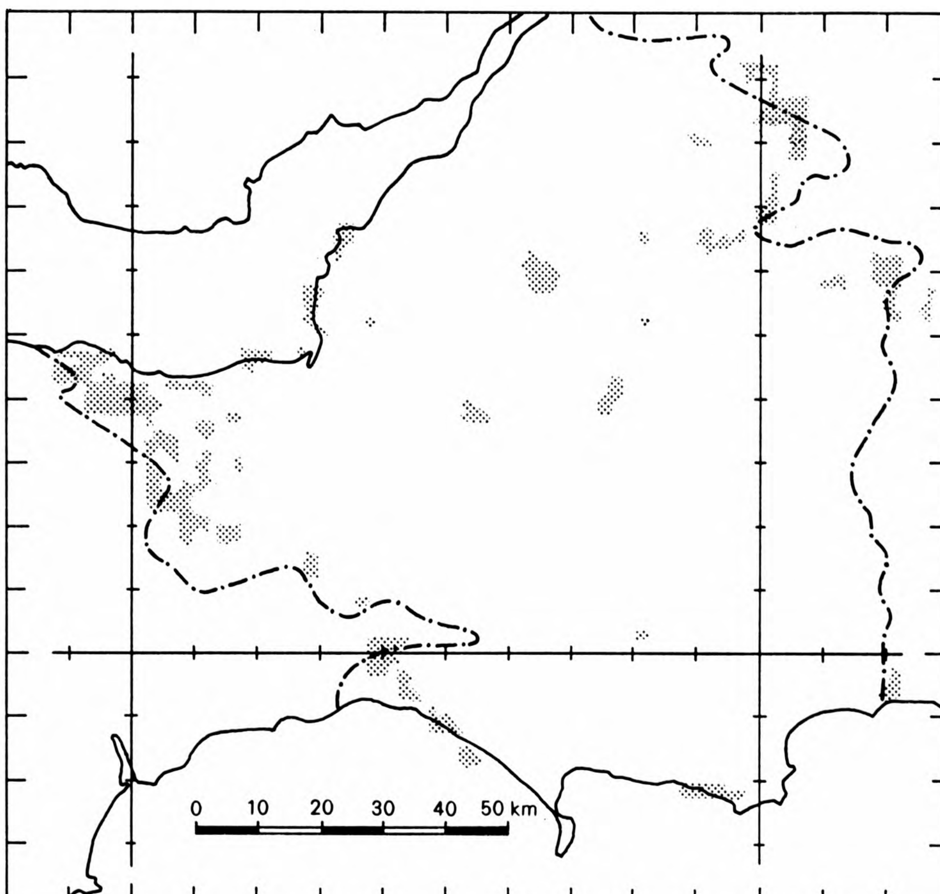

Figure 4. Regions (shaded) for which the root-mean-square error of optimal interpolation is greater than 1·5 mm for days with widespread rainfall of over 1 mm.
Final Design Network of 220 gauges.
·—·—· Wessex Water Authority area boundaries.

Work is continuing on the general application of the methods to other areas, including those with highly variable topography (and hence highly variable rainfall) and those which are covered by precipitation-measuring radar systems.

However, it will be necessary, if the full benefits of rain-gauge network rationalization are to be derived, to consider ways in which the collection, processing and dissemination of rainfall data can be made more efficient.

Acknowledgements

The Rain-gauge Network Rationalization Project described in this paper was a collaborative effort involving many people from the Institute of Hydrology, Wessex Water Authority, the Meteorological Office, and the Department of the Environment.

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The performance of a Campbell-Stokes sunshine recorder compared with a simultaneous record of the normal incidence irradiance

By H. E. Painter

(Meteorological Office, Bracknell)

Summary

The duration of bright sunshine has been evaluated from the record of normal incidence irradiance at Kew Observatory for specific thresholds of the irradiance. These durations are compared with the corresponding values obtained with a Campbell-Stokes sunshine recorder, using cards manufactured in the United Kingdom. The irradiance threshold to produce a burn on the sunshine recorder card varied from 106 to 285 W m^{-2} provided the sphere was unaffected by dew etc. The most important factor affecting the measurements of sunshine cards is the extension of the burn during intermittent strong sunshine; this can produce overestimations of sunshine durations for hourly or daily values of more than 100 per cent. The loss of record by the sunshine recorder due to dew, frost, etc. on the sphere is discussed.

Graphs are presented from which the monthly records of duration of sunshine at Kew could be corrected to a given threshold of irradiance, on the assumption that the experimental period is representative of previous years.

Introduction

For over a century the duration of bright sunshine has been recorded by comparatively simple devices. In many parts of the world the Campbell-Stokes recorder has been, and still remains, the instrument for such measurements. The principle of operation of this instrument is the production of a burn on a card by the sun's rays brought to a focus on the card after passing through a glass sphere. Bright sunshine, as thus measured, is therefore the duration for which the normal incidence irradiance exceeds a threshold which will produce a discernible burn on the card. This threshold has not been precisely defined. The World Meteorological Organization in its *Guide to meteorological instrument and observing practices* (1971), section 9.10.1, suggests that the threshold can vary between 70 and 280 W m^{-2}. It is essential with such an instrument that the specification of its dimensions and of the composition of the glass sphere and the card are precisely defined in order to get comparability of results from different instruments.

The limitations of the Campbell–Stokes type of sunshine recorder are well known and have been discussed by Bider (1958). The two major problems are the variability of the threshold of irradiance to produce a burn and the overburning of the card in conditions of intermittent high irradiance. Bider (1958) showed that on average throughout the year the threshold for burning was about 8 per cent less at sunsets than at sunrises and attributed this fact to the card being more subject to dampness from dew in the early morning than in the evening. The problem of overburning is very difficult to evaluate; one small burst of high normal incidence irradiance causes a burn of duration far longer than the few seconds of its actual duration and rules have therefore been made to take account of this fact when measuring the lengths of burns.

Although the Campbell–Stokes sunshine recorder is an inexact instrument it has its advantages in that it can be used at isolated sites without an electrical power supply, is comparatively easy to maintain and use and is likely to be in service for a considerable time in the future. A demand has arisen for a sunshine recorder with an electronic output to be used on automatic weather stations. From a climatological viewpoint, a relationship would be required between any new type of sunshine recorder and the Campbell–Stokes sunshine recorder. With modern data logging methods and computer facilities it is now possible to investigate in more detail the performance of a sunshine recorder in relation to the record of normal incidence irradiance measured by a pyrheliometer. Such a comparison is here presented for the period from May 1979 to February 1980 from Kew Observatory, about 16 km west of central London.

Instrumentation

The sunshine recorder was the standard Meteorological Office instrument used for routine measurements, with cards manufactured in the United Kingdom. The cards were changed after sunset and measured in the approved manner. There is, of course, an element of subjectivity in measuring the burns on sunshine cards. The cards from Kew were measured by a number of different observers and each card was checked by a second observer; also random-check measurements were made by the Climatological Services Branch of the Meteorological Office to ensure that the national standard of measurement was being maintained.

The normal incidence pyrheliometer was the standard instrument which automatically tracks the sun. The solar alignment of the instrument was checked several times daily. The output from this instrument was punched on paper tape and also plotted by an analogue recorder. The analogue record was inspected and whenever it was defective because of instrumental failure (this includes the few occasions when the pyrheliometer was not correctly aligned) such records were deleted for this comparison. The normal incidence irradiance was sampled at one-minute intervals and thus there was not a continuous record of the irradiance and, therefore, on occasions of intermittent sunshine there could have been rapid changes between successive samplings. Hereafter the term irradiance is to be understood as referring to the normal incidence irradiance.

Analysis of the data

The irradiance data were formed into a continuous record by drawing straight lines between successive one-minute data. The durations, when the irradiance was above certain threshold values, were then evaluated. This was done for each hour of local apparent time corresponding to the times of the evaluations of the cards of the sunshine recorder. Durations were evaluated for each threshold of irradiance from 20 W m^{-2} by increments of 20 W m^{-2} up to 240 W m^{-2}. For each of these durations there was also given the number of times the irradiance record traversed the threshold value. These traverses could be either from below to above or from above to below the threshold. Hence, from the irradiance data were formed a series of durations of sunshine for each hour of each day for specified values of irradiance thresholds. The ratios of the monthly totals of these durations to the corresponding monthly durations from the sunshine recorder are shown in Fig. 1 for each month of the period under consideration. Each month comprised days of widely different sunshine conditions and another set of curves are shown in Fig. 2 for selected days as examples of particular conditions. The 14 May and 25 December were selected as days with continuous sunshine apart from a few breaks just after sunrise and just before sunset. The overburns on the cards for these days were likely to be minimal. The 17 January, 25 June and 14 August were examples of days with intermittent strong sunshine and any overburning of the records would be accentuated because of the numerous breaks in the sunshine. The 14 August was

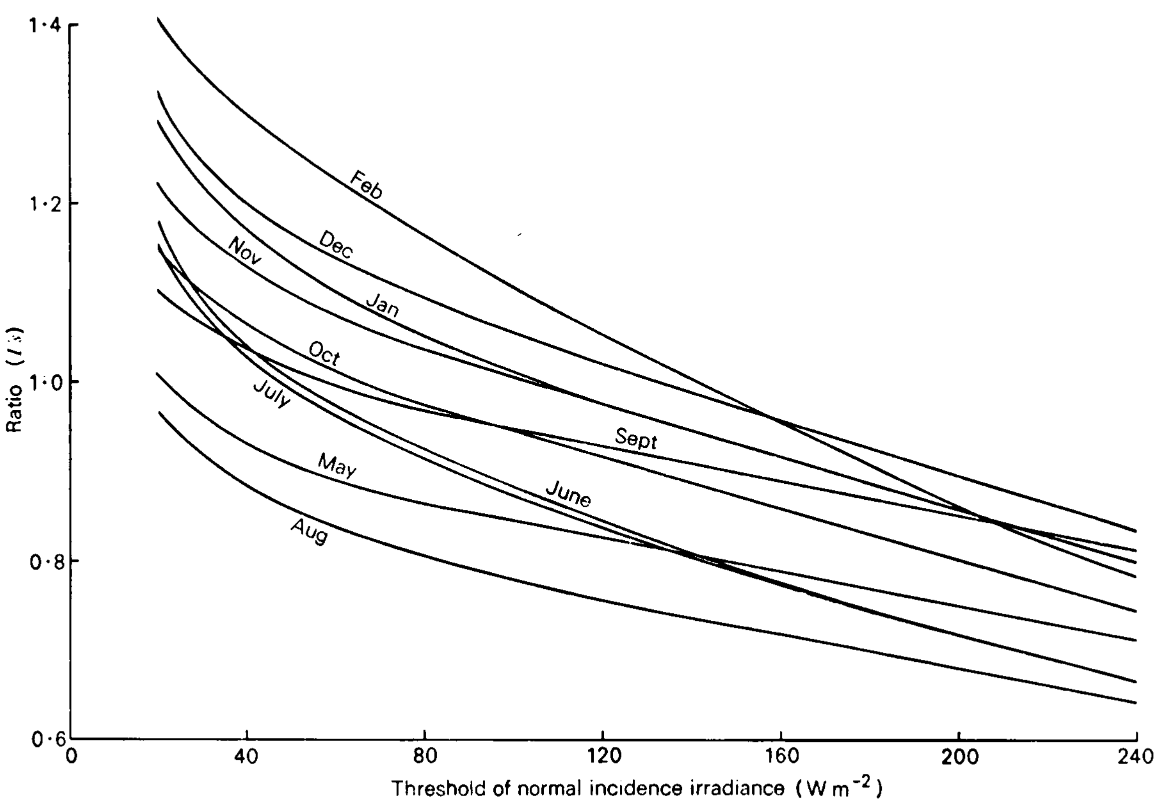

Figure 1. Ratios of monthly sunshine durations for various thresholds of normal incidence irradiance (*I*) to the corresponding values from the Campbell–Stokes sunshine recorder (*s*).

the day with the maximum number of traverses of the irradiance thresholds; for five hours there were over 20 traverses per hour. The 19 February was a hazy day with intermittent but not very strong sunshine.

The particular point of interest in Fig. 2 is the range in the threshold of equality between the two methods of evaluating the sunshine duration. In the case of the three days in which overburn is minimal the threshold of equality is about 130 W m^{-2} in summer and about 200 W m^{-2} in winter. (These thresholds are the average daily values; there are variations from these mean values at different times throughout each day.) The three days with strong intermittent sunshine have a threshold of equality of 45 W m^{-2} or less and there is obviously some other factor affecting the measurements of the burns on the sunshine cards which was not present in the previous cases. The implication from these curves is that if 130 W m^{-2} is the approximate threshold for burning in summer, then on 14 August the sunshine recorder measurement is overestimated by a factor of about 2·3.

A further analysis was made of all hours throughout the 10-month period when the sunshine recorder measured 0·9 hours of sunshine. Mean values of the corresponding durations from the irradiance data were evaluated for each of the irradiance thresholds used above and also for 1, 2–5, 6–10, 11–15, and more than 15 traverses of these thresholds. The results are shown in Fig. 3 where it is seen that, for a given threshold, the greater the number of traverses the smaller is the duration of sunshine evaluated

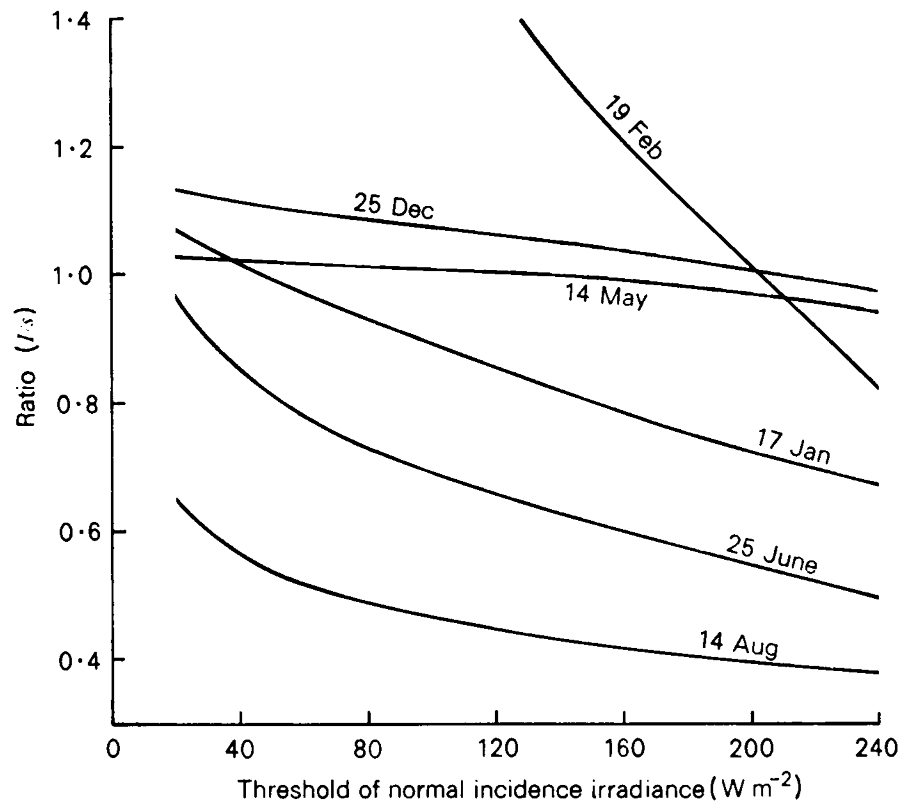

Figure 2. Ratios of sunshine durations for various thresholds of normal incidence irradiance (*I*) to the corresponding values from the Campbell–Stokes sunshine recorder (*s*) for particular days.

from the irradiance data. In the extreme case the 0·9 hours of the sunshine recorder is on average only 0·5 hours from the irradiance data. There can be little doubt that the increasing overestimation of the sunshine-card records with the increasing number of breaks in the record results from an extension of the burns, particularly with high irradiances.

From Fig. 1 it is seen that the curves show a marked seasonal effect. This arises firstly because the threshold of burning is higher in winter than in summer as a result of generally lower temperatures and damper conditions, and secondly because irradiances are generally lower in winter than in summer and therefore the overburn of the cards (and hence the overestimation of the measurements) will be less in winter than in summer.

In Figs 1 and 2 the threshold of equality, or in other words the effective threshold of the sunshine recorder, is the irradiance threshold necessary in order to equate daily or monthly sunshine durations produced by the two methods. From Fig. 1 it is seen that the effective threshold ranged from 142 W m^{-2} for February to about 16 W m^{-2} for August.

The monthly curves in Fig. 1 apply only to the period under consideration and are not necessarily representative of their respective months for other years. In order to arrive at more general mean curves the data for May to August, for September and October, and for November to February have been combined to give in Fig. 4 representations of the mean curves for summer, equinox and winter respectively. The slight difference in shape between the equinoctial curve and the other two curves is probably due to poor sampling for the equinoctial curve for which only two months' data were available.

The threshold of burning

The irradiance threshold of burning of the card of the sunshine recorder has been estimated from some of the data given above but actual measurements of this threshold were also made. As has been observed, for example by Bider (1958), the threshold of burning is on average higher in the early morning than in the late evening and so on all suitable occasions an examination was made of the commencement of burns after sunrise and of the cessation of burns before sunset. Examples were used only if the rate of change of irradiance with time was very small, so that errors of two minutes in estimating the time of the burn did not make a big difference to the irradiance value. Over the 10-month period the mean irradiance threshold was 193 W m^{-2} for 41 samples in early mornings and 154 W m^{-2} for 44 samples in late evenings. The lowest value of this threshold was 106 W m^{-2} in the evening on a day of almost continuous bright sunshine. The highest value of the threshold was 301 W m^{-2} on a hazy morning in September; it is possible that there may have been dew on the sunshine recorder sphere on this particular day. The next highest threshold of 285 W m^{-2} appears to be a genuine case of the card being wet after rain earlier in the night.

As a matter of general interest solar elevations were evaluated for a number of occasions of very early or very late burns on the sunshine card. There were six occasions with solar elevations of less than 3°, the lowest value being 2·3°. These low values were in summer and winter.

Loss of record from the sunshine recorder

The discussion above on the irradiance threshold was concerned only with the performance of the card of the sunshine recorder and assumed that the instrument, particularly the glass sphere, was otherwise in perfect condition. The measurements of threshold values, however, indicated that there were notable losses of record which must be attributed to dew or other water deposits on the glass sphere. There were three days on which the card did not produce a burn until the irradiance was greater than 400 W m^{-2}. If one assumes a mean threshold of burning of 200 W m^{-2} this implies a loss of

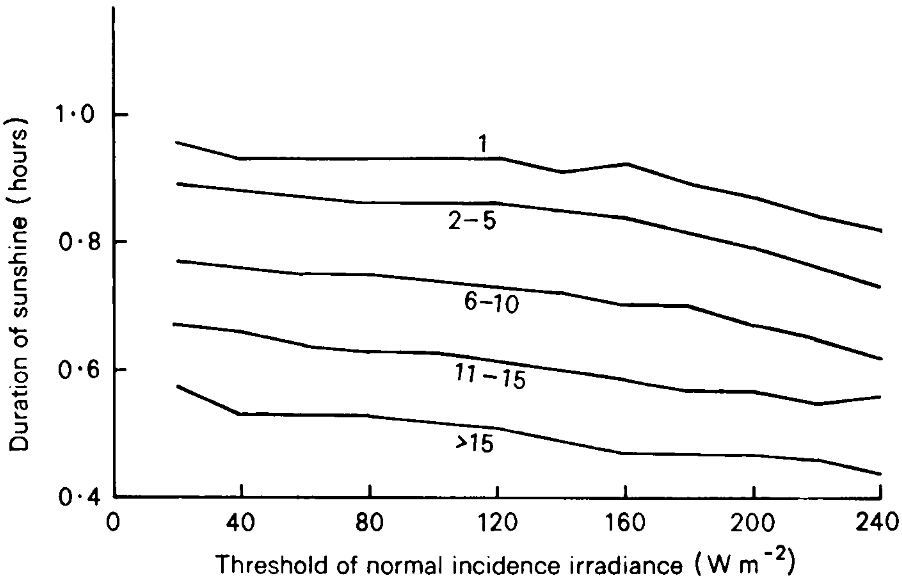

Figure 3. Mean durations of sunshine (hours) for various thresholds of normal incidence irradiance and for various frequencies of traverses of the threshold values on all occasions when the Campbell–Stokes sunshine recorder measured 0·9 hours.
Period: May 1979–February 1980.
The numbers of traverses of the thresholds are given against each curve.

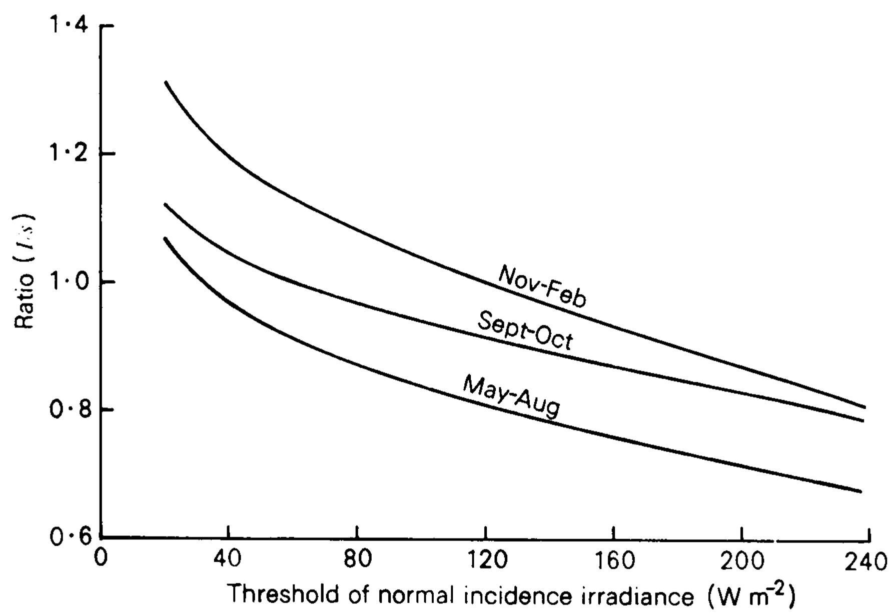

Figure 4. Ratios of sunshine durations for various thresholds of normal incidence irradiance (*I*) to the corresponding values from the Campbell–Stokes sunshine recorder (*s*) for various periods.

sunshine record of 0·8 h on 3 May, 1·2 h on 1 June and 0·7 h on 25 February. There were a number of days when there was a loss of record of 0·2 or 0·3 h from this cause. It seems probable that whenever the threshold of burning is above 300 W m^{-2} the transmission of the glass sphere of the sunshine recorder is reduced by dew, frost, rime, or even rain deposits. There was no very striking example in this comparison of losses of record from the sunshine recorder due to frost or rime.

Conclusions

The performance of the sunshine recorder is very variable because of the effect of weather conditions on the state of the card and of the glass sphere, but chiefly because of the overburning of the card in conditions of intermittent sunshine. The average measured irradiance threshold for a burn is about 170 W m^{-2} but the effect of overburn is to produce a mean threshold of equality of about 60 W m^{-2} over the period under consideration. There is a marked seasonal effect in this threshold which ranges for average conditions from about 30 W m^{-2} in summer to 120 W m^{-2} in winter.

Although rules are given to take account of overburn when measuring sunshine cards, nevertheless, on occasions of very broken sunshine a measurement of sunshine duration over an hourly period can be overestimated by over 100 per cent and if these conditions continue throughout a day there will be an error of the same magnitude in the daily total.

As the effective threshold will vary with weather conditions, daily values from the sunshine recorder must be treated with considerable reserve when used synoptically over an area or country.

It would be difficult, if not impossible, to construct another instrument that would reproduce the performance of the Campbell–Stokes sunshine recorder and, therefore, to obtain continuity of records using a new instrument it would be necessary to reduce archived monthly records of sunshine duration obtained from the sunshine recorder to a fixed threshold of irradiance by reference to curves of the type given in Fig. 4. There is therefore an urgent need for a scientific definition of bright sunshine.

The problem of frost on the glass sphere of the recorder will be greater at some stations, not only because of the greater prevalence of frost but also because the instrument may be visited only once a day when the card is changed. The instrument at Kew was inspected before the 06 and 09 GMT observations and the sphere cleaned when necessary.

The results of this comparison apply strictly to the weather conditions that prevailed at Kew during the period under consideration and when sunshine cards of United Kingdom manufacture are in use.

An unpublished comparison between the IRSR and the instrument system used in this trial showed the IRSR to record 6 per cent less sunshine over a two-year period. In the present trial the Campbell–Stokes recorder with UK cards recorded about 19 per cent more sunshine than did a pyrheliometer.

The specifications of the Campbell–Stokes recorder and cards are not, in practice, standardized throughout the world. The World Meteorological Organization (1971) paras 9.10.2.1 and 9.10.2.2)) recommended the Interim Reference Sunshine Recorder (IRSR) which complied with the detailed specification issued by the Meteorological Office together with cards which complied with the detailed specification issued by Météorologie Nationale. An unpublished report of a comparison between the IRSR system (i.e. with French cards) and the UK system (i.e. as used in the present trial) showed the IRSR system to record on average 6 per cent less sunshine over a two-year period. In the present trial the Campbell–Stokes instrument recorded about 19 per cent more sunshine than the pyrheliometer, using the average observed threshold of 170 W m^{-2}. To account for this 13 per cent discrepancy, the IRSR system must also over-register in intermittent sunshine (although perhaps to a lesser extent than the UK system) unless the burning threshold for the French cards is considerably lower than that for the UK cards.

Acknowledgements

I am indebted to Mr R. J. Armstrong for programming the data and to Mr F. Lumb for calculating the solar elevations.

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Noctilucent clouds over western Europe during 1980

By D. H. McIntosh and Mary Hallissey

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Table I summarizes the observations of noctilucent cloud (NLC) over western Europe during 1980 as reported to the Department of Meteorology, University of Edinburgh.

The times given in the second column of the Table do not necessarily indicate the duration of the display, though appearance and disappearance times are referred to in the Notes where known. In the third column brief notes of the displays enlarge on the facts listed in other columns—NLC forms discernible, tropospheric cloud conditions, photographs and sketches available. Co-ordinates of the observing stations and selected details of elevation and azimuth appear in the remaining columns.

Routine hourly observations were made at 15 meteorological stations in the United Kingdom, 4 in Sweden, and at Reykjavik in Iceland when darkness permitted. Observers at these stations provide information of sky conditions during all hours of darkness; the significance of 'negative' nights is obviously great when trying to assess the overall appearances of NLC.

Positive reports of the clouds were received for 32 nights during the 1980 observing season; this compares with 43 for 1979. Several observers have expressed the opinion that the clouds appeared less often and were not merely less often visible due to the prevalence of tropospheric cloud during the 1980 summer months. Mr Olesen of Denmark reported that, most unusually, he did not see a single appearance of NLC. Mr Parviainen's list of 9 displays visible at Turku, in Finland, makes a welcome contribution to the summary. His last sighting was on 7/8 August, and the last of the list was recorded by Mr Solås of Norway on 9/10 August—some weeks earlier than the end of the 1979 season. (An early sighting reported from Sundsvall for 6/7 April and a late one from Leuchars for 31 August/ 1 September are both treated as doubtful, as in each case the SDA (solar depression angle) is greater than 16°.)

Positive observations were received from 10 meteorological stations of the (hourly observing) group mentioned above, 5 from other British meteorological stations, from 3 Swedish stations, 1 Icelandic station, a Lufthansa pilot, and from voluntary observers in Dundee, Joppa (Edinburgh), Milngavie, Newton Stewart, Fiane and Turku. Points of observation of some displays were well scattered—on 2/3 July as far apart as Turku and mid-Atlantic.

Time-lapse photography was again carried out at the Department of Meteorology, Edinburgh, throughout the observing season, providing a record of nightly conditions there. The three clearest displays were on the nights of 21/22, 26/27 and 29/30 June. These two last dates and 13/14 July were the most widely reported displays of the season, but there was no outstandingly bright display. On 25/26 June a photograph of the display was taken at Machrihanish; on 29/30 June, 30 June/1 July and 31 July/1 August the displays were photographed at Milngavie, the last event, not because it was a striking display, but rather because the appearance was later in the season than Dr Simmons had previously recorded.

The help and co-operation of the many observers who were fortunate enough to see appearances of NLC and of the many more who watched in vain is gratefully acknowledged. A grant from the Meteorological Office makes possible the collection, collation and publication of the written and photographic data. All data so far have been incorporated by Dr Fast of the University of Tomsk into his catalogue of NLC data.

Table I. *Displays of noctilucent clouds over western Europe during* 1980

Date— Night of	Times UT	Notes	Station position*	Time UT	Max. elev.	Limiting azimuths
					degrees	
1980						
11/12 May	0243–0330+	Silvery-blue patches of NLC in zenith, medium brightness: tufted and striated formation. Possible W–E movement. Identification uncertain after 0330 in brightening sky. SDA approx. 10° (Sketch from Lyneham).	51·5°N 02°W	0300	90	—
13/14	0215	NLC suspected visible low on N horizon above distant hills from SW Scotland.	55°N 04·5°W	—	—	—
1/2 June	2400–0030	Suspected NLC veil visible Edinburgh with faint banded formation (time-lapse photo.).	56°N 03°W	—	—	—
5/6	2400, 0020	NLC veil with billow formation, medium brightness, visible Jönköping. Faded by 0045.	58°N 14°E	2400 0020	60 70	010–060 350–069
6/7	2200–2400+	Thin veil of NLC visible Leeming, hidden by tropospheric cloud before 0100.	54·5°N 01·5°W	2200 2300	5	360
11/12	0200	NLC suspected visible Tiree through cirrus. Nil visible at earlier observations of 2400, 0100.	56·5°N 07°W	—	—	—
15/16	2300	NLC visible N. Ireland. (Tropospheric cloud hampered visibility at 2200 and 2400.)	54·5°N 06°W	—	—	—
17/18	0030–0115 0200–0315	From Edinburgh, possible NLC behind tropospheric cloud. Completely obscured 0130.	56°N 03°W	—	—	—
19/20	0130–0300	NLC along N horizon visible Edinburgh through breaks in tropospheric cloud.	56°N 03°W	—	—	—
21/22	2400–0330	2 small patches of NLC visible Boulmer 2400, 0100. In Edinburgh NLC suspected visible between tropospheric clouds 0100, 0200. Clearance at 0215 showed parallel bands of NLC, medium brightness. Bands brightened against veil background at 0300. Faded into brightening sky at 0330.	56°N 03°W 55·5°N 01·5°W	0215 0315 2400 0100	10 — 4	020 020 030
24/25 June	2400–0230	At 2330 Benbecula noted clear sky and no NLC. At 2400 thin white veil of NLC visible, brightening slightly 0100, until fading into dawn light at 0230.	57·5°N 07·5°W	2400	5	330–010

* To nearest 0·5 degree.

Date—Night of	Times UT	Notes	Station position	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
25/26	0100, 0200	Bright rippled bands of NLC visible N–NE at Tiree and Machrihanish; obscured by tropospheric cloud at Tiree at 0200, but still seen faintly farther south until fading into brightening sky.	56·5°N 07°W	0100	18	045
			55·5°N 05·5°W	0100	12	360–020
26/27	2130–0345	NLC became visible above tropospheric cloud to 16° elevation from SW Scotland. Bands of NLC to 7° visible NE England before midnight, rising to 10° with increasing brightness. At Joppa (Edinburgh) small patches visible 0035 to 15° elevation increased in brightness and elevation to 20°. Visible on film at Edinburgh from 0130—extensive display of bands and billows to high elevation by 0315; banded formation still visible faintly in NE at 0345. NLC visible at Tadcaster to 23° elevation around 0200, as 'flame-like' streaks. Most southerly point of recording, Marham (Norfolk) where highest elevation was at 0200–0225, when wispy patches reached 20°. Medium brightness reported generally.	56°N 03°W	0035	15	340–020
				0050	20	010
				0145	20	
				0245	30	360–045
				0315	30	360–040
			55·5°N 03°W	0100	12	320–030
			55·5°N 01·5°W	2345	7	360–020
				0045	10	350–030
			55°N 04·5°W	2215	16	360
			54°N 01°W	0200	23	360
			52·5°N 0·5°W	0148	10	340
				0200	20	340–020
				0225	20	340–020
29/30	2230–0315	NLC fleetingly visible at various points from Jönköping in E, across central and SW Scotland and N England; showing striated structure. From Edinburgh display visible for some 3 hours until fading into light sky at 0315 at high elevation. Band and billow formation clearly discernible for most of time, with densely packed NLC formation 0200 and 0215.	58°N 14°E	2350	50	360–050
			56°N 03°W	0020–0030	10	340–040
				0300	30	340–040
			56°N 04·5°W	2330	17	340–040
			55·5°N 04·5°W	0015	7	015–020
			55·5°N 01·5°W	0100	11	340–020
			55°N 04·5°W	2230		
30 June/1 July	2225–2301	NLC visible in W and SW Scotland for brief period, with streaks to fairly high elevation, joined by lateral wisps.	56°N 04·5°W	2230	21	045
			55°N 04·5°W	2230	16	360–040
1/2 July	2200, 0556	NLC seen at E and W extent of our coverage (Turku and Lufthansa aircraft): no details.	60°N 22°E	2200	—	—
			51°N 40°W	0556	—	—
3/4	2320–0015	Billow formation NLC remaining steady at high elevation reported from Visby; medium brightness fading to less bright, with slight extension of western edge during observation.	57·5°N 18·5°E	2320	30	020–030
				2350	30	010–030
				0015	30	350–030
4/5	2035, 2245	Faint display—no details—reported from Turku and Dundee.	60°N 22°E	2035	—	—
			56·5°N 03°W	2245	—	—
6/7	2400–0200	First visible Benbecula as thin veil of NLC above cirrus, with some brilliant white patches. At last observation visible showing brightly in gaps in tropospheric cloud.	57·5°N 07·5°W	2400	12	330–010
13/14	2100–0230	Uninterrupted viewing from several stations; fibrous and rippled formation, bright or brilliant at times, especially in NE quadrant: extensive azimuthal spread. Very detailed description of display as seen from Carlisle.	60°N 22°E	2100–2400	55	315–060
			57·5°N 07·5°W	2300	14	320–050
				0200		360–030
			55·5°N 04·5°W	0116		045
				0220		020–045
			55·5°N 01·5°W	2320	4	020–030
				0100	5	
				0200	11	010–035
			55°N 01·5°W	0040	8	010–035
			55°N 03°W	0045	8	350–020
				0100	8	360–020
				0130	9	
				0150	10	360–020
			55°N 04·5°W	0040		360–045
15/16	2145–2245	Lenticular patches and narrow bands of NLC visible Boulmer and, at same time, just faintly from Turku.	60°N 22°E	2230	15	???–025
			55·5°N 01·5°W	2200	9	350–010
				2245	7	340–020
18/19	2145–2300	Bright NLC visible—no other details.	60°N 22°E	2200	15	350–045
22/23	2215	Faint NLC visible Turku—no details.	60°N 22°E	2215	10	—
23/24	2120–2200	Small amount of NLC visible—medium bright—first at Turku and later at same latitude at Lerwick.	60°N 22°E	2130	—	—
	0050–0135		60°N 01°W	0100	10	360, 045
24/25	2110	Report of possible very weak NLC to zenith from Fiane.	59°N 09°E	2110	90	250
25/26	2120–2200	From Turku, at similar time as report of previous night from Fiane—faint NLC, but no further details.	60°N 22°E	2130	—	—
29/30	0400	Rippled formation NLC seen from Tiree in NE sector.	56·5°N 07°W	0400	10	040

Date—Night of	Times UT	Notes	Station position	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
31 July/1 Aug.	2149–2345 0200	Earliest sighting 2149 at Joppa—very small faint patch of NLC, brightening 2210 into 3 bands. By now visible Milngavie, where veil and band structure visible for 30 minutes (SDA estimated 12°). Billowed formation bright at Benbecula 2300 to NW, seen as patch in NNW from Wick. Brightness also increased at Joppa as 3 bands merged into layer in NW. At 0200 NLC again visible from Wick in NNW.	58·5°N 03°W	2300	13	310–350
				0200	12	345
			57·5°N 07·5°W	2300	10	290–010
			56°N 04·5°W	2212	8	340–020
				2240	4	340–020
			56°N 03°W	2145	7	360
				2210	7	355–005
				2250	7	335-005
1/2 Aug.	2110	Spread of NLC to high elevation seen from Fiane.	59°N 09°E	2110	90	340
2/3	0030–0100	Bands of bright NLC visible Reykjavik to high elevation, visible until covered by altocumulus at 0100.	64°N 22°W	0030	25	—
7/8	2130	Very faint NLC visible—no further details.	60°N 22°E	2130	5	—
9/10	2110–2115	Diffuse veil of NLC to NE and E seen Fiane—possible banded formation.	59°N 09°E	2110	90	045, 090

Awards

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday 28 November 1980 at the Main Building, Ministry of Defence, Whitehall (see Plates I–V). Since the previous prize-giving Mrs Dorothy Groves had died, little more than a year after the death of her husband, Major K. G. Groves, so that all present felt strongly aware that for the first time both founders of this remarkable series of awards were no longer with us. The Vice Chief of the Air Staff, Air Marshal D. B. Craig, C.B., O.B.E., M.A., presided.

Air Marshal Craig opened the proceedings and referred to Mrs Dorothy Groves with warmth and respect. He then called on Mr Nicholas Abbott, as current representative of the Groves family, to present the prizes and congratulate the winners. Mr Abbott in his turn also referred to his great-aunt's death, and said that she had left a substantial legacy for the furtherance of the various prizes and awards. He welcomed in particular among those present who were members of or connected with Major Groves's family, Miss Patricia Halahan whose father, the late Air Vice Marshal F. C. Halahan, had joined the Royal Naval Air Service on its foundation by Churchill in 1914 together with Mr Abbott's grandfather, Robert Marsland Groves (Major Keith Groves's brother), having previously married one of the Groves sisters.

The 1980 Aircraft Safety Prize was awarded to Flight Lieutenant J. G. Ticehurst of Royal Air Force Coningsby for his proposals regarding the use of metal detectors for clearing air-to-ground ranges, with the following citation:

'During weapon training in the last four years, ricochet damage has been responsible for 10 RAF accidents classified Category 3 or worse, and 67 incidents where lesser degrees of damage occurred. The cost of the 10 accidents alone was just under £2·2 million. Although only one aircraft was destroyed, it is largely a matter of luck where the aircraft is struck by the debris and each impact could cause a major accident. Ricochet damage is caused by aerial-delivered weapons bouncing off the target structure, rocks or metallic debris in the ground from earlier weapon deliveries. To reduce this hazard, target structures are made suitably resilient and any rocks that can be found are removed from the area. However, locating and removing buried metallic debris is more difficult and time-consuming. The method used on most air-to-ground ranges is to rake over the surface and dig up the debris that is revealed but this method is not one hundred per cent efficient and some debris will remain undetected. Flight Lieutenant Ticehurst researched this problem and discovered that a readily available and relatively cheap treasure hunters' metal detector would accurately pin-point buried metal in the immediate target area, where there is the greatest risk of a ricochet occurring. He therefore carried out an assessment to confirm the detector's suitability for the task. As a result, Flight Lieutenant Ticehurst has recommended that range personnel should be equipped with light-weight and inexpensive metal detectors to ensure more efficient removal of metal debris from our air-to-ground ranges, thus reducing the amount of costly ricochet damage.'

The 1980 Meteorology Prize was awarded to Dr P. J. Mason of the Boundary Layer Branch of the Meteorological Office for his work on airflow over hilly country and the numerical simulation of atmospheric boundary layers, with the following citation:

'Dr Mason has modelled various aspects of flow over hills, advancing our appreciation of the physical processes involved and significantly improving our ability to forecast the effects of hills and valleys on airflow. In support of this theoretical work he and his collaborators have organized several field experiments designed to measure the airflow characteristics over actual hills, seeking thereby to test the results of his computations. Recently he has capitalized on this work by developing a very elegant technique for representing roll vortices over flat terrain.'

The 1980 Meteorological Observer's Award was awarded to Squadron Leader M. J. Bibby, now serving at Royal Air Force Upavon, with the following citation:

'Squadron Leader Bibby joined the Meteorological Research Flight (MRF) as Officer Commanding the RAF unit in the summer of 1977 and was posted out three years later. During this time he quickly established his competence in the role of Officer Commanding MRF and also participated fully in the interpretation of the scientific objectives as far as the flying was concerned. His drive and enthusiasm proved his leadership qualities in the air and on the ground, not only to the other RAF crew members but also to the civilian scientists. In particular should be mentioned his contribution to the Joint Air–Sea Interaction (JASIN) project held in 1978 where, despite early difficulties due to poor weather and aircraft unserviceability, the whole of the flying contribution to the project was nevertheless achieved, largely by Squadron Leader Bibby's efforts and dedication.'

The 1980 Second Memorial Award was awarded to Mr T. Denholm of the Meteorological Office, with the following citation:

'The development of North Sea oil resources has required accurate weather forecasting services which are dependent *inter alia* on reliable observations from the offshore installations. Mr T. Denholm has served for the past four years as the first meteorological adviser to the offshore operators based at Aberdeen. During this time he has made over 100 visits to platforms and rigs both in the North Sea and to the west of Shetland, often in very adverse weather conditions, in order to advise and train oil company observers on the required procedures and associated instrumentation work. The observations so obtained have been especially important to helicopter flight safety. His zeal and initiative have undoubtedly improved observing standards in this area and have thus contributed towards a better weather service for operators working in a particularly hazardous environment.'

Review

Environmental instrumentation, by L. J. Fritschen and L. W. Gay. 240 mm × 160 mm, pp. xvi + 216, *illus.* Springer-Verlag, New York, Heidelberg, Berlin, 1979. Price DM 42, US $23.60.

The authors of this book intended it to be used as a text for advanced students and a manual for researchers studying the relations linking biological responses to atmospheric variables. A meteorologist will find the balance of the book rather unfamiliar, as certain topics receive an unusually detailed treatment, whereas others are discussed rather too briefly. However, the book includes descriptions of most of the types of instrument currently in use for near-surface meteorological measurements, and the authors give due emphasis to explaining the physical principles of operation of each device including the potential sources of errors, so the meteorologist too will find this book useful.

The first two chapters are entitled 'Measurement fundamentals' and 'Review of physical fundamentals', and are probably the least satisfactory chapters in the book. In Chapter 1 the sections on measurement errors and error estimation are too short to be of much use to anyone unfamiliar with these topics, and that person would benefit more by being referred to one of the standard texts. The introduction to the book states that the user is expected to have a basic physics and mathematics background and would therefore be familiar with most of Chapter 2, especially with such basics as Ohm's law or the formula for conduction of heat in a solid bar.

The most useful part of the book is made up of Chapters 3 to 8, which describe methods and devices for measuring temperature, soil heat flux, radiation, humidity and moisture, wind speed and direction, and pressure. Each chapter begins with a section which outlines some of the basic physics and mathematics involved in each type of measurement and the following sections describe types of sensors, usually with some guide to their suitability for a particular application and how to minimize errors. The examples of actual devices are chiefly of American origin, but at the end of each chapter the bibliography and list of literature cited include copious references from all parts of the world. Some of these references might appear rather old but, as the authors point out in the introduction, environmental instrumentation has not been drastically changed by recent technological developments and most of the advances have been in the methods of data recording and handling. These chapters, therefore, augmented by their references, provide a good review of current instrumentation, although the space devoted to each topic is not necessarily commensurate with its true importance. For example, the section on thermo-couples, with 16 out of 48 pages, takes up too much of the temperature chapter, and the chapter on pressure is far too short so that many modern types of transducer have not been mentioned.

The final chapter, 'Data acquisition systems', attempts too large a task in dealing with this vast and rapidly developing subject in only 16 pages. Much useful information is presented in this chapter, but anyone unfamiliar with the subject will probably be more confused than enlightened and sometimes the authors also seem confused.

The book is well printed and illustrated, with clear diagrams and excellent photographs of sensors. There are many useful tables which help to make it complete as a work of reference and there are few obvious misprints, although the section on radiation errors of thermometers is a notable exception since it contains several mistakes in equations which make them useless for calculating the magnitude of these errors.

This book satisfies many of the requirements of a reference manual of instrumentation. It may not provide the newcomer to the field with all the information required to solve a particular problem, but the reader should have gained sufficient knowledge to enable him to define the problem and evaluate a solution provided by experts or in a more complete text.

K. L. Webber

THE METEOROLOGICAL MAGAZINE

No. 1305 April 1981 Vol. 110

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NOTICES

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Issues in Microfiche starting with Volume 58 may be obtained from Johnson Associates Inc., P.O. Box 1017, Greenwich, Conn. 06830, U.S.A.

Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1.80 monthly **Annual subscription £23.80 including postage**

Dd 716670 K15 4/81

ISBN 0 11 726281 1
ISSN 0026-1149

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

May 1981

Met.O. 942 No. 1306 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1306, May 1981, Vol. 110

551.501.45: 519.24/.25

Smoothing and filtering of meteorological data

By A. C. L. Lee

(Meteorological Office, Bracknell)

Summary

The concept of filtering is discussed as a means of estimating a representative signal from data that have been corrupted by noise. Comparisons are made between the meteorologically common 'arithmetic average' filter and other filters. The Bessel filter emerges as a filter that gives a more representative estimate, can be readily implemented, and is particularly useful where considerable smoothing is required.

1. Introduction

In meteorology, in common with many other physical sciences, there is a need to make representative measurements of a relatively slowly moving 'signal' (such as wind direction), that is corrupted by 'noise' (such as turbulence) which has a wide spectral content.

A common technique is to smooth or filter the data over some period of time. This paper is not intended to consider the length of time over which any specific meteorological phenomenon should be smoothed, but rather to discuss the concept of filtering as a method of representing the underlying phenomenon of interest, often referred to as the 'mean' value. Several alternative filters, having the property of easy implementation, are considered, and the conflict between noise removal and phase distortion is highlighted. The Bessel, or Thompson, filter is shown to be a useful compromise. Its performance in estimating 'mean' quantities is shown to be superior to that of a simple arithmetic average in non-stationary situations, which are always those of interest. This is particularly true where derivative quantities, such as wind veer, are significant. Finally, a technical discussion is presented indicating how Bessel, or similar, filters can be implemented in hardware or in economical software. The latter is particularly significant in an era of cheap, although low-performance, microprocessor technology.

2. The purpose of filtering

It is helpful to pursue the specific example of wind direction further. We may wish to measure the synoptic wind direction, but a single sensor will measure the synoptic variable with turbulent noise superimposed. There will also be effects due to topography and the friction layer, but this is a separate issue which for our purpose will be ignored.

For the above example, we might ideally have a dense network of sensors and use spatial averaging over a 'synoptic' scale length to smooth out noise. Clearly this is impracticable; instead some form of 'time averaging' or filtering is often used, the assumption being made that the 'noise' has a zero mean, and that if we can average for long enough the residual noise will be small.

Unfortunately we cannot 'average' for an arbitrarily long time; the synoptic situation also changes and we are interested in following certain rapidly changing situations such as occur during the passage of a front.

There are two subtly different viewpoints when considering data from a single sensor:

(a) We are interested in temporal structures of time-scales longer than a certain 'characteristic time'. Longer structures are essentially synoptic, while shorter structures are essentially unwanted turbulent noise. However, we do wish to discriminate between separate events in time as far as possible in order to distinguish the sequence of events.

(b) We are interested in spectral frequencies below a certain 'characteristic frequency'. Lower frequencies are essentially synoptic, while higher frequencies are essentially unwanted turbulent noise. Thus we wish to be able to discriminate frequencies as far as possible so as to retain the wanted lower frequencies, and reject the unwanted high frequencies.

The two viewpoints are not mutually exclusive; they can both be satisfied using a 'low-pass' filter which attempts to exclude frequencies above the 'characteristic frequency', whose value is related to the scale length of the desired spatial averaging.

In general 'noise' will have a continuous spectrum, and for any characteristic frequency there will always be a contribution to the final signal from the low-frequency noise below the characteristic frequency in addition to any high-frequency noise which may not be adequately suppressed. At the same time we wish to be able to follow the more rapid synoptic variation without undue suppression or other (phase) distortion.

It must be realized that filtering is not the same as taking an arithmetic 'average' over some strictly defined period of time. If the latter is specifically required, it defines a specific type of filter. If, however, the problem is left more general, in the sense that the purpose is to monitor synoptic variations while suppressing 'noise' which has a zero average, this leaves more flexibility in the design of the filter. This extra flexibility can result in a filtered signal which more nearly approximates to the 'synoptic' signal than does the arithmetic average. In particular, different types of filter can place different emphases on distortion and noise removal, corresponding to the two viewpoints above.

In this paper, the purpose of low-pass filtering is taken to be the estimation of a representative non-stationary signal which has been corrupted by noise having a zero mean.

3. Approaches to filter implementation

Filtering is a subject well familiar to engineers, and there appears to be spasmodic interest in the meteorological literature. This interest has usually centred around low-pass filtering of data series consisting of samples equally spaced in time. Most authors have discussed various approaches to weighting the time series with a suitable finite set of weights, often in the form of a bell-shaped distribution.

An early paper in the geophysical literature is by Holloway (1958). He discusses the problem of assigning weights, without reaching any conclusion on 'optimum' methods. Craddock (1968) suggests an empirical scheme for determining a suitable distribution. Passi (1976) shows that 'smoother' data can be obtained by making the distribution correspond to a mathematical function. Ruthroff and Bodtmann (1976) emphasize the 'smoothness' by showing how noise-reduced derivatives can be extracted from filtered data. Charnock (1957) uses a truncated approximation to a (sin x)/x impulse response in order to obtain a highly discriminating frequency response. Kaiser and Reed (1977) exhibit a more modern approach by finding alternative ways of approximating an ideally sharp cut-off frequency, while avoiding undesirable spreading into higher frequencies through 'ringing', by recognizing that only a finite number of weights will be used. A feature of their approach is to manipulate mathematical functions having known properties such as the maximally flat Butterworth polynomial, or the equi-ripple Chebyshev polynomial. By proper manipulation of the known functions, the desired type of approximation can be made to the ideally sharp cut-off low-pass filter.

The above papers share a common trait—they do their best to remove high frequencies, but pay little regard to the shape of the weighting function itself. To obtain the sharpest cut-off, the weighting function will have large ringing excursions, and so the filter response to an isolated 'impulse' will exhibit the same ringing. As sharper cut-off is achieved at some characteristic frequency, the necessary ringing weighting function extends in time. In this sense higher discrimination in the frequency domain leads to poorer temporal discrimination. If both time and frequency discrimination are considered important, the resulting set of weights closely resembles the smooth bell-shaped Gaussian or normal distribution, and this sort of distribution has been used by many authors. The necessary truncation of this smooth curve tends to throw up minor ringing in the frequency domain. In a recent review paper, Harris (1978) describes a number of useful alternative 'optimum' approaches to obtaining finite sets of weights which are discriminating in both domains.

From the viewpoint of smoothing time-series data, the finite weighting function approach has an important drawback. If the original continuous data contained high frequencies, then frequent samples must be taken if the data are to be fully represented. Specifically, a minimum of two samples must be taken per cycle at the highest frequency present in the data at any significant amplitude i.e. the Nyquist constraint (Shannon 1949). If the data are to be 'smoothed' over a relatively long period, then a large number of weights are involved. In a software implementation this implies a large number of multiplications per time-step, which is computationally expensive. In a hardware environment it is difficult to implement such a finite set of weights conveniently and accurately, if at all.

An alternative approach is to use a sampled data version of the modern analogue filter theory. The basic ideas of modern filter theory are discussed in textbooks such as Herrero and Willoner (1966), and Zverev (1967). Here the data are filtered by implementing a transfer function in the frequency domain which can be mathematically represented by numerator and denominator polynomials in the complex frequency s. In the analogue world, such transfer functions are easily implemented because most useful linear signal transmitting media approximate to this sort of transfer function.

In a sampled data system, it is possible to approximate such transfer functions closely by evaluating recursive relations between the data going into and out of a filter. Meyer and Isacker (1975) discuss recursive filters, although they emphasize high-frequency discrimination without regard to time discrimination. An exact equivalence cannot be obtained between the effective weighting function produced by these transfer functions and the finite set of weights described above, because the effective weighting function is strictly infinite in duration, although only a finite portion contributes significantly to the filter output. Thus the two approaches produce different types of filter. It will be shown in later sections that these recursive relationships can often be implemented with little more than one multiplication per time-step on average, especially if the data are smoothed over a relatively long period, and that this multiplication can often be degenerated into an accumulator shift. This has obvious advantages for microprocessor applications.

The nearly exact equivalence of the modern filter theory approach in both continuous analogue and sampled data systems means that the same filter can be implemented either way, or else by a hybrid, which can have advantages.

The simplest low-pass filters are obtained when the numerator becomes unity, leaving just a denominator polynomial. The resulting class of filters are the so-called 'polynomial filters'. The order of the filter corresponds to the highest power of s in the denominator polynomial. A good deal of attention has been paid over the years to obtaining the optimum performance (in some carefully defined manner) from low-order polynomial filters, which correspond to simple physical or recursive realizations. These will be emphasized in the next section. It will be seen that, for our purposes, little is lost by degenerating the numerator.

4. Polynomial filters and the arithmetic-average filter

Figs 1–4 describe the properties of several low-pass types of polynomial filter. Each has been normalized in frequency so that the 'characteristic frequency' (defined here as having 3 dB attenuation) occurs at $\omega = 1$ radian per second. The most widely known polynomial filter is the Butterworth, whose characteristics are shown in Fig. 1. Fig. 1(a) shows the filter attenuation in decibels against frequency on a logarithmic scale for several orders ($n = 1$–10) of filter. Note the change in scale at $\omega = 1$. The polynomial coefficients in the Butterworth transfer function have been arranged so that all the derivatives of the absolute value of the transfer function with respect to frequency, except the nth, are zero at $\omega = 0$. In this sense the transfer function is maximally flat at low frequencies, while at high frequencies it is dominated by the highest power of s present.

The Butterworth is an excellent filter for separating sinusoidal signals at low and high frequencies. Unfortunately, the time by which the signal is delayed on passing through the filter (the group delay, shown in Fig. 1(b)) varies with ω, and this applies to frequencies below the characteristic frequency. The distortion which this produces on non-harmonic signals can be clearly seen in Figs 1(c) and (d) which show the filter response to a Dirac impulse (of vanishingly small width and unit area), and to a unit step. The filter 'rings' for a considerable time. The impulse response is of particular interest as, with a reversed time-scale, it represents the continuous weighting function which must be applied to the previous history of the raw data sequence to produce the filtered output. Evidently the Butterworth's ringing intermingles discrete events in time.

Fig. 2 shows the properties of a particular Chebyshev filter. In this filter a considerable increase in the rate of change of attenuation near the characteristic frequency can be achieved at the expense of allowing a defined amount of ripple (here 0.5 dB) in the passband (below the characteristic frequency). As might be expected, the group delay and impulse responses are even worse, from our point of view, than the Butterworth.

The Butterworth and Chebyshev filters are optimized in the frequency domain, and represent attempts to obtain a box-like discrimination with zero attenuation below the characteristic frequency, and infinite attenuation above. It can be shown using the Hilbert transform (Zverev 1967) that attempts to produce this 'ideal' frequency discrimination will always exhibit large variations in group delay and considerable spreading of the impulse response through ringing, independently of whether polynomial or other transfer functions are used. Thus box-like frequency discrimination produces poor time discrimination.

It is common practice in meteorology to form an arithmetic average of the measured signal for some finite time, e.g. a 10-minute average wind direction or wind speed. Some measuring devices will integrate a signal, present the integrated values, and restart a new integration. This form of widely spaced

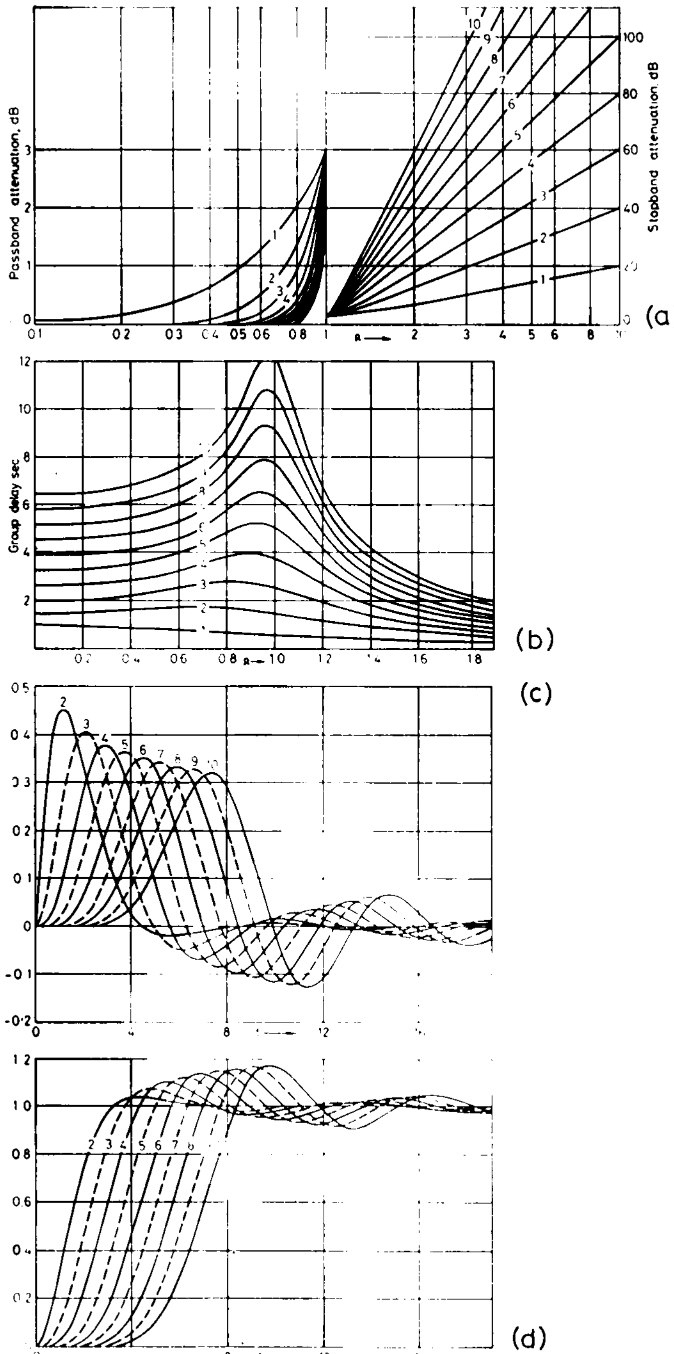

Figure 1. Butterworth filter characteristics. (a) Attenuation (decibels) v. frequency (radians per second). (b) Group delay (seconds) v. frequency. (c) Impulse response (for unit impulse) v. time (seconds). (d) Step response (for unit step) v. time.

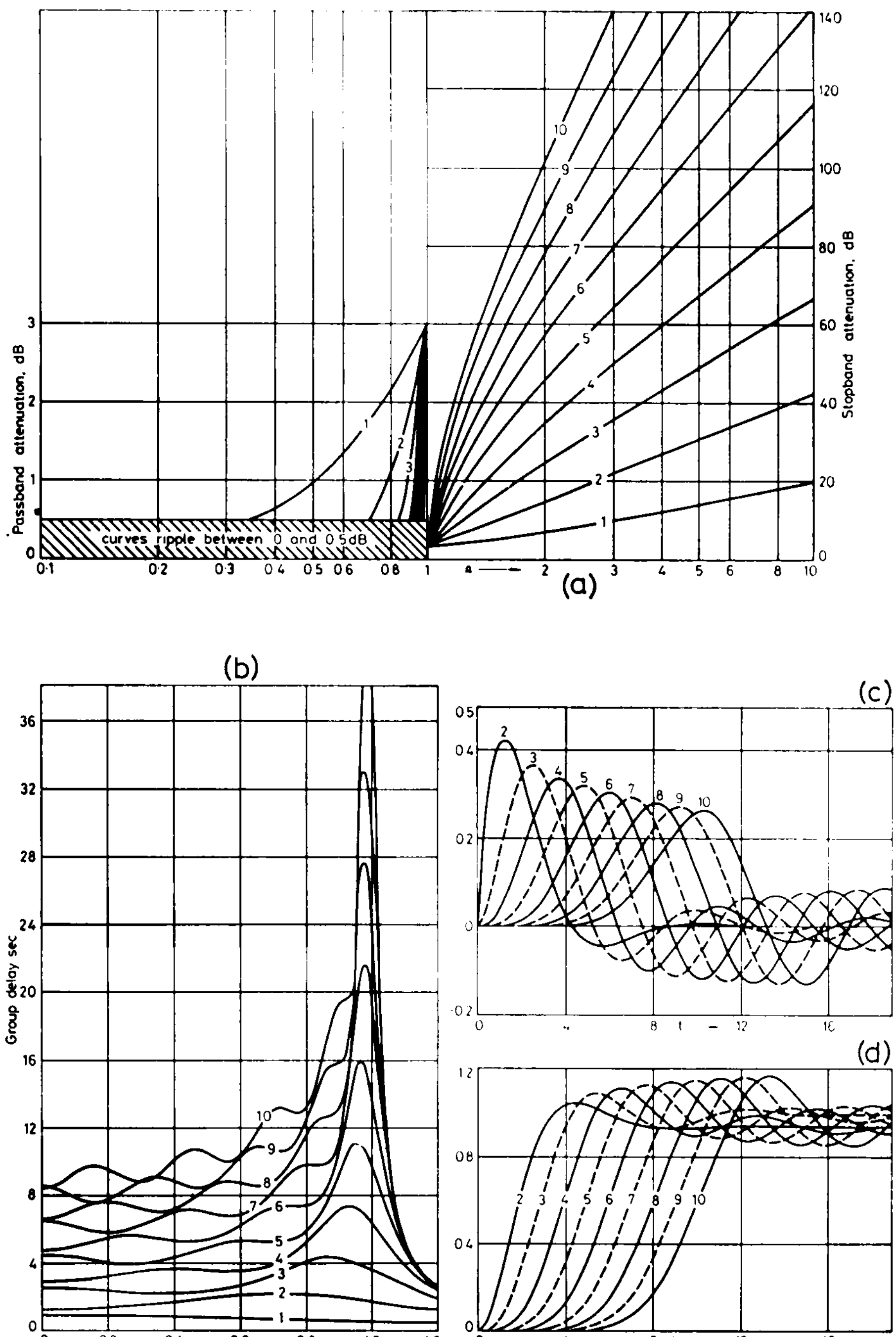

Figure 2. 0·5 dB Chebyshev filter characteristics. (a) Attenuation v. frequency. (b) Group delay v. frequency. (c) Impulse response. (d) Step response.

sampled output is difficult to compare with a continuous filter as the results from the two systems will in general be different, and there is no continuous trace to show how representative the samples are of the previous 10 minutes. Instead a filter will be considered which continuously presents the result of an arithmetic average over the previous T seconds, and whose response $\mathrm{R}(\omega)$ to a harmonic signal $\sin(\omega T + \delta)$ is given by:

$$\mathrm{R}(\omega) = (1/T)\int_{t}^{t+T} \sin(\omega T + \delta).\mathrm{d}t = \{2/(\omega T)\}\sin(\omega T/2)\sin(\omega t + \delta + \omega T/2).$$

The factor $\sin(\omega t + \delta + \omega T/2)$ represents the original harmonic input with a phase delay of $\omega T/2$, or a group delay of $T/2$ seconds at all frequencies. The remaining factor, $\{2/(\omega T)\}\sin(\omega T/2)$, represents the amplitude response as a function of frequency. At low frequencies this tends to unity. For compatibility, choose $T = 2.778697$ seconds, so that we have 3 dB attenuation at $\omega = 1$. Fig. 3 shows the properties of this filter. The impulse response, Fig. 3(c), shows constant weighting over T seconds. It will be no surprise to find that we have achieved 'ideal' box-like discrimination in the time domain.

The transfer function of a filter and its impulse response form a Fourier transform pair. Moreover, the transform from frequency to time domain is identical to that from time to frequency domain, apart from a scaling factor. As we have already observed that a box-like discrimination in the frequency domain gives rise to poor discrimination through ringing in the time domain, we should not be surprised to find that a box-like discrimination in the time domain gives rise to poor discrimination through ringing in the frequency domain, as evidenced in Fig. 3(a). The attenuation peaks of the arithmetic-average filter, which go to infinity, occur at frequencies whose periods are exact submultiples of the integration period. Apart from these peaks, the general level of attenuation is rather low, increasing at a rate of about 12 dB per octave, or 20 dB per decade. This means that high-frequency noise, which usually contains most of the noise energy, is poorly suppressed compared to the performance of previous filters. Lewis (1960) describes the 'Slutzky–Yule' effect where a moving-average filter can appear to give apparent periodicities in the smoothed data. Peacock (1970) points out that the phase reversals in the arithmetic-average transfer function which occur after each infinite attenuation peak can have the effect of reversing the sign of quasi-periodic events which can still be seen in the smoothed time series.

If infinite attenuation peaks, which are necessarily associated with instantaneous phase reversals, are avoided, flat group delay is a reliable indicator of a distortion-free filter. The arithmetic-average filter has this desirable property in its passband, as can be seen by the constant group delay of $T/2$ shown in Fig. 3(b).

We have now reached a point where it appears that excessive zeal in producing the 'ideal' filter in one domain produces problems in the other, and we should consider filters that give nearly equal importance to both domains. A mathematical function of great interest in this context is the Gaussian function $\mathrm{g}(t)$:

$$\mathrm{g}(t) = \exp\{-t^2/(2\sigma^2)\}.$$

It will be seen that this is the bell-shaped normal distribution curve, familiar to statisticians. Its Fourier transform $\mathrm{G}(\omega)$ is given by:

$$\mathrm{G}(\omega) = \sigma \exp\{-(\sigma^2/2)\omega^2\}.$$

It can be seen that the time-domain Gaussian transforms to a Gaussian shape in the frequency domain. Thus we now have a frequency domain function which, if used as a low-pass filter, gives equal discrimination in both time and frequency domains. The characteristic frequency can be varied by changing σ.

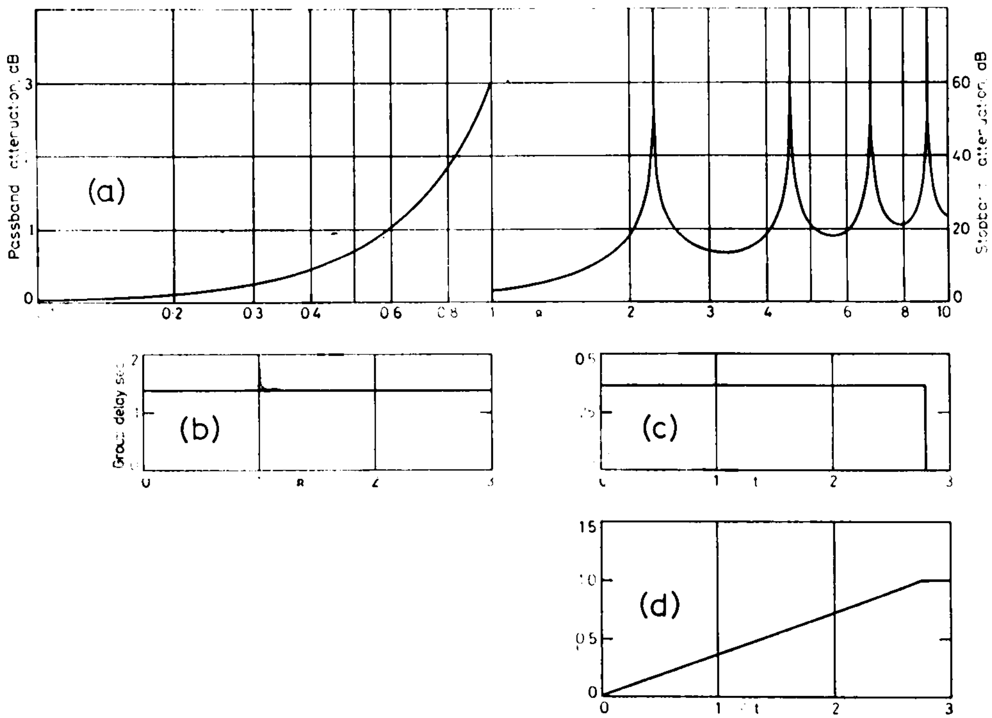

Figure 3. Arithmetic-average filter characteristics. (a) Attenuation v. frequency. (b) Group delay v. frequency. (c) Impulse response. (d) Step response.

Because $G(\omega)$ is purely real (having no imaginary part), the phase shift is zero at all frequencies, so the group delay has the highly desirable property of being constant—at zero. However, if we consider $g(t)$ as an equivalent time-reversed weighting function, we see that it is non-zero for negative values of t; we require future values of data for the filter as well as past values. These will obviously not be available, so that a physical realization is not possible. We can begin to by-pass this problem, without losing the equal discrimination property, by considering the delayed Gaussian $g_\tau(t) = g(t-\tau)$. In the frequency domain, the attenuation of $G_\tau(\omega)$ is the same as for $G(\omega)$, but we now have phase shifts corresponding to a constant group delay of τ seconds. Negative values of t will still correspond to non-zero values of $g_\tau(t)$, but as τ is increased these values rapidly approach zero. Thus, although we may not be able to implement the Gaussian filter exactly, there is hope that it can be approximated arbitrarily closely provided that we can accept a group delay which increases with the closeness of the approximation.

In the weighting function approach discussed earlier, the finite extent of the weights limits the degree of approximation that can be achieved. The closest approach uses weights extending in time considerably beyond that period which contributes most significantly to the filter output, implying a large number of multiplications per time-step. It also implies that a filtered value representing any particular point in time must await data well beyond that time before calculation of the filter output can be made. In this way the closeness of approximation to $G_\tau(\omega)$ extracts its penalty of group delay, although much ingenuity has been expended in optimizing the approach to approximation (Harris 1978).

Thomson (1952) attempted to implement the highly desirable property of constant group delay in polynomial filters by arranging that the group delay was maximally flat (in the same sense as discussed earlier). The result is usually called a Bessel filter, and is shown in Fig. 4. As the order of the filter is increased, the flatness of the group delay (Fig. 4(b)), and the approximation of the attenuation characteristic to the Gaussian shape (Fig. 4(a)), extends to higher frequencies, until deviation from either Gaussian property is important only for those frequencies which are regarded as not significant, and thus are strongly attenuated by the filter. Thus the ideal of the Gaussian filter can be adequately approximated to without the need for a numerator polynomial in the transfer function.

The attenuation characteristics are much more gradual than either the Butterworth or Chebyshev filter. However, in comparison with the arithmetic-average filter we find:

(a) Within the passband, i.e. for the 'signal' frequencies, the attenuation characteristic of a Bessel filter of order greater than 3 is almost indistinguishable from that of an arithmetic-average filter; and for orders greater than about 5, the flatness of the group delay is adequate. Thus the signals of interest are essentially identical for Bessel or arithmetic-average filters. In this sense a Bessel filter of any relatively high order can be thought of as an 'n-second mean filter', where $n = 2.778697/\omega_c$, and ω_c is the 3 dB attenuation frequency in radians per second.

(b) Within the stop-band, the general level of attenuation by the Bessel filter is considerably greater than the arithmetic average, thus suppressing noise more effectively. For most purposes, extension of flat group delay to frequencies significantly higher than the 3 dB frequency is unnecessary. We are now seeing 'noise', and at the higher frequencies we have attenuation; in any case, the Bessel filter avoids the problems of phase reversal. For some applications, however, a high-order Bessel can be used to extend the flat group delay.

Thus the Bessel filter passes 'signals' in essentially the same way as the arithmetic-average filter which has the same 3 dB frequency, but attenuates high-frequency 'noise' better. In this sense the filter output is a better approximation of the underlying 'representative' value.

Some authors (e.g. Craddock and Grimmer 1960) have suggested that an 'exponential average' or time-constant filter might be applied. This corresponds to a first-order polynomial filter, whose characteristics are in Figs 1, 2 or 4 which give identical curves for first order. Attenuation is considerably less discriminating than with the higher-order Bessel or arithmetic-average filters, and the group delay is less flat in the significant frequency range.

There are other methods of approximating to a Gaussian filter using a polynomial implementation. Zverev (1967) discusses an equi-ripple (rather than maximally flat) approximation to constant group delay. For any order of filter, this gives a group delay which allows a defined amount of ripple about the mean value. In return, the 'flat' group delay extends to somewhat higher frequencies, and marginally higher frequency discrimination is available. The 'best' amount of ripple to allow depends on both 'signal' and 'noise' spectra, and the weighted significance of certain frequency bands in the context in which the data are to be used. The root-mean-square deviation between pure 'signal', and 'filtered signal plus noise' could be minimized to determine two parameters—the 3 dB frequency and the optimum amount of ripple allowed. This method could also be used to determine all the parameters available—the polynomial coefficients—without particular regard to known filter types as described above. In practice, a great deal of confidence in the representativeness of the available data, the weighting of the significance, and the penalties involved in unusual situations, would be required before such an abstract approach could replace the semi-intuitive approach described above, or be allowed to deviate too far from it. The results are not likely to be significantly different to those from a Bessel filter

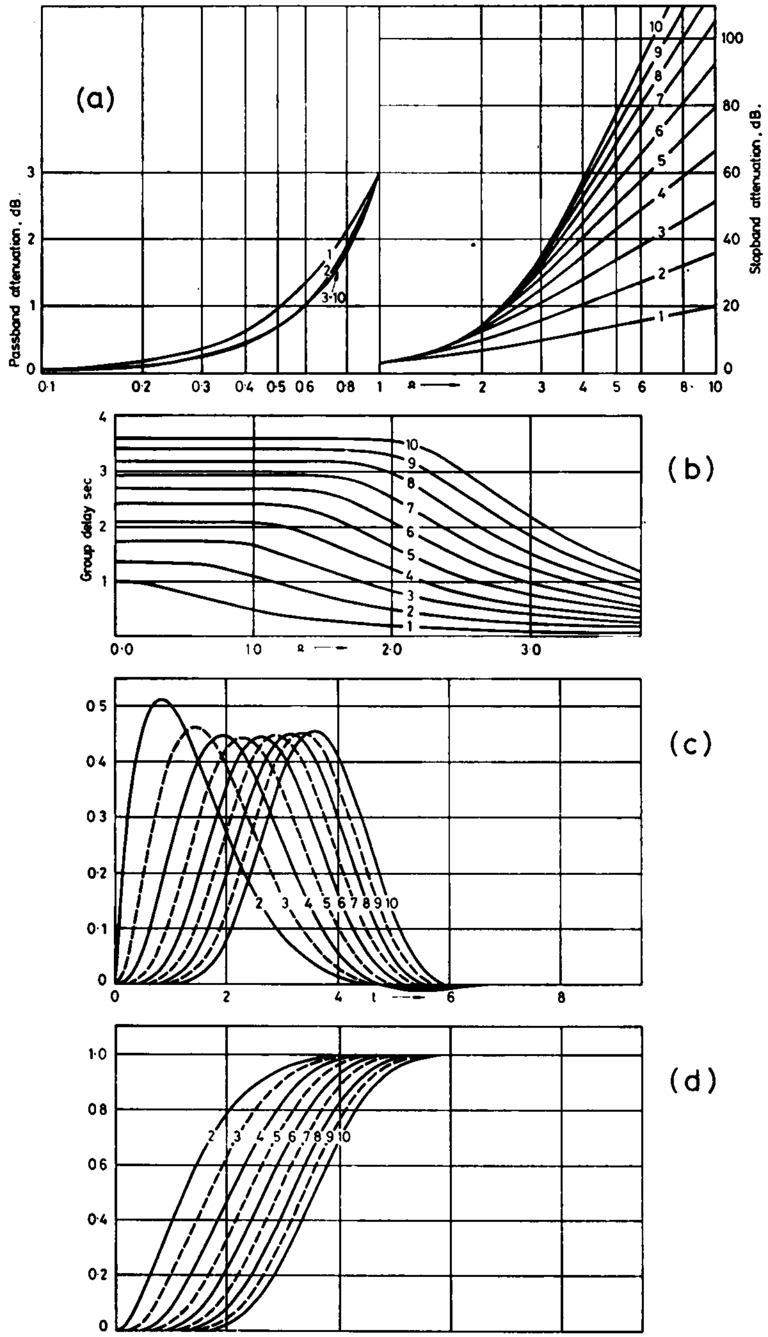

Figure 4. Bessel filter characteristics. (a) Attenuation v. frequency. (b) Group delay v. frequency. (c) Impulse response. (d) Step response.

at a suitable characteristic frequency for the application; the most important step has already been taken in moving away from a time-domain viewpoint (the arithmetic average) to a combined time- and frequency-domain viewpoint.

5. Some examples of filtering

Two examples of filtering of wind data are shown here, both based on the same sample of Cardington wind-vector data. Fig. 5 shows about 90 minutes of raw data (curve (a)), the results of a 10-minute arithmetic-average filter (curve (b)), and a 10-minute 6-pole Bessel filter (curve (c)). Curves (a) and (b) are shifted horizontally and vertically with respect to (c) to allow for group delay, and to avoid overlapping of the curves. Curve (c) commences at time zero, and the extent of the horizontal shift for (a) and (b) can be seen from their initial flat portions.

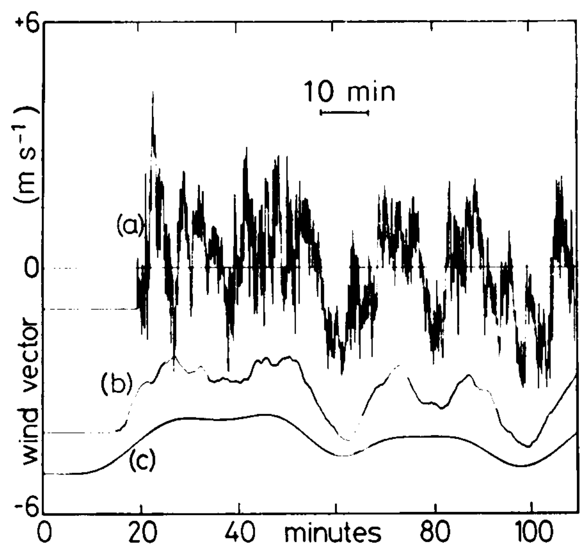

Figure 5. Wind-vector data and 10-minute averages. (a) Raw data. (b) 10-minute arithmetic-average filtering. (c) '10-minute' 6-pole Bessel filtering.

The effect of filter initialization and group delay can be seen in the first 15 minutes or so of data. Because data are delayed on filtering, the early filtered output does not correspond to real data, but rather depends on the initial values present in the filter stores. For cosmetic reasons these have been chosen to be near the expected raw data values, and this is the way to minimize the initial transient filter response. Where data are being measured continuously the transient response occurs only on first installation and does not cause problems.

Because of its poor high-frequency attenuation, the moving-mean filter exhibits structure on a time-scale significantly shorter than 10 minutes. As a consequence, values on the curve intended to give a measurement representative of the surrounding 10 minutes or so are sensitive to the exact time at which the value is chosen, i.e. the reported signal is noisy.

A highly subjective way of comparing the filters is to decide which is the closest to the curve one would draw by eye through the data when 'smoothing' over a 10-minute interval. This process may more accurately approximate to a real human observer estimating 10-minute winds, than a machine implementing WMO rules for 'mean' wind.

Fig. 6 shows in more detail 35 minutes taken from the middle of Fig. 5. Arithmetic-average and Bessel-filtered data are also shown for 2-minute filters, suitably shifted as before. Although the raw data are the same, the different averaging time means that different structures are selected by the filter, so that a new comparison between filters is being made. Note that the arithmetic-average filter still reports noisy data.

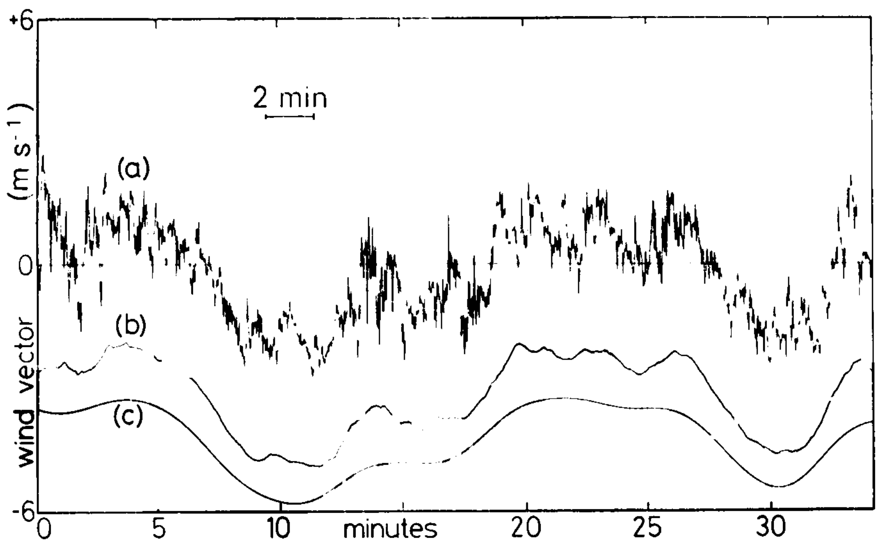

Figure 6. Wind-vector data and 2-minute averages. (a) Raw data. (b) 2-minute arithmetic-average filtering. (c) '2-minute' 6-pole Bessel filtering.

The particular examples shown above are for the absolute value of a function. In meteorology one is often interested in the derivatives of functions. This is analogous to being interested in the shape of the contours on a chart rather than their absolute values. Examples of a potential interest in time derivatives might be:

(a) Looking for variations in wind direction or speed, or in temperature, to denote the passage of a front.

(b) Use of isallobars, being contours of derivatives of pressure. The shapes of the contours are functions of the second derivative of pressure.

(c) Estimating wind speed and direction from the values of radar range, azimuth and elevation of a balloon.

In all these examples the process of differentiation accentuates the higher frequencies and makes the filter rate of attenuation more important. In the time domain, e.g. in Figs 5 and 6, the arithmetic-average curves are rougher than the corresponding Bessel curves, so that their derivatives will be more noisy. Similar comments have even greater force for higher derivatives.

6. Poles, zeros and filter synthesis

The transfer function F(s) of a continuous data filter represents the linear relationship in frequency space between the filter input $V_{IN}(s)$ and the output $V_{OUT}(s)$ as a function of the complex frequency s. For a more complete discussion of this type of description see Di Stefano *et al.* (1976). For a polynomial filter we have:

$$F(s) = V_{OUT}(s)/V_{IN}(s) = b_0/(b_0 + b_1 s + b_2 s^2 + \ldots + b_n s^n),$$

where n is the order of the filter, and b_0 to b_n are the polynomial coefficients. This low-pass filter tends to unity gain as s tends to zero, and at high frequencies the rate of increase of attenuation depends primarily on n. The polynomial can be factorized into factors of the form $(\alpha_0 + s)$ or $(\alpha_r + i\omega_r + s)$, and the values of s obtained by putting each factor equal to zero are termed the poles of the filter—they are those complex frequencies for which F(s) becomes infinite. Non-polynomial filters have a numerator polynomial in F(s) and, by a similar method, those complex frequencies for which F(s) becomes zero are termed zeros.

Values for poles (and zeros) which characterize various types of polynomial and other filters are to be found in books such as Zverev (1967) and Christian *et al.* (1966). For convenience, Table I shows the poles for Bessel filters up to order 8 having 3 dB attenuation at 1 radian per second. De-normalizing to give 3 dB attenuation at ω_c radians per second requires multiplying the poles by ω_c.

Table I. *Bessel filter poles* $(-\alpha,\omega)$ *normalized to* 3 *dB at* 1 *radian per second*

Order	$(-\alpha,\omega)$	
2	(−1·10349, ±0·63710);	
3	(−1·32475, 0);	(−1·04909, ±1·00085)
4	(−1·37222, ±0·41085);	(−0·99681, ±1·25913)
5	(−1·50470, 0);	(−1·38301, ±0·71904)
	(−0·95913, ±1·47345);	
6	(−1·57404, ±0·32145);	(−1·38405, ±0·97304)
	(−0·93219, ±1·66457);	
7	(−1·68713, 0);	(−1·61464, ±0·59014)
	(−1·38113, ±1·19353);	(−0·91130, ±1·83942)
8	(−1·76034, ±0·27330);	(−1·63966, ±0·82417)
	(−1·37613, ±1·39067);	(−0·89433, ±2·00166)

Realization of a polynomial filter corresponds to realization of a transfer function having the right poles. The complex factors of the polynomial are combined in complex conjugate pairs to form real coefficient quadratic factors in s. It is common to implement transfer functions using the first- and second-order real coefficient factors now generated into individual realizations or stages, and to realize the overall filter by passing data through each stage in turn (cascading).

It is possible to implement individual sections independently in the most convenient way. For example, the first stage of an odd-order polynomial filter might be the single real pole implemented as a simple electrical time-constant, as this is the least critical pole with respect to tolerances. This first stage does reduce the bandwidth of the raw data, so that if later stages are implemented by sampling and digitization followed by sampled data filtering, the Nyquist criterion allows the use of a lower sampling rate, and this requires less computation. Each successive sampled data filter stage reduces the bandwidth further, so that after each stage it may be possible to reduce the sampling rate further to keep the computational load light. In general, analogue techniques have the advantage of being able to handle wide-bandwidth data easily, while digital techniques have the advantage of being stable—especially when smoothing over long periods, when analogue methods lose accuracy. Thus the combination described above makes good use of both methods of implementation.

7. Hardware implementation

Sections 7 and 8 are intended to introduce the interested reader to some of the available technical literature, and provide an idea of the complexity of implementation. Without this, the advantages of polynomial implementation of Bessel-like filters are not apparent.

Implementation of filters using passive components is discussed in Zverev (1967). However, at the relatively low characteristic frequencies that are usually of interest in meteorology (say 100 Hz to 10^{-3} Hz), active electrical filters are likely to be more practical. Implementation of filters specified in terms of poles and zeros is discussed by Huelsman (1976) in a collection of significant papers together with an editorial. Implementation of a single real pole corresponds, of course, to a simple time-constant. For low-pass Bessel filters, which are relatively undemanding of component tolerances at meteorological frequencies, the simplest (Sallen and Key) filter implementation is likely to be adequate for many applications, and Shepard (1969) lists components for Bessel and other filters. Roughly speaking, one resistor, one capacitor and half an amplifier are required per pole. At the lowest characteristic frequencies, however, accuracy is likely to suffer, giving distorted signals.

8. Digital recursive implementation

The theory of sampled data systems is covered by Tou (1959). A more practical discussion of recursive implementation is presented by Gold and Rader (1969).

Standard *z*-transform theory (Tou 1959), shows how polynomial filter transfer functions can be expressed as recursive relations between sampled data points. Two important results from a modified theory (see Appendix) are:

(a) Implementation of a real pole:

$$\mathrm{F}(s) = K\alpha/(s+\alpha).$$

F(s) represents a time-constant of $1/\alpha$ seconds, with a low-frequency gain of K.

Using starred symbols to represent quantities sampled every T seconds, the integer n to indicate time and := to mean 'is replaced by', to implement F(s) we have:

$$\left.\begin{aligned} v_{\mathrm{OUT}}^*(nT) &:= C_1 v_{\mathrm{IN}}^*(nT) + C_2 v_{\mathrm{OUT}}^*\{(n-1)T\} \\ C_1 &= K\{1-\exp(-\alpha T)\} \\ C_2 &= \exp(-\alpha T), \end{aligned}\right\} \quad \ldots \quad (1)$$

where v_{IN}^* and v_{OUT}^* represent the filter input and output respectively as sampled functions of time.

(b) Implementation of a complex conjugate pole pair:

$$\mathrm{F}(s) = K(\alpha^2+\omega^2)/\{s^2+2\alpha s+(\alpha^2+\omega^2)\}.$$

F(s) represents a low-pass second-order resonant structure (complex conjugate pole pair) with an undamped natural frequency of ω radians per second, a damping time-constant of $1/\alpha$ seconds and a low-frequency gain of K. For more information see Di Stefano *et al.* 1976.

Using starred symbols, K, T and n as before:

$$\left.\begin{aligned} v_{\mathrm{OUT}}^*(nT) &:= C_3 v_{\mathrm{OUT}}^*\{(n-1)T\} + C_4 v_{\mathrm{OUT}}^*\{(n-2)T\} + C_5 v_{\mathrm{IN}}^*\{(n-1)T\} \\ C_3 &= 2\cos(\omega T)\exp(-\alpha T) \\ C_4 &= -\exp(-2\alpha T) \\ C_5 &= K\{1-2\cos(\omega T)\exp(-\alpha T)+\exp(-2\alpha T)\}. \end{aligned}\right\} \quad \ldots \quad (2)$$

With these two recursive relations, any low-pass polynomial filter can be implemented by cascading stages.

When using any sampled system, the process of converting from continuous analogue data to sampled data (sampling) must be regarded as a significant process. Unfortunately, this is not always done in meteorology. If the sampling rate is $1/T$ samples per second, then frequencies above the Nyquist frequency $1/(2T)$ Hz in the analogue data cannot be represented (Shannon 1949, Tou 1959). The energy in these higher frequencies will appear in the sampled data under an alias frequency (aliasing). For example, a sine wave at just under $1/T$ Hz aliases as a low frequency, irreversibly corrupting the significant data. Thus, when using digital forms of filtering, the sampling rate must be high enough to ensure that only negligible energy is aliased. This is achieved either by making use of known frequency limitations of the sensor/environment (and ensuring that no other form of noise can intrude), or else by using an analogue filter before sampling. This can either implement a required real pole, or else implement a non-critical short time-constant pole which will have little effect on the overall filter.

The concept of bandwidth reduction by a filter stage, to allow operation at a lower sampling rate for the next stage, can be carried right through the recursive implementation. In fact, the low characteristic frequencies of many meteorological filters (when compared with the upper frequency limit of the raw data) makes it useful to precede the required filter by one or more spurious real-pole digital filters with suitably short time-constants, merely so that the following stages can be operated at a lower sampling rate to reduce the computational load. It is useful in this situation to use odd-order filters, and to ensure that all the real-pole time-constants involved accumulate to the required real-pole time-constant, to ensure the minimum distortion of the final filter performance.

As the actual values of the spurious time-constants are not critical, values can be chosen so that equation (1) degenerates to:

$$v_{OUT}^*(nT) := v_{IN}^*(nT) + [v_{OUT}^*\{(n-1)T\} - v_{IN}^*(nT)]/(2^m),$$

where m is an integer, so that the division can be implemented with an accumulator shift. Many low-performance microprocessors do not have a hardware multiply, so that this technique combined with reduced sampling rates can reduce the computational load to considerably below one multiplication per time-step. This option is not immediately applicable to the weighting function approach to filtering.

At some stage, multiplication by fixed non-binary numbers is required. Computational loading can be reduced by replacing each multiplication with several operations of the type 'shift right n bits, then add to (or subtract from) accumulator'. Resolution to i decimal places seems to require about i operations of the above type, considerably reducing loading over a general multiply routine. This technique is theoretically available to the weighting function approach, but the required increase in software, because of the large number of required weights, tends to preclude its use.

Detailed examination of equations (1) and (2) shows that when αT is small, the values of C_1 and C_5 tend to be small compared to unity. Thus, as v_{OUT}^* is comparable with v_{IN}^*, digital implementation using a system with a short word-length can reduce the effective resolution of the input data. This is not as catastrophic as it sounds. Provided that the noise level exceeds the effective resolution limit, the noise itself ensures that the signal is above and below the relevant digitization level for the correct proportion of time, and the output signal/noise ratio is nearly independent of the effective resolution. In fact, it is well known that high-resolution filtered signals can be extracted from suitable systems by filtering the output of a single bit digitizer (Davenport 1953).

Thus, only a small number of discrete digitization levels (although correctly spaced) are required in hardware, or early-stage software, for noisy signals such as wind direction or speed, provided that the result is to be filtered. This can lead to economies in hardware, and this effect is used in at least one commercial wind vane which uses a small number of reed relays to sense wind direction. In practice, of course, any serious software resolution problems can be overcome by using spurious real-pole stages where αT is not too small.

9. Conclusions

In meteorology, data are often smoothed or filtered to reduce the effects of noise while measuring a representative signal. A common meteorological filter is the arithmetic average, or moving mean. A filter which gives a more accurately representative value, while retaining the ability to avoid excessive smoothing of wanted frequencies, is a Gaussian filter.

Close approximations to the unrealizable Gaussian filter can be made on sampled data using a weighting function approach. Due attention must be paid, as with all sampled data systems, to the Nyquist constraint. The weighting function approach implies a heavy computational load.

An alternative approach is to use polynomial transfer functions, which can be implemented in analogue or sampled data form. The analogue form can be implemented in simple hardware, but the sampled data (digital) form gives a more stable transfer function. A suitable approximation to the Gaussian ideal is the Bessel filter. By splitting the Bessel filter into a number of stages, each of which reduces the bandwidth required to represent the data presented to the next stage, the more critical stages can be implemented in recursive digital equations at a relatively low sampling rate. This method can be realized with a much lower computational loading on a processor, making it a practical proposition for applications such as automatic weather stations.

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Appendix

We wish to replace an analogue system with signals limited to frequencies below $1/(2T)$ Hz, and transfer function F(s), by a sampler which samples the analogue data every T seconds, followed by a digital filter operating on these samples. Provided we are prepared to regard the filtered samples as being from a time series which is limited to frequencies below $1/(2T)$ Hz, the required z-transformed relationship between output and input sampled signals is given by:

$$V_{\mathrm{OUT}}(z)/V_{\mathrm{IN}}(z) = T\,\mathrm{G}(z), \qquad (1)$$

where G(z) is the z-transform of F(s). The apparently spurious T is required to offset the gain of the sampler. A discussion of the relative gain of sampled to analogue signals and tables of z-transforms can be found in Tou (1959).

We can manipulate equation (1) and then take the inverse z-transform to obtain an equation for $v_{\mathrm{OUT}}{}^*(nT)$ in terms of known quantities. Consider, for example, the real-pole transfer function:

$$\mathrm{F}(s) = K\alpha/(s+\alpha).$$

Substituting its z-transform into equation (1) we have:

$$V_{\mathrm{OUT}}(z)/V_{\mathrm{IN}}(z) = K\alpha zT/\{z-\exp(-\alpha T)\},$$

and a little manipulation gives:

$$V_{\mathrm{OUT}}(z) = K\alpha T V_{\mathrm{IN}}(z) + \exp(-\alpha T)z^{-1}\,V_{\mathrm{OUT}}(z).$$

Taking the inverse z-transform, and remembering that z^{-1} corresponds to a time-shift of T, we have:

$$v_{\mathrm{OUT}}{}^*(nT) = K\alpha T\,v_{\mathrm{IN}}{}^*(nT) + \exp(-\alpha T)\,v_{\mathrm{OUT}}{}^*\{(n-1)T\}. \qquad (2)$$

In this way, standard z-transform theory can be made to give recursive equations for $v_{\mathrm{OUT}}{}^*(nT)$ in terms of $v_{\mathrm{IN}}{}^*$ at various times, and previous values of $v_{\mathrm{OUT}}{}^*$ for any F(s). The same results can be obtained from first principles without the use of the z-transform. The impulse response, or inverse Laplace transform, of F(s) is sampled every T seconds (using the 'ideal sampler': Tou 1959) producing an infinite sampled time series. Taking the Laplace transform, using the quantity exp $(-sT)$ as the transform of a delayed impulse, an infinite series in the frequency domain is obtained which can be summed and manipulated as above. The inverse Laplace transform gives equation (2).

This basic method of using recursive equations to represent a sampled impulse response does have an important limitation in the data smoothing context. Any analogue impulse response will contain frequencies up to infinity, but a sampled data stream cannot represent frequencies above the Nyquist frequency $1/(2T)$ Hz. Thus the sampled time-series cannot fully represent the impulse response, and the recursive equations cannot exactly implement F(s). Where T is sufficiently short compared to $1/\alpha$ and $1/\omega$, there is little error; but there is an incentive to make T relatively long in the final filter stages to reduce computational 'loading'. The most important effect of this error is that if equation (2) is used directly, it gives the wrong gain at zero frequency. This can be seen by setting K equal to unity, and considering a constant signal which should give the same value for v_{IN}^* and v_{OUT}^*. To obtain this condition, the sum of the coefficients should be unity. Clearly they are not, although they approach unity for small αT. Replacing the first (gain) coefficient by $K(1-\exp(-\alpha T))$ ensures the necessary unity sum of coefficients for unity K, and this form is given in Section 8 equation (1). The other small errors due to large T in the implementation of F(s) can be tested for engineering significance using test signals, or predicted from the known complementary signal components produced by a sampler (Tou 1959).

Similarly, standard implementation of the complex conjugate pole-pair transfer function in Section 8 gives a similar recursive relationship to equation (2) of Section 8, except that C_5 appears as:

$$KT\{(\alpha^2 + \omega^2)/\omega\}\exp(-\alpha T)\sin(\omega T).$$

The form given in Section 8 is also modified to ensure unity sum of coefficients for unity K, and hence correct gain.

The necessity for ensuring unity sum of coefficients if unity gain is required should be taken right through to binary implementation of the coefficients. The limited resolution often available for C_2 or C_5 can mean that an error in the least significant bit has noticeable effects.

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The accuracy of London Weather Centre forecasts of surface wind and total wave heights and their comparison with computer products

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Summary

Forecasts of wind speed and total significant wave height for spot locations on the Continental Shelf are part of the continuous service provided by London Weather Centre for the Offshore Industry. A check on the accuracy of these forecasts has been carried out over a three-year period for a number of sites where verifiable data are considered to be sufficiently reliable. Forecasters receive considerable numerical support from the operational 10-level model in the prediction of winds and waves and a check has also been made upon the accuracy of the computer products and results compared with the London Weather Centre 'man–machine mix' versions.

Introduction

London Weather Centre (LWC) is responsible for the preparation of weather and sea-state forecasts and their dissemination to the Offshore Industry for any part of the Continental Shelf. Most of the forecasts are for specific fixed sites, e.g. production platforms and drilling rigs, but forecasts are also prepared for tows of rigs and barges to and from the offshore sites.

The fixed-site forecasts usually consist of wind speed and direction (10-minute mean at 10 metres and also at deck level, with appropriate gusts), visibility, weather, cloud, total significant wave height* and swell direction, height and period, for forecast periods up to five days ahead. Undoubtedly the most important of these elements for on-site operations are wind speed, visibility, total significant wave height, and the range of significant wave periods. The forecasts are issued twice a day with almost all companies taking an early morning issue between 0600 and 0800 local time, but the second issue is split between those companies that prefer to have an afternoon forecast on their shore-base desks before 1700 and those companies that are able to take a more realistic and up-to-date issue between 1800 and 2000.

Until the middle of 1977 the forecasts were prepared using the routine 24-hour surface prognoses issued by the Central Forecasting Office (CFO) at Bracknell every 6 hours and the twice-daily issues of 48- and 72-hour surface prognoses. The sequence of wind evolution would be interpolated between current analyses and the winds deduced from the forecast (surface-pressure) charts. Routine conferences between the forecasters in CFO and the offshore forecasters at LWC facilitated the exchange of views on the synoptic developments and communicated the degree of confidence felt by CFO in the prognoses.

The prediction of sea state was based entirely on graphical methods derived by Darbyshire and Draper (1963) and later upon techniques contained in a comprehensive WMO publication (World Meteorological Organization 1976). Essentially, the use of these graphical techniques requires a knowledge of the wind speed, duration and fetch at specific points in order to predict the growth and decay of waves.

* Total significant wave height is defined as the mean of the highest one-third of all the waves observed during a period of 12–15 minutes and necessarily refers to the combined effects of wind-sea and swell; the expression 'total seas' is sometimes used in this paper as a convenient brief synonym.

In August 1977 LWC began receiving directly from COSMOS (the Meteorological Office computing system) computed values of surface wind speed and direction at each grid point of the fine-mesh version of the 10-level model (Benwell *et al.* 1971). These winds are derived from the 900 mb winds in the model, using the relationships described by Findlater *et al.* (1966). The forecast wind fields are in 3-hour steps up to 36 hours and are derived twice daily from the early operational fine-mesh model computations at about 0300 GMT and 1500 GMT.

Numerical computation of wind-waves and swell over the Continental Shelf also became available to LWC on an operational basis (once a day initially, but later twice daily) in spring 1978. The computation of sea state is based on the work of Golding (1979) and takes into account variations of depth. Values of wave height, direction and period are calculated for each of the fine-mesh grid points and forecast values are produced in 6-hour steps up to 36 hours.

More recently, in the spring of 1979, surface wind forecasts were derived from the octagon version of the 10-level model, covering the period from 36 to 72 hours ahead in 12-hour intervals, and these winds are sent to LWC twice daily some one or two hours after the fine-mesh data. All the numerical products are received at LWC in digital code and graphical chart formats by dedicated teleprinter and facsimile lines respectively.

The derivation of the 'man–machine mix' product is a rather complex process. Continental Shelf charts (1 in 3×10^6 scale) are plotted and analysed every 3 hours and sea-state analyses on a similar scale and for a similar area are prepared every 6 hours on the offshore bench at LWC. First of all the forecaster will compare the computer analysis field with his own hand-drawn analysis to look for errors in small detail. He will also compare the early stages of the computer prediction fields with his own latest updated analyses to evaluate the early trends. Similarly, the forecaster will check the computer sea-state analyses with his own hand-analysed charts and will also check the forecasts for certain specific locations using the empirical graphical techniques.

Since the forecaster is predicting conditions for individual rig or platform locations, there is no doubt that for the first 6–12 hours of any period the skilled forecaster should be able to improve on a numerical model output, if necessary by his superior appraisal of the fine detail. Beyond 12 hours the forecaster's modifications to the model depend upon how well he thinks the model has predicted the early stages and also how good he thinks the model is at predicting particular types of weather pattern. If the forecaster makes modifications to the wind forecasts then, clearly, he must modify the sea-state forecasts too.

It is clearly essential to know how useful the numerical guidance has become to the offshore forecasters at LWC. Unfortunately, staff availability did not permit verification of offshore forecasts to be carried out objectively before the summer of 1977 and hence comparisons of forecast performance before and after the advent of numerical guidance are not available. However, a comprehensive verification scheme has been fully maintained since September 1977 with the help and co-ordination of the offshore forecasters.

Verification is important for two fundamental reasons:

(a) It reveals how useful forecasts are to the user and highlights certain strengths and weaknesses of both forecaster and forecast.

(b) It brings out the qualities and deficiencies of the numerical model, which not only helps the forecaster but also maintains an effective feedback from the forecaster to the research modeller who needs the information to improve his product.

Probably the most important reason of all for verification is the fact that forecasts are sold under commercial contract. It is essential to know how good (or poor) the forecasts are in order to sell the forecast service to a market that is not obliged, of necessity, to take the products of the state weather service.

Method and scope

Offshore verification is carried out on five sets of data but, because of the continual development of the output program since August 1977, the verification is not uniform. Table I displays the amount of verification carried out on each set of data so far.

Table I. *Amount of verification carried out on five sets of data for offshore forecasts*

	Forecast period					
	T+0	T+12	T+24	T+36	T+48	T+72
Fine-mesh winds	Sept. 1978 to date	Sept. 1977 to date	Sept. 1977 to date	Sept. 1977 to date		
Octagon winds				May 1979 to date	May 1979 to date	May 1979 to date
Fine-mesh total seas	Sept. 1978 to date	May 1978 to date	May 1978 to date	May 1978 to date		
LWC winds		Sept. 1977 to date	Sept. 1977 to date		Sept. 1977 to date	Sept. 1977 to date
LWC total seas		Sept. 1977 to date	Sept. 1977 to date		Sept. 1977 to date	Sept. 1977 to date

Verification of the numerical products is carried out at six grid points (total seas verified at five points prior to September 1978), three of which are in the North Sea and a fourth corresponds to the national data buoy DB 1. The fifth and sixth points are different for winds and total seas. Since the wind verification started before that of the total seas, two points were chosen west of Ireland and north-west Scotland within the Continental Shelf to complete the circle of points. However, it seemed more prudent to verify the total seas at the Ocean Weather Stations 'L' and 'R' in view of the general lack of sea-state data immediately west of the British Isles. The three points in the North Sea were chosen to coincide with the main areas of offshore activity where it was also convenient to verify the LWC forecast issues.

The method of carrying out the verification needs to be carefully explained. Since the verification is for fixed times there is no difficulty in extracting the computer wind and total seas data from the digital code. The LWC forecasts are for 12- and 24-hour periods, which means that interpolation is required to extract the appropriate figures. In practice this is usually not difficult because, if the forecaster gives a trend through a period, invariably the following period will start with the values appropriate to the end of the previous period, e.g. forecast 0800–2000, 20 kn increasing to 30 kn and later to 35 kn; forecast 2000–0800, 35 kn, decreasing slowly to 25 kn. Interpolation would yield: 1200, 30 kn; 1800, 35 kn; 0001, 30 kn; 0600, 25 kn. The data used to verify the forecasts are derived from the routine surface and sea-state analyses prepared by the offshore forecasters. These analyses embrace the Continental Shelf (1 in 3 × 10^6 scale) at 3-hourly (weather) and 6-hourly (sea state) intervals. The quality of offshore observations is not a subject that can be dealt with in a few sentences, but it should be recognized that offshore forecasters acquire a considerable amount of skill in interpreting observations from familiar installations.

It is realized that verification for fixed times will tend to penalize forecasts which often contain useful and important details on the trend of wind and wave heights. Not only are these details ignored but timing errors tend to be more heavily penalized than is perhaps justified. Ideally, the verification should be carried out at 6-hourly intervals during the first 24 hours and perhaps at even 3-hourly intervals during the first 12 hours. This problem can also be tackled by plotting graphs of forecast values against observed values.

The three North Sea verification points were chosen in regions where certain observations are considered reliable and are also supported by good quality data nearby. In general the quality control of wind is much easier than that of sea state, mainly because the latter tends to be a mixture of instrumental and visual observations. Every attempt has been made in this verification work to rely on known instrumental observations with the possible exception of sea state at the Ocean Weather Stations 'L' and 'R'.

Verification is confined to two parameters, wind speed and total significant wave height. Verification of wave-period forecasts would be extremely useful but this can be adequately carried out only by examination of the wave-trace charts. This sort of analysis should be possible with data from the buoy DB 1 when they become available.

Results

It will be convenient to discuss winds and waves separately whilst making comparisons between computer guidance and the LWC forecasts. These are not independent, of course, and one of the aims of this study is to ascertain how much improvement the forecaster can make to direct computer predictions.

(a) *Winds*

(1) *Computer forecasts.* For six months there were two types of verification, a qualitative assessment of the chart as a whole and a quantitative assessment at six grid points. The qualitative assessment was based upon a scale of six divisions, defined as follows:

A: Good guidance.
B: Feature movement too slow, good wind speeds.
C−: Good feature movement, underestimated wind speeds.
C+: Good feature movement, overestimated wind speeds.
D: Poor feature movement, poor wind speeds.
E: Major evolution errors.

The results of the six-month assessment are shown in Table II and clearly indicate why the wind fields are highly regarded by forecasters, though with a reservation that wind speeds tend to be underestimated. This method of assessment was discontinued when it became clear that results were constant.

Table II. *Chart assessment summary for the period from September* 1977 *to February* 1978, *expressed in percentage of total marks allocated for each forecast period*

	Forecast period					
	T+6	T+12	T+18	T+24	T+30	T+36
Assessment						
A	54	44	39	37	36	32
B	1	2	4	4	6	3
C−	41	46	47	45	41	42
C+	1	2	1	1	3	3
D	2	4	6	9	10	13
E	1	2	3	4	4	7

The quantitative verification is presented in two ways. Mean modulus errors over all wind speeds for each grid point are contained in Table III. The data are for up to and inclusive of August 1980 and it should be noted that the rectangle period started in September 1977 and the octagon period started in May 1979. Errors were calculated up to one decimal place before rounding off in Table III.

Table III. *Mean modulus wind speed errors in knots*

	Forecast period Rectangle T+0	Rectangle T+12	Rectangle T+24	Rectangle T+36	Octagon T+36	Octagon T+48	Octagon T+72
Position							
61°N 02°E	4	5	5	5	6	6	8
60·5°N 06°W	4	5	5	5	5	5	6
57·5°N 03°E	4	4	5	5	5	6	7
53·5°N 04°E	4	4	5	5	5	5	6
55·5°N 10°W	5	5	5	5	5	5	6
48·5°N 09°W	4	4	5	5	4	5	5

Table III reveals a marked uniformity in wind speed errors as regards location and irrespective of forecast period, except for T + 72 in the northern North Sea. Mean errors of this magnitude are extremely good. However, it is important to know how these errors relate to the actual wind speeds reported.

Table IV reveals the errors with respect to ranges of wind for two points. The upper section of each box refers to 61°N 2°E and the lower section refers to 48·5°N 9°W.

Considering the fine-mesh (rectangle) figures first, there are three main points to make:

(i) The relatively small mean errors in Table III are due to the high frequency of observed wind speed below 20 kn.

(ii) The errors do not increase significantly with increasing forecast period even at high wind speeds (excepting from T + 12 to T + 24, range 30–39 kn at DB 1).

(iii) Mean errors are roughly 20–25% of observed wind speed at all wind speeds.

Table IV. *Errors (in knots) with respect to ranges of wind speeds for two points. For each forecast period the upper figures refer to* 61°N 2°E *and the lower figures refer to* 48·5°N 9°W.

	Ranges of observed wind speeds (knots) 0–19		20–29		30–39		≥40	
Forecast period	No. of occns	Mean error	No. of occns	Mean error	No. of occns	Mean error	No. of occns	Mean error
			Rectangle—September 1979–August 1980					
T+0	475	4	179	5	59	9	12	13
	665	4	127	3	20	5	3	10
			Rectangle—September 1978–August 1980					
T+12	1007	4	330	6	104	9	18	11
	1139	5	243	5	43	5	7	12
T+24	1005	5	326	6	102	8	20	9
	1142	5	254	5	35	7	7	12
T+36	1005	5	323	7	100	11	18	11
	1137	5	254	5	43	9	7	19
			Octagon—May 1979–August 1980					
T+36	723	5	196	10	59	14	11	18
	832	4	130	6	21	9	2	21
T+48	722	5	195	9	59	15	12	20
	828	4	131	7	21	10	3	19
T+72	721	6	190	10	63	18	11	27
	833	5	127	8	21	12	2	29

Turning next to the octagon figures and noting that the number of cases is much less than that of the fine-mesh set, we find that there are also three main points to make:

(i) At T + 36 the octagon errors tend to become significantly greater than the rectangle errors at higher wind speeds at 61°N 2°E but not at 48·5°N 9°W.

(ii) Octagon errors increase with increasing period of forecast and more substantially with increasing wind speeds, especially above 30 kn.

(iii) Mean octagon errors are generally 30% and perhaps 50% in the northern North Sea for observed wind speeds over 20 kn.

Undoubtedly the octagon wind errors are not simply due to a loss of wind speed in the model; phase and evolution errors must be increasingly important at extended forecast periods.

(2) *LWC forecasts.* Table V contains mean forecast wind speed errors for observed wind speed ranges for forecasts issued by LWC to three locations in the North Sea. Table V contains an extra range below 20 kn compared with Table IV. There are some interesting features which may be listed as follows:

Table V. *Mean modulus wind speed errors (in knots) in forecasts issued by London Weather Centre from September* 1977 *to August* 1980

		Ranges of observed wind speeds *knots*										
		0–9		10–19		20–29		30–39		⩾40		All speeds
Position	Forecast period	No. of occns	Mean error	No. of occns	Mean error	No. of occns	Mean error	No. of occns	Mean error	No. of occns	Mean error	Mean error
Statfjord 61°N 2°E	T+12	299	7	873	5	670	6	280	6	55	7	6
	T+24	303	9	873	6	674	6	282	6	55	9	6
	T+48	302	11	870	7	676	6	282	7	55	14	7
	T+72	302	12	870	7	676	6	282	9	55	14	8
Montrose 57·5°N 1·5°E	T+12	237	6	894	5	680	5	215	5	41	5	5
	T+24	237	7	894	6	683	5	217	6	41	7	6
	T+48	237	9	893	6	683	6	217	8	41	15	7
	T+72	237	11	893	7	681	7	217	9	41	15	8
Placid 53·5°N 2°E	T+12	335	6	1107	5	589	4	140	5	22	5	5
	T+24	341	7	1107	5	589	5	140	5	22	10	5
	T+48	344	9	1107	5	589	6	140	8	22	16	6
	T+72	344	10	1107	5	589	6	140	10	22	17	6

(i) Not surprisingly, errors are greatest at both low and high observed wind speeds and it is clearly almost as difficult to predict very light winds as to predict very strong winds for periods beyond 24 hours ahead.

(ii) For the broad range 10–39 kn the forecast errors are impressively small.

(iii) For all wind speeds mean errors increase slowly with increasing forecast period.

(3) *Comparison of computer forecasts with LWC forecasts.* The only comparison between computer forecasts and LWC forecasts is available for 61°N 2°E (Statfjord) and even here the length of verification period is different (cf. Tables IV and V). Even so, there are probably enough data to show whether

the forecaster is making a significant improvement to the computer guidance. An illustration is shown in Table VI which contains comparisons at the Statfjord Field (61°N 2°E) for two ranges of observed wind speed. The variations in verification period should be borne in mind, particularly for the octagon winds.

Table VI. *Mean modulus errors (in knots) of wind speeds in the ranges* 0–20 *and* 30–39 *knots at* 61°N 2°E *with respect to period of forecast*

Method	Range of wind speeds (kn)	Forecast period T+12	T+24	T+36	T+48	T+72
Rectangle	0–20	4	5	5	—	—
	30–39	—	—	5	5	6
Octagon	0–20	9	8	11	—	—
	30–39	—	—	14	15	18
LWC forecaster	0–20	6	7	—	8	8
	30–39	6	6	—	7	9

Table VI reveals that for observed light winds the computer guidance is slightly superior to the LWC forecasts, but for observed strong winds the LWC forecasts are significantly better and substantially so at extended forecast periods. The computer products undoubtedly tend to underforecast wind speeds and this fact probably explains the computer superiority at low wind speeds. Table VI suggests, then, that the LWC forecasters are making a positive improvement to the rectangle wind forecasts (up to 36 hours ahead) in strong wind situations with some help from the CFO 24-hour surface prognostic chart. Since the LWC forecaster is dependent upon discussion with the CFO medium-range forecaster for forecast periods beyond 36 hours, then Table VI presents indirect evidence that the medium-range forecaster at CFO is producing a superior surface prognosis than is produced by the computer for 48 hours and 72 hours ahead.

(4) *Trends in accuracy*. The verification results examined so far do not contain any discrimination for time of year. Verification has been carried out in two-calendar-month periods from March 1978 (the periods from September 1977 to February 1978 were combined) and there are probably just enough data to identify any marked seasonal bias. Tables VII and VIII show the trend of wind forecast accuracy at 61°N 2°E for both light and strong winds.

Table VII. *Trend of accuracy in forecast surface wind speeds issued by LWC forecasters for* 61°N 2°E. *Mean errors with respect to observed wind speed range* 0–19 *knots*

Forecast period	Sept. '77– Feb. '78	Mar.– Apr. '78	May– June	July– Aug.	Sept.– Oct.	Nov.– Dec.	Jan.– Feb. '79	Mar.– Apr.	May– June	July– Aug.	Sept.– Oct.	Nov.– Dec.	Jan.– Feb. '80	Mar. Apr.	May– June	July– Aug.
T+24	9	8	5	6	8	11	7	6	5	4	6	8	8	7	5	5
T+48	11	9	5	6	9	10	8	7	6	4	7	11	10	8	6	6
T+72	11	9	6	7	10	11	9	9	7	6	9	14	11	9	7	6

Table VIII. *Trend of accuracy in forecast surface wind speeds issued by LWC forecasters for* 61°N 2°E. *Mean errors with respect to observed wind speed range* 30–39 *knots*

Forecast period	Sept. '77– Feb. '78	Mar.– Apr. '78	May– June	July– Aug.	Sept.– Oct.	Nov.– Dec.	Jan.– Feb. '79	Mar.– Apr.	May– June	July– Aug.	Sept.– Oct.	Nov.– Dec.	Jan.– Feb. '80	Mar.– Apr.	May– June	July– Aug.
T+24	6	6	7	7	7	7	6	7	6	6	5	5	7	3	10	2
T+48	7	5	14	15	7	5	7	6	11	12	7	6	10	3	10	2
T+72	8	8	16	12	8	6	11	8	13	15	9	8	11	8	13	5

The forecasters' ability to predict light winds shows no significant trend other than that it is more difficult in winter than in summer (from May to August) with mean errors about double the values in other seasons.

(b) *Total significant wave height*

(1) *Computer forecasts.* Table IX contains mean errors of forecast total significant wave height at each of the six verification points. The most striking aspects of the results are as follows:

(i) Except locally at very high seas the forecast errors are no greater than analysis errors; neither do the errors tend to increase with increasing forecast periods.

(ii) At practically all locations, up to 9-metre seas, forecast errors do not increase greatly with increasing observed seas. In fact there is a tendency for errors to become proportionally smaller with higher observed seas.

The T + 0 total seas analyses are derived entirely from the wind fields and although some of the error must be due to error in the wind analysis itself, forecasters' experience with the computer output suggests that the modelling of swell may be the chief cause of these errors. The analysis of swell is a highly subjective process, although forecasters with long experience can usually detect the presence of swell from a series of observations at a fixed location. Impressive as the results are in Table IX it is generally

Table IX. *Rectangle total seas verification, March* 1978–*August* 1980. *Mean modular differences in half-metre units. Height ranges in actual significant waves.*

		Height range							
		0–3 m		3·1–5·5 m		5·6–9·0 m		>9·0 m	
Position	Forecast period	No. of cases	Mean modular diff.	No. of cases	Mean modular diff.	No. of cases	Mean modular diff.	No. of cases	Mean modular diff.
Grid 3–5 (Statfjord)	T+0	757	1·3	272	1·7	23	1·4	4	6·3
	T+12	938	1·3	316	2·0	30	2·2	4	7·6
	T+24	938	1·3	316	1·9	28	3·2	4	8·3
	T+36	938	1·3	318	2·2	28	3·5	4	7·9
Grid 4–6 (Forties)	T+0	834	1·2	188	1·3	14	1·7	0	—
	T+12	992	1·1	205	1·8	14	2·1	0	—
	T+24	1057	1·2	203	2·0	14	3·3	0	—
	T+36	1065	1·3	209	2·3	14	4·3	0	—
Grid 5–7 (Placid)	T+0	1027	1·0	63	1·3	0	—	0	—
	T+12	1169	1·0	75	1·5	0	—	0	—
	T+24	1259	1·1	69	1·6	0	—	0	—
	T+36	1248	1·2	74	1·6	0	—	0	—
Grid 6–2* (OWS 'L')	T+0	523	1·7	405	2·2	59	1·8	7	5·4
	T+12	600	1·7	468	2·0	78	2·5	8	7·0
	T+24	656	1·7	485	2·1	76	2·5	8	7·9
	T+36	660	1·7	483	1·9	70	2·9	9	7·5
Grid 9–4† (OWS 'R')	T+0	461	2·6	227	2·5	55	3·4	10	5·7
	T+12	626	2·0	290	2·4	58	4·4	14	6·2
	T+24	637	2·1	269	2·2	68	4·4	15	6·0
	T+36	631	2·0	283	2·4	58	4·7	12	6·2
Grid 8–5 (DB 1)	T+0	666	1·6	249	2·1	37	2·9	3	1·4
	T+12	642	1·7	263	2·1	31	2·9	3	3·7
	T+24	696	1·7	258	1·9	36	3·0	3	4·5
	T+36	692	1·6	266	1·7	31	2·8	3	4·9

* Excludes March–April 1980.
† March 1978–February 1980 only.

believed by forecasters that underforecasting of the wind seas by the model (associated with under-forecast wind fields) is compensated by overforecasting of swell. Unfortunately, only careful scrutiny of the data tapes from DB 1 will confirm or deny these views, since no other verification point can include measurements of direction in the wave height and period data.

Table X reveals the trend of forecast performance through the verification period. The T + 0 errors have a distinct minimum during May–June which is probably the period of least cyclonic activity over the North Atlantic and therefore the period of minimum swell generation. It is noticeable that the minimum errors are maintained through July–August at Statfjord but not at DB 1. This latter period was markedly cyclonic over the east Atlantic and the United Kingdom. There is no evidence from Table X that forecast performance has improved over the period, nor is there any suggestion that better analyses produce better forecasts.

Table X. *Trend of mean errors in computer forecasts of total significant wave heights in the range* 3–5·5 *metres* (*errors in half metres*)

Position	Forecast period	1978 Mar.–Apr.	1978 May–June	1978 July–Aug.	1978 Sept.–Oct.	1978 Nov.–Dec.
Statfjord	T+0	—	—	—	—	2·2
	T+24	2·5	1·2	1·3	1·4	1·9
DB 1	T+0	—	—	—	—	2·0
	T+24	—	—	—	2·7	1·9

Position	Forecast period	1979 Jan.–Feb.	1979 Mar.–Apr.	1979 May–June	1979 July–Aug.	1979 Sept.–Oct.	1979 Nov.–Dec.
Statfjord	T+0	1·4	2·4	1·0	1·0	1·6	1·8
	T+24	1·4	2·2	1·4	2·5	1·9	2·1
DB 1	T+0	1·7	2·1	1·1	2·8	1·7	2·9
	T+24	1·5	1·4	1·2	1·0	1·8	2·7

Position	Forecast period	1980 Jan.–Feb.	1980 Mar.–Apr.	1980 May–June	1980 July–Aug.
Statfjord	T+0	1·5	1·6	1·1	1·4
	T+24	1·7	1·9	2·3	2·4
DB 1	T+0	2·3	2·0	0·8	2·1
	T+24	2·2	1·6	1·4	2·0

(2) *LWC forecasts.* Table XI contains mean errors of forecast total significant wave height in forecasts issued by forecasters at LWC for three main locations in the North Sea. (Forecasts for periods beyond 36 hours are based upon graphical techniques using the forecast wind speed, fetch and duration, and taking into account the general development of the sea state during the first 36 hours of the period.)

Table XI. *Verification of LWC forecasts of total significant wave heights during the period September* 1977–*August* 1980. *Mean modular differences in half-metre units. Height ranges in actual significant waves.*

Height range: 0–3 m

Position	Forecast period	No. of cases	Mean modular diff.	PERS	CLI
Statfjord	T+12	1415	1·0	1·0	1·9
	T+24	1410	1·2	1·4	
	T+48	1410	1·4	1·9	
	T+72	1412	1·7	2·0	
Montrose	T+12	1600	1·1	1·0	1·6
	T+24	1600	1·3	1·4	
	T+48	1600	1·5	1·5	
	T+72	1600	1·6	1·9	
Placid	T+12	1959	0·9	0·8	1·2
	T+24	1959	1·0	1·3	
	T+48	1959	1·2	1·4	
	T+72	1959	1·4	1·6	

Height range: 3·1–5·5 m

Position	Forecast period	No. of cases	Mean modular diff.	PERS	CLI
Statfjord	T+12	652	1·5	1·6	2·3
	T+24	659	1·9	2·3	
	T+48	659	2·0	2·6	
	T+72	659	2·3	2·6	
Montrose	T+12	412	1·7	2·2	2·6
	T+24	412	1·9	2·7	
	T+48	412	2·2	3·1	
	T+72	412	2·8	3·3	
Placid	T+12	160	1·2	1·8	3·9
	T+24	160	1·4	2·5	
	T+48	160	2·3	2·9	
	T+72	160	2·9	3·3	

Height range: >5·5 m

Position	Forecast period	No. of cases	Mean modular diff.	PERS	CLI
Statfjord	T+12	124	2·6	2·6	7·2
	T+24	124	3·1	4·9	
	T+48	124	4·8	5·2	
	T+72	124	5·6	6·0	
Montrose	T+12	50	2·7	3·6	7·5
	T+24	50	3·9	6·1	
	T+48	50	5·7	6·8	
	T+72	50	6·5	7·4	
Placid	T+12	8	1·5	3·5	9·3
	T+24	9	2·5	5·1	
	T+48	9	5·5	6·5	
	T+72	9	6·0	6·8	

In Table XI, London Weather Centre mean forecast errors are compared with mean errors that would have occurred using persistence (PERS) and climatology (CLI); errors are in units of half-metres. The main features of Table XI are:

(i) Below 5·5 m waves, forecaster errors show only a small tendency to increase with increasing forecast period.

(ii) Below 5·5 m waves, forecaster errors do not markedly increase with increasing observed wave heights.

(iii) Above 5·5 m waves, forecaster errors are greater but still probably below 30% except for the longer-range forecasts.

(iv) Apart from the first 12-hour forecast period, LWC forecasters are on average superior to persistence forecasts, particularly when waves are high.

(v) Climatology forecasts are substantially inferior to LWC forecasters when waves are high.

Table XII shows the trend in LWC forecaster accuracy throughout the verification period, for one range of wave heights for one location. There is no evidence of any significant trend but it is interesting to note that for T + 72-hour forecasts the largest errors are on average occurring in early summer. This is the time of shortest wavelengths in the tropospheric circulation and small errors in forecast synoptic evolution may make relatively large errors in wind and associated sea state.

Table XII. *Trend of mean errors in forecasts of wave heights in the range* 3–5·5 *metres for Statfjord (errors in half-metres)*

	1977			1978						1979					1980		
	Nov.–Dec.	Jan.–Feb.	Mar.–Apr.	May–June	July–Aug.	Sept.–Oct.	Nov.–Dec.	Jan.–Feb.	Mar.–Apr.	May–June	July–Aug.	Sept.–Oct.	Nov.–Dec.	Jan.–Feb.	Mar.–Apr.	May–June	July–Aug.
Forecast period																	
T+24	1·8	2·2	2·0	1·8	0·8	2·0	2·0	2·0	2·3	2·0	2·1	1·9	2·1	2·2	2·2	1·6	2·4
T+48	2·2	2·2	2·4	3·6	1·4	2·4	1·7	2·4	2·3	2·6	1·7	1·8	1·9	2·4	2·6	2·2	2·6
T+72	2·2	2·6	2·8	4·0	1·6	2·6	1·7	2·5	2·5	2·4	3·2	2·1	2·1	2·4	2·2	3·0	2·4

Table XIII compares the computer forecast errors with the LWC forecaster errors for the Statfjord location. This Table reveals that forecasters are usually making a positive contribution by improving upon the computer guidance. However, the differences are not great.

Table XIII. *Computer forecast errors compared with LWC forecaster errors for the Statfjord location (errors in half-metres)*

Forecast period	T+12			T+24			T+36			T+48			T+72		
	Ranges of wave heights in metres														
	0–3	3–5·5	>5·5	0–3	3–5·5	>5·5	0–3	3–5·5	>5·5	0–3	3–5·5	>5·5	0–3	3–5·5	>5·5
Method															
Rectangle	1·3	2·0	2·7	1·3	1·9	3·8	1·3	2·2	3·7	—	—	—	—	—	—
LWC forecaster	1·0	1·5	2·6	1·2	1·9	3·1	—	—	—	1·4	2·0	4·8	1·7	2·3	5·6

(c) *Concluding remarks*

Although the verification results support the assertion that forecasters are making a positive contribution to the computer guidance in the prediction of wind and waves up to 72 hours ahead, the generally high performance of the rectangle (up to 36 hours ahead) cannot be overstressed. There are occasions when forecasters are under considerable pressure due either to bad or complicated weather conditions or to the volume of forecast enquiries and requests. Under these circumstances the need to have readily available detailed quantified objective predictions of wind and sea state around the Continental Shelf is absolutely essential and the computer guidance provides invaluable material for this purpose.

The verification of wind and sea-state forecasts is maintained continuously at LWC.

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Review

Weather modification: prospects and problems, by G. Breuer (translated from the German by H. Mörth). 220 mm × 140 mm, pp. xiii + 178, *illus*. Cambridge University Press, London, 1980. Price £10.50.

This book reviews the science and practice of weather modification and discusses its potential impact upon society. The author has consulted a wide range of workers in this field and writes more in the style of a reporter than from the viewpoint of an active participant. According to the dust-jacket the presentation is aimed at informing the non-scientist.

Chapter 1 describes the scientific and technical background to the practice of weather modification. It opens with an extremely compressed account of the factors governing the general circulation and the predictability of the atmosphere. One of the principal difficulties in the evaluation of weather modification techniques is the separation of real effects from the natural variability of the atmosphere. The statistical nature of this problem is clearly brought out by the author. The chapter concludes with a brief but reasonably clear description of cloud microphysical processes.

Chapter 2 provides a comprehensive review of weather modification, both scientific experiments and commercial schemes. Many untested proposals are also discussed. An interesting account of the history of cloud seeding is followed by a discussion of 'warm' and 'cold' fog dispersal, rainfall enhancement, hail and lightning prevention, and the modification of tropical storms. The chapter concludes with a discussion of inadvertent and intentional climate modification. The presentation is often uncritical and, therefore, very dependent upon the quality of the source material. For example, despite the reasoned discussion on the need for statistical proof in Chapter 1, on page 61 the author states: 'Since farmers, who are known to be good with figures, year after year employ the services of weather modifiers for working on cumulus clouds, it must be assumed that they do so on the grounds of their experience, irrespective of the fact that a firm statistical proof of success—or failure—of these operations can generally not be produced'.

The third and concluding chapter is concerned with the legal, social, ecological, and military implications of weather modification. The quality of the presentation is again very variable. There is an interesting discussion on the difficulty of performing cost–benefit calculations and also on potential conflicts of interest—for example between the farming and tourist industries. Unfortunately, a few pages later one finds the fanciful suggestion that present technology is sufficiently advanced to make it possible, at a reasonable expenditure, to clear fog from cities, in order to provide the inhabitants with a few hours of extra sunshine. The author makes the valid point that if weather modification is to be controlled effectively, international agreements should be established before it is widely used. However, the overall impression left by Chapter 3 is that, considering the limited proof of the efficacy of most weather modification techniques, it would be more profitable to worry about existing world problems than about hypothetical new ones.

Weather modification will be of interest to those who wish to acquaint themselves with a wide range of proposals for modifying the weather on all scales. They may also appreciate the copious references. However, anybody interested in a critical scientific discussion of weather modification techniques will be disappointed.

R. Brown

Mr Frederick James Parsons, M.B.E., M.A.

The death occurred at his home in Porthcawl, on 10 December 1980, of Mr Frederick James Parsons, M.B.E., M.A. He was 89 years of age.

Mr Parsons commenced weather observing at the County Observatory, Ross-on-Wye, in July 1914. Apart from absence on war service during the First World War, he maintained a program of meteorological observations until his retirement on 1 June 1975. Meteorological readings from Ross-on-Wye commenced in 1859 and Mr Parsons succeeded only two earlier observers. The station closed soon after his retirement.

In June 1965 he was awarded the M.B.E. in recognition of his long and valuable service.

Miss Dorothy Redfearn, B.E.M.

The death occurred on 18 December 1980 of Miss Dorothy Redfearn, B.E.M.

Miss Redfearn, with her sister Miss Mary Redfearn, had made regular weather observations from the post office at Forest-in-Teesdale, Co. Durham. Reports commenced on 13 December 1937 and terminated with the sisters' retirement on 31 December 1978. The reports were made hourly between 0700 and 1800.

Miss Redfearn and her sister were each awarded the B.E.M. in 1978 in recognition of their unfailing service.

Correction

In the article by Bond, Browning and Collier, *Meteorol Mag*, *110*, 1981, 29–40, in the third line of the caption to Fig. 4, '10 m s^{-1}', should be '5 m s^{-1}'.

THE METEOROLOGICAL MAGAZINE

No. 1306 May 1981 Vol. 110

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1.80 monthly **Annual subscription £23.80 including postage**

Dd. 716670 K15 5/81

ISBN 0 11 726282 X
ISSN 0026-1149

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

June 1981

Met.O. 942 No. 1307 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1307, June 1981, Vol. 110

551.509.313 : 551.509.324.2 : 551.515.41

A mesoscale forecast for 14 August 1975—the Hampstead storm

By M. J. Bailey, K. M. Carpenter, Laurina R. Lowther and C. W. Passant
(Meteorological Office, Bracknell)

Summary

A three-dimensional numerical atmospheric model has been used to obtain a forecast for the afternoon of 14 August 1975, when an intense stationary multicell storm formed over London and produced extensive flooding. The forecast shows a well-defined area of convergence at the right place, but about four hours later than the actual storm. Shading by an observed layer of medium-level cloud is included in the forecast model, and it is clear that this has an important effect on the forecast.

1. Introduction

On 14 August 1975, a stationary storm centred over north-west London caused extensive flooding. The natural history of this storm, the Hampstead storm, has been well rehearsed (Keers and Wescott 1976, Atkinson 1977) and the dynamics of the storm itself have been studied using a numerical model (Miller 1978). With this background, this situation is a natural choice as a case-study for testing a mesoscale forecast model. Such a model should provide detail that is not achievable in a synoptic-scale model and thus help to elucidate or forecast the environment in which strictly local events like the Hampstead storm might occur. Tapp and White (1976) have described a model that is designed to give mesoscale weather forecasts for the British Isles, and this model has been used to attempt an experimental forecast for 14 August 1975.

A limited-area atmospheric model needs initial conditions, which will describe the synoptic situation as well as any mesoscale detail that can be inferred from observations, and boundary conditions, through which information about synoptic changes can be supplied. In the present study, no attempt has been made to use observations to improve the initial conditions, which were interpolated from a synoptic-scale model. In this respect, and in many others, it is exactly like an earlier case-study reported by Carpenter (1979). This simplification was made because we do not yet have the ability to calculate mesoscale initial conditions automatically, and it was not thought appropriate to go to the considerable effort of carrying out and digitizing subjective analyses. The boundary conditions were also calculated from the synoptic-scale forecast for the period in question.

The model is still being developed and does not include any treatment of clouds. Fortunately, the most obvious feature of the cloud cover was a bank of altocumulus spreading from the west. With the exception of small areas in the west of the country, once this cloud arrived at any place it remained cloudy there for the rest of the day. Thus it was possible to allow for the effect of this cloud on the surface heat fluxes by coding its time of arrival at each grid point. Two forecasts, with and without this cloud, were carried out and we shall argue that the effect of the cloud is so marked in the forecast that it must be relevant to the mesoscale dynamics of the storm, and that cloud shading is an important part of any reasonable local weather forecast model.

2. Observational background

The synoptic surface-pressure analysis for 12 GMT on 14 August 1975 is shown in Fig. 1, which also shows the positions of Hampstead and Crawley. The radiosonde ascent at 12 GMT from Crawley is shown in Fig. 2.

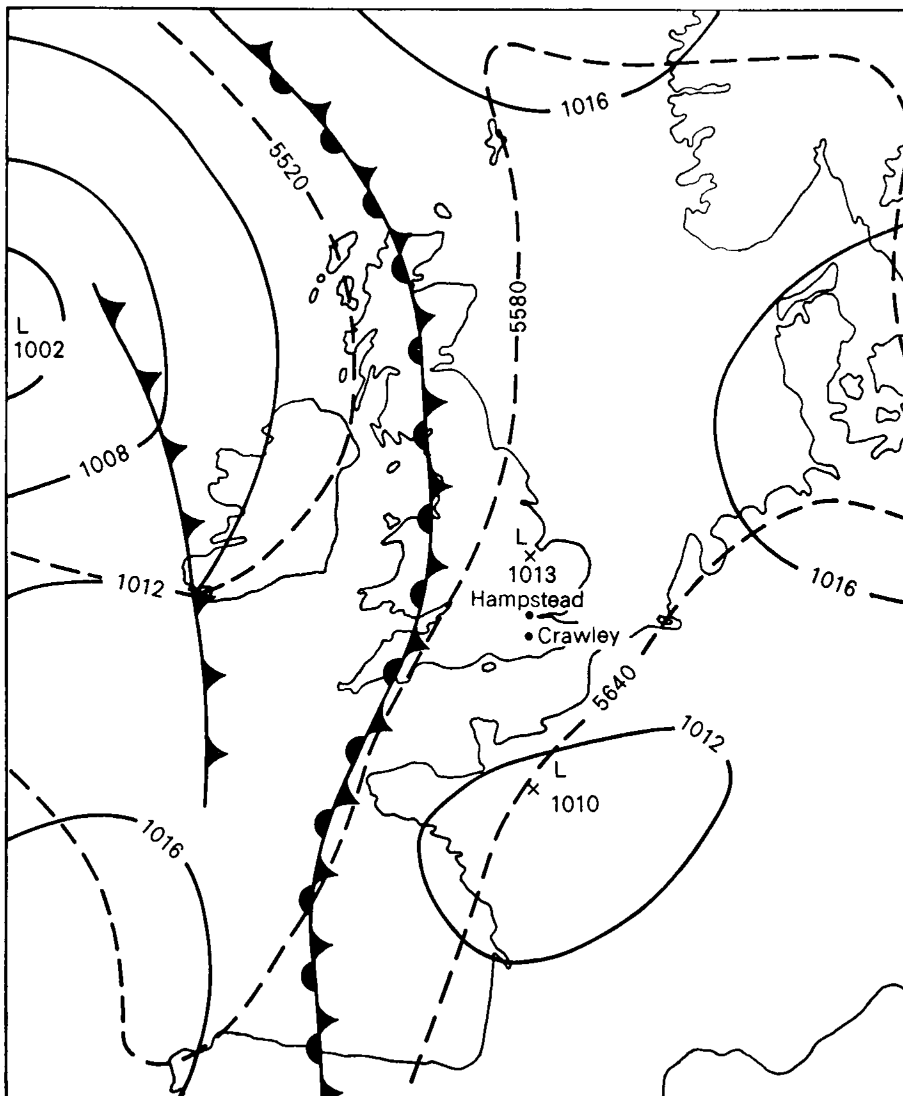

Figure 1. The synoptic situation over the British Isles at 12 GMT on 14 August 1975.

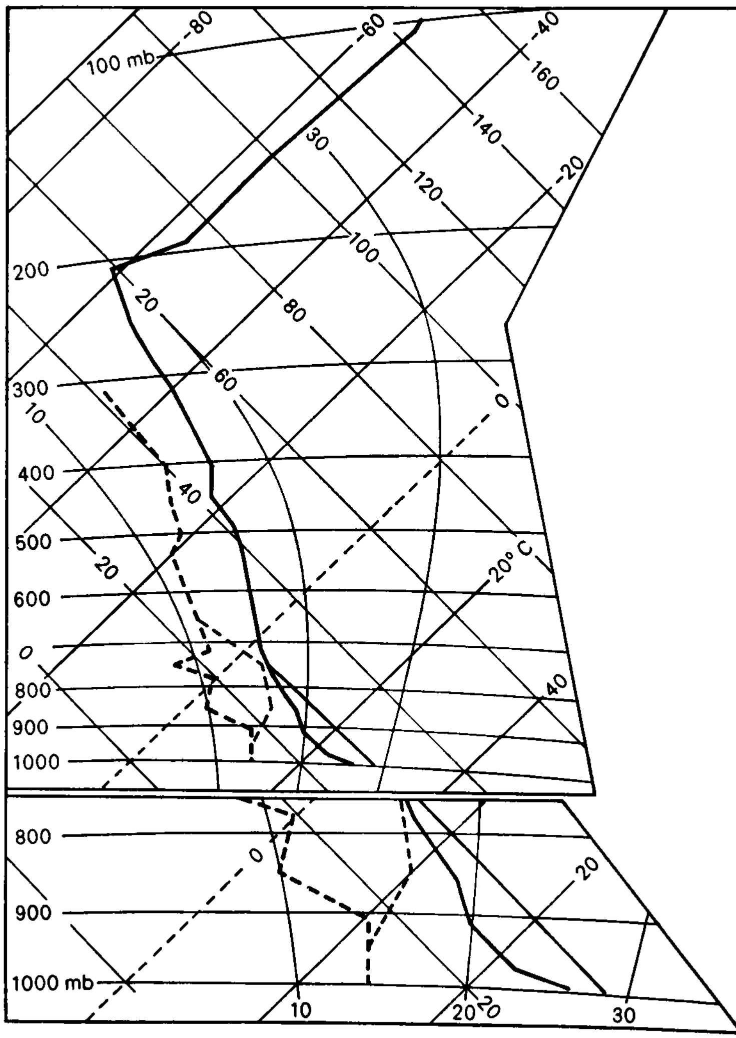

Figure 2. Radiosonde ascent from Crawley in south-east England at 12 GMT on 14 August 1975. Modifications that Miller (1978) found necessary in order to simulate the Hampstead storm are shown by the lighter variant lines.

It is natural to ask why a storm developed in this environment, why it was stationary and why it was over London. The ascent is conditionally unstable and south-east England is in the confluence between air moving round the depression to the north-west of Ireland and south-easterlies circling the low-pressure areas over France; the storm at Hampstead was not the only thunderstorm on this day. Miller (1978) has demonstrated that the storm was a multicell storm, in which each cell moved northwards in the ambient southerlies. The cold outflow from the succession of cells spread rapidly to the north-west, but the southern edge of the cold air was more or less stationary. Warm air from the south was forced over this cold air, triggering the release of latent heat and the growth of further cells. The initial development of the storm over Hampstead has been ascribed to Hampstead Hill, or to the urban heat-island effect of central London (Atkinson 1977). Miller's work does not resolve this problem, and it might be asking too much to expect to be able to identify the precise perturbation amongst the many that could have precipitated a storm of this nature. The main reason for carrying out the mesoscale forecast reported here is to discover whether it would have been possible to give warning that the London area might be a preferred location for severe thunderstorms.

As part of his study of London's urban heat-island effect, Atkinson has produced mesoscale streamline analyses for the surface on 14 August 1975. These are reproduced in Fig. 3 so that they can be compared with the present forecast.

3. The model

The model has been described in detail by Tapp and White (1976) and Carpenter (1979). It is based on a finite-difference approximation of the non-hydrostatic compressible equations of motion on a three-dimensional grid. The horizontal grid has 61 × 62 points, a grid length of 10 km and covers England and Wales. There are 10 levels and the top level is at 4 km. This grid is not a permanent feature of the model and it might have been natural to increase the model depth for this study. However, that could only be done at the expense of resolution and, in the event, the results suggest that there would be little benefit from using a deeper model.

Boundary-layer turbulence is included in the model, using a *K*-theory approach, and there is a convective adjustment. However, the effects of moisture, cloud and radiation are only described in so far as they affect the exchanges of heat at the surface.

The calculation of surface fluxes of heat and momentum has been described by Carpenter (1977). Monin–Obukhov similarity theory is used, and the surface temperature is given by requiring heat balance at the surface:

$$S + R\downarrow = H + LE + G + R\uparrow, \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where S is the solar heating of the surface,
$R\downarrow$ and $R\uparrow$ are the thermal radiation fluxes at the surface,
H is the sensible heat flux into the atmosphere,
E is the flux of water vapour into the atmosphere,
L is the latent heat of vaporization,
and G is the heat flux into the ground.

The calculation of the evaporation E needs a value for humidity mixing ratio, which is otherwise absent from the model, at the bottom level; a constant value of 0·01 has been used. The solar radiation S is given by:

$$S = 558 \cos(t/12) + 72 \qquad (\mathrm{W\ m^{-2}}) \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

before the arrival of the medium cloud and

$$S = 279 \cos(t/12) + 36 \qquad (\mathrm{W\ m^{-2}}) \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

later in the day, where t is measured in hours from midday. Thus the solar heating is halved following the arrival of the cloud. Equations (2) and (3) are intended to allow for atmospheric attenuation and reflection from the surface.

The facts that humidity was not a forecast variable and that the altocumulus was not the only cloud observed during the day reduce the reliability of the estimate of the sensible heat flux. Thus, it seemed inappropriate to consider the precise form of equations (2) and (3) too carefully, and the reduction of

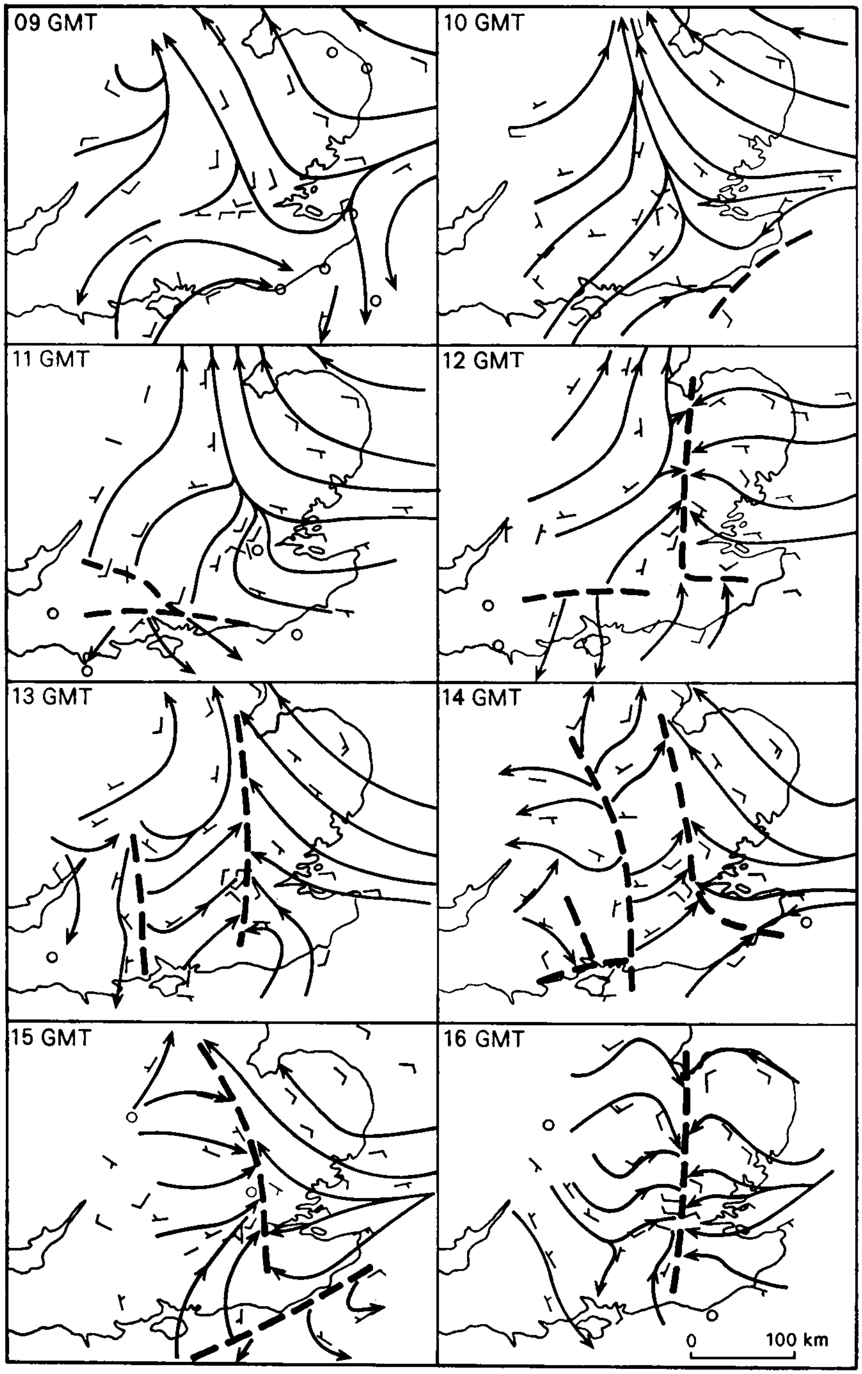

Figure 3. Surface streamline analyses for 14 August 1975. This figure is a direct copy from Atkinson (1977).

the solar beam by 50% was chosen for its simplicity. If we assume a transmissivity of 0·3 for medium-level cloud (e.g. Liou 1976), a solar beam S will be reduced to $(1–0{\cdot}7C_m)S$ by a cloud amount C_m. The cloud was recognized by the British Isles forecaster in the Central Forecasting Office, Bracknell, as a layer of more than 5/8 altocumulus, so about 55% of the solar beam should have penetrated the cloud. Thus equations (2) and (3) should give a qualitatively correct description of the shading effect of this altocumulus.

The leading edge of the cloud, as coded in the model, is shown in Fig. 4.

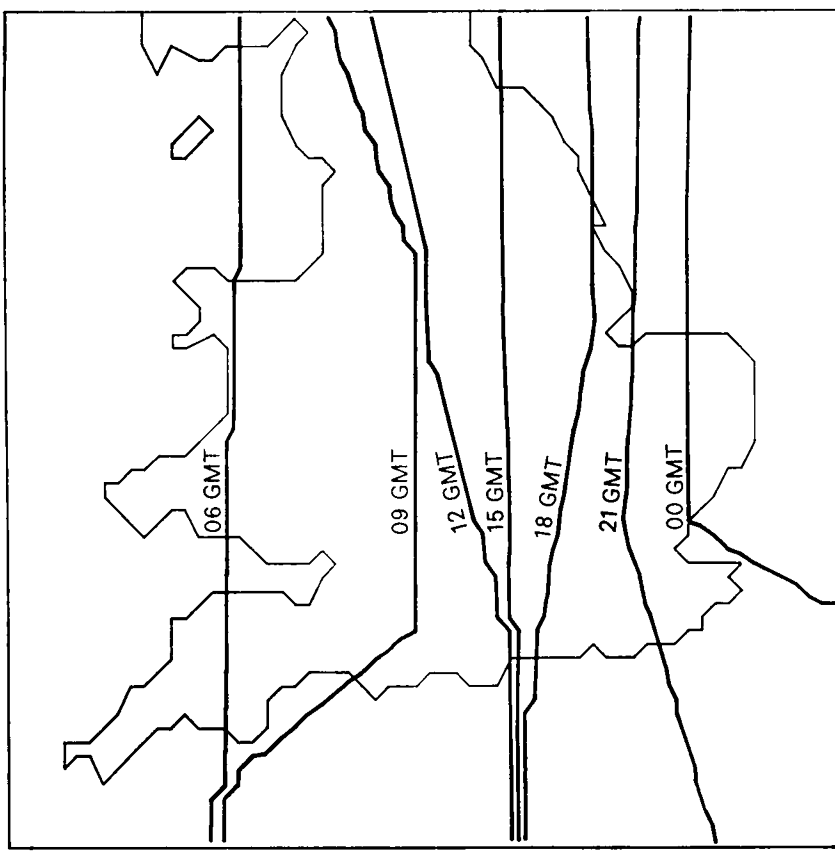

Figure 4. The position at various times of the leading edge of a layer of cloud that moved across England on 14 August 1975.

A synoptic-scale model starting at 00 GMT on 14 August 1975 was used to obtain initial and boundary conditions. The mass field forecast for 06 GMT was interpolated to the mesoscale model grid, and the Ekman layer equations were solved for the winds. The boundary conditions were updated throughout the mesoscale forecast using a second 'initialization' carried out for 18 GMT.

4. Results without cloud

A forecast was made using only equation (2) to calculate the solar warming of the surface. This gave the winds and temperatures shown in Figs 5 and 6 for 12 GMT and 18 GMT respectively.

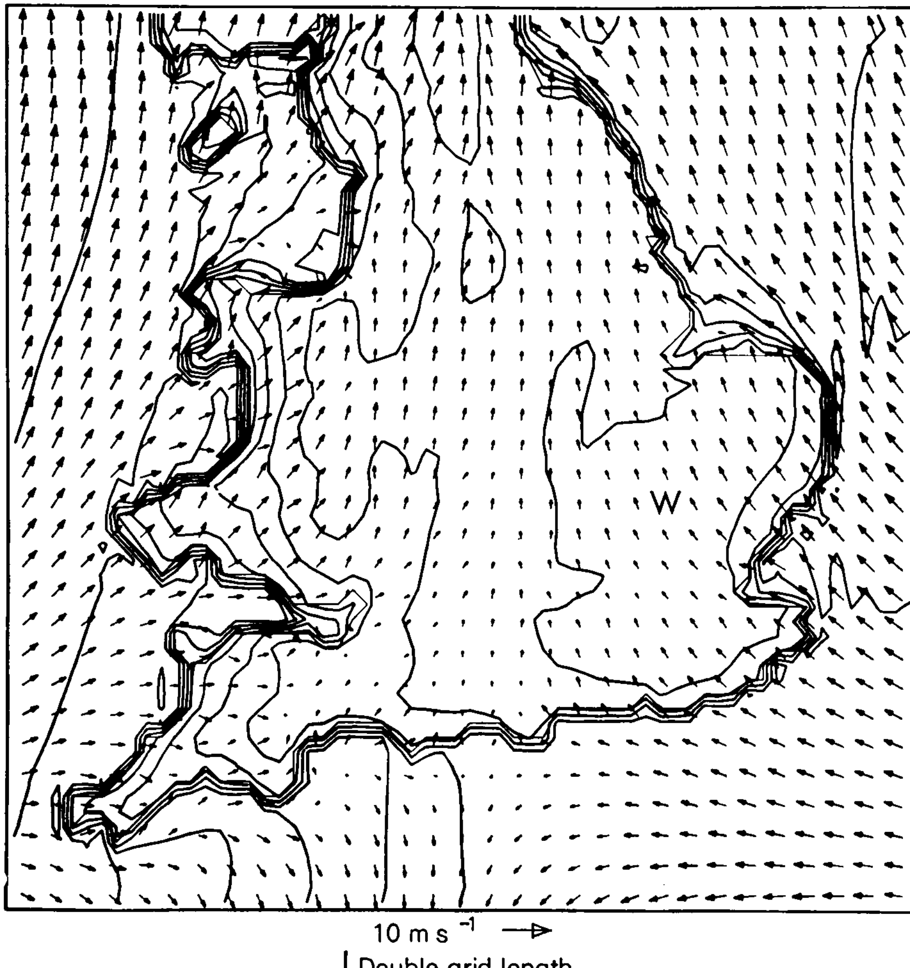

Figure 5. Forecast 10 m winds and potential temperatures for 12 GMT on 14 August 1975, when cloud effects were excluded from the forecast model. Wind speed indicated by length of arrow and plotted at double grid-length intervals. Isotherm interval 1 K; W = warm.

Given ascents resembling the Crawley ascent shown in Fig. 2, it is possible that the sea-breezes apparent in Figs 5 and 6 will trigger cumulus. Further, the convergence of breezes from the south and east coasts might indicate London as a preferred location for cumulonimbus. Nevertheless, it seems more likely that the results with cloud, shown below, are relevant to the special events on 14 August 1975.

5. Results with cloud

Figs 7 and 8 show the forecast of low-level winds and temperature for 12 GMT and 18 GMT, and are

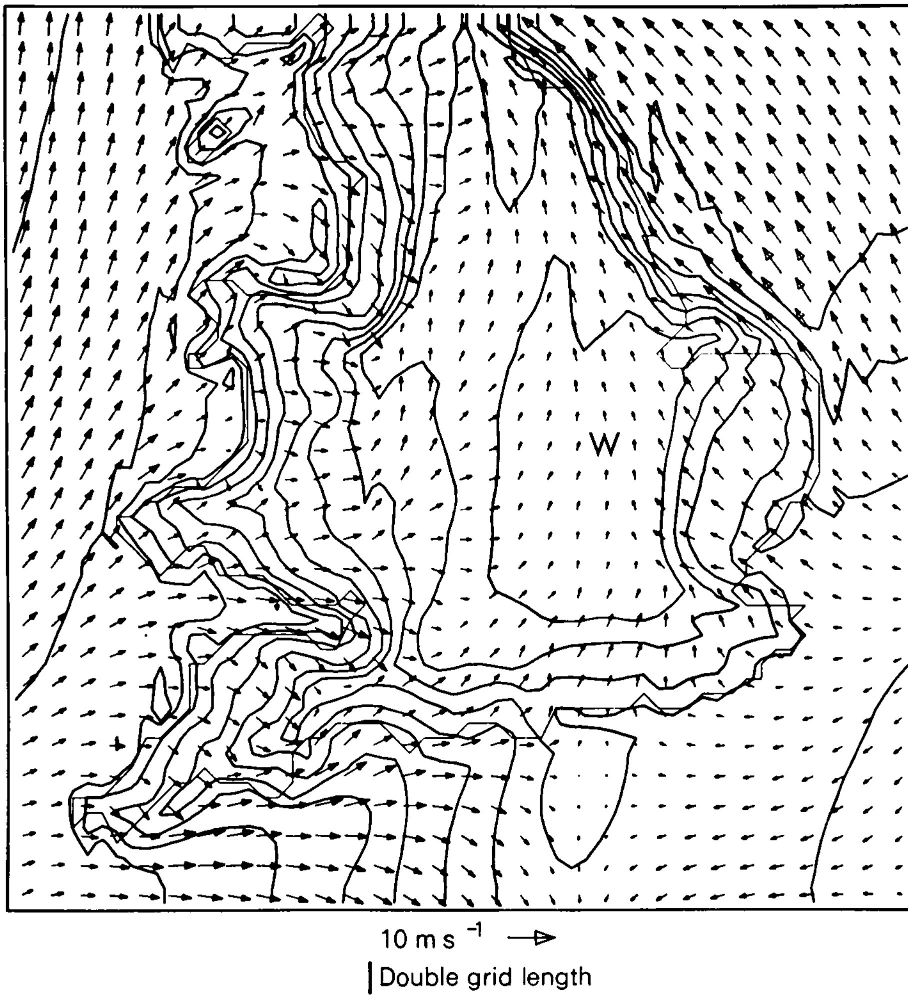

Figure 6. Forecast 10 m winds and potential temperatures for 18 GMT on 14 August 1975, when cloud effects were excluded from the forecast model.

directly comparable with Figs 5 and 6. The forecast for 18 GMT encouraged us to continue the forecast to 20 GMT, with the result shown in Fig. 9. Fig. 10, which shows forecast ascent and reports of thunder or cumulonimbus, shows Hampstead to be at the southern end of a line of ascent, and Fig. 9 shows a well-defined vortex in the same place. Superficially, this is a remarkable success, but it must be borne in mind that the storm started at 16 GMT, so this forecast is four hours late.

Fig. 11 shows a comparison between the forecast surface temperatures and the observed screen temperatures. In general, the surface temperatures are about 1 K too high, which might be reasonable for the decrease in temperature from the surface to screen level. The sharp discontinuity across the cloud edge is not proved by the observations, but the drop in temperature from the eastern half to the western half of England seems correct.

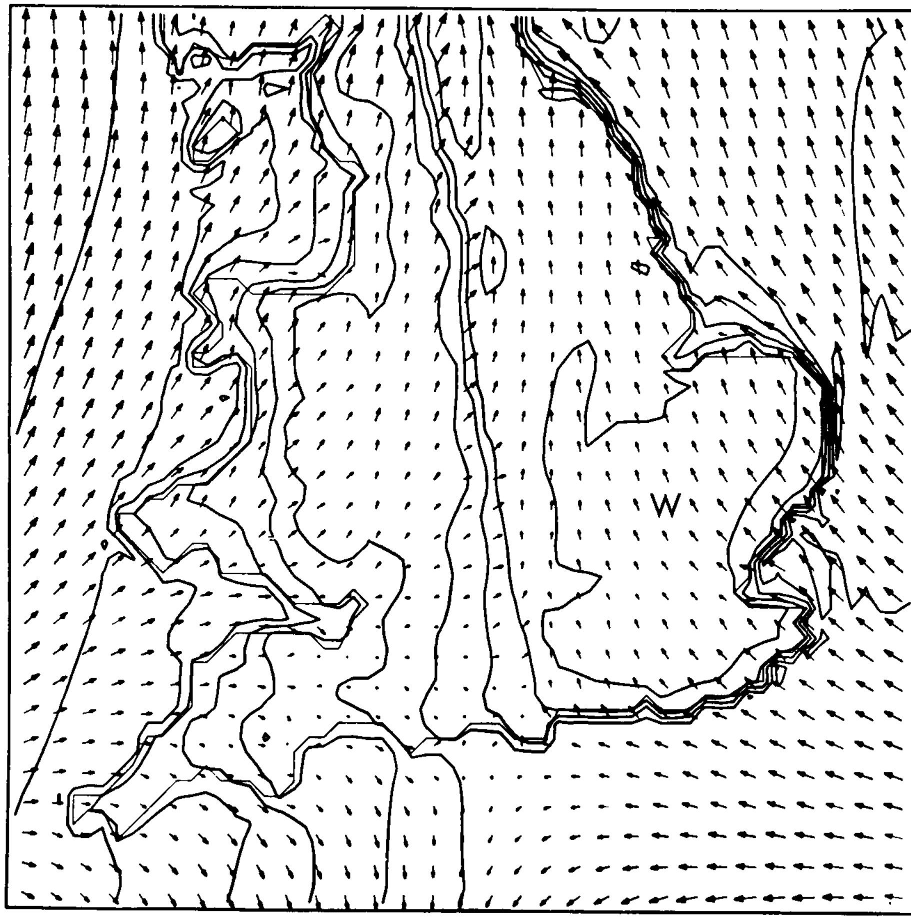

Figure 7. Forecast 10 m winds and potential temperatures for 12 GMT on 14 August 1975 when the effects of the layer of cloud shown in Fig. 4 were included in the forecast model.

6. Discussion

When the forecast with cloud is compared with the analyses in Fig. 3 it can be seen that some details of the forecast are quite wrong. In the analysis a line of divergence moves across the country in a way that is similar to the movement of the cloud edge and its associated convergence line in the forecast. The forecast shows divergence behind the convergence line and it is possible that a more realistic description of the cloud, with the amount increasing more gradually towards the west and the inclusion of some higher cloud further to the east, would lead to a forecast more like Atkinson's analysis. Atkinson's line of convergence is aligned along the east of the country far earlier than any similar feature in the forecast, and it seems unlikely to us that this has much to do with the advancing cloud parametrized in the forecast.

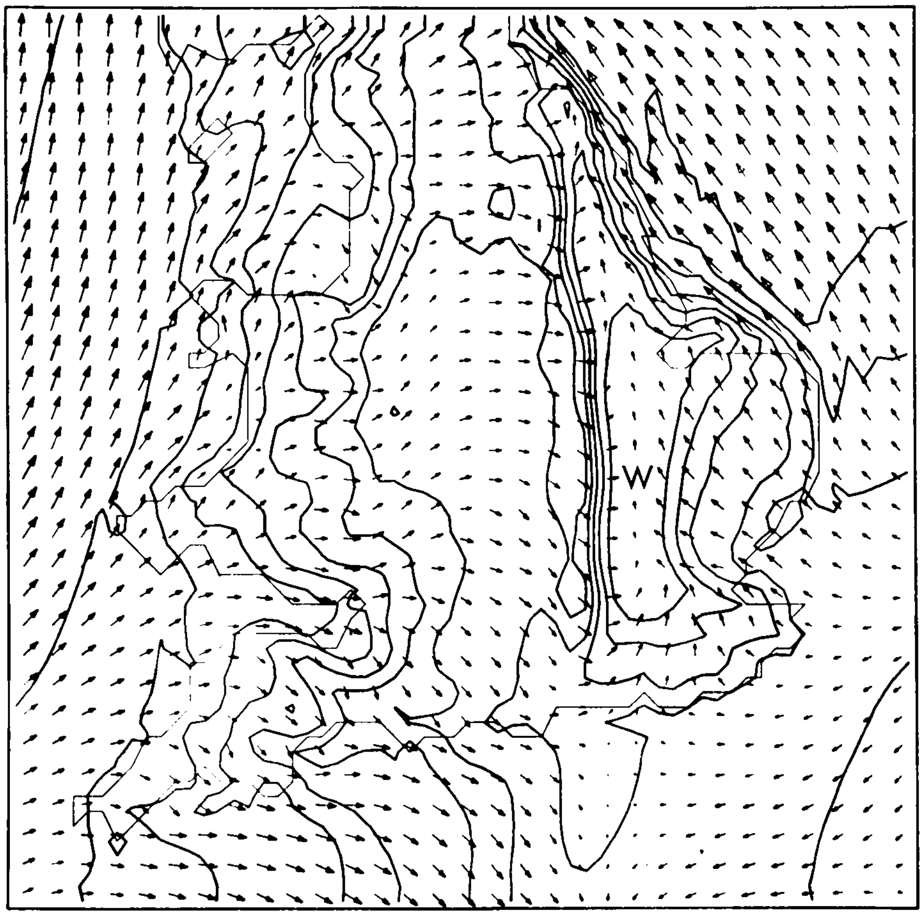

Figure 8. As for Fig. 7 but for 18 GMT.

Nevertheless, the comparison between the forecasts is conclusive evidence that the effects of the cloud are important, and the location of all the thundery activity close to the leading edge of the cloud (see Fig. 10) cannot be dismissed as a coincidence. Fig. 12 shows a west–east section through the model, and thus the cloud edge. It is clear that the cloud shading has induced a considerable temperature contrast throughout the boundary layer. This has in turn induced a thermally direct circulation in some ways similar to a sea-breeze or gravity current. It is hoped that this response will be studied further, and a further case-study in a similar situation is planned (the Skipton storm, 13 June 1979).

It seems clear that any reasonable local forecast model must include calculations of the shading effect of clouds. The importance of calculating the latent heat release during cloud and rain formation is familiar, but it is possibly no more important than the radiative effects of cloud. This presents modellers with a substantial problem because it is not clear that it is easy to calculate cloud cover or cloud type with reasonable accuracy in a numerical model. In this forecast we have, in effect, treated the cloud

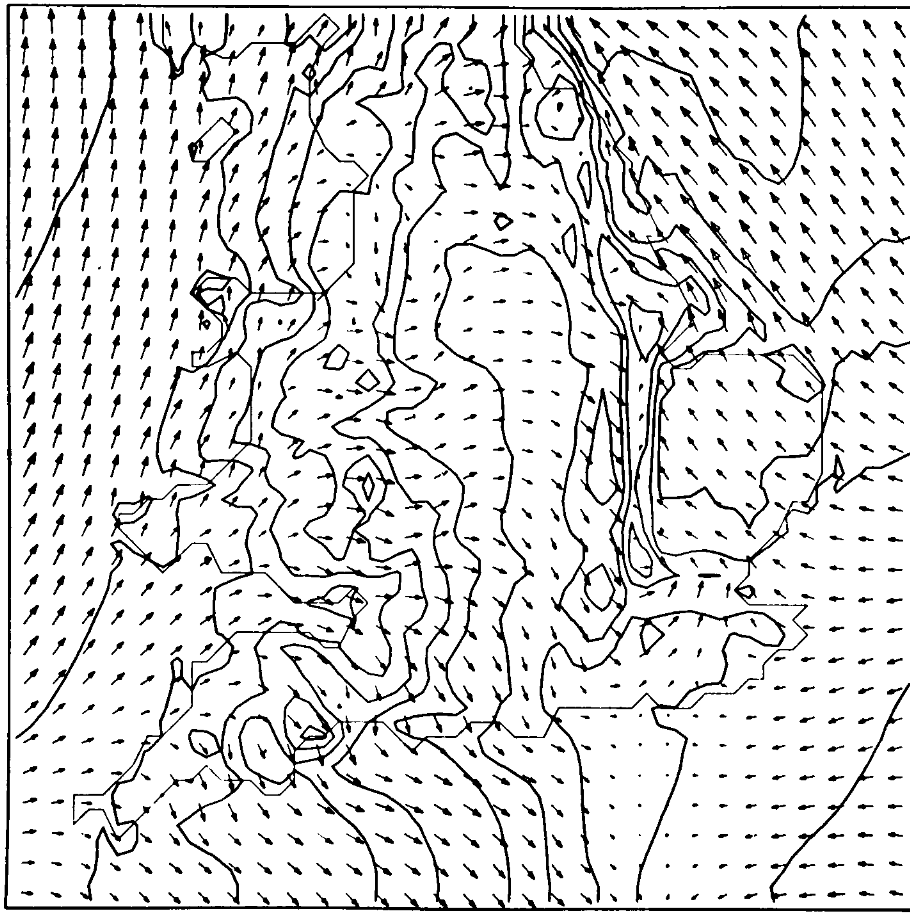

Figure 9. As for Fig. 7, but for 20 GMT.

amount as a boundary condition that must and can be obtained from some external source. In operational practice, we would not have observations of clouds in advance, but it is possible that forecasts of cloud type and amount could be obtained using some objective extrapolation of satellite and surface observations. This suggests that an approach like, but more sophisticated than, that used in the present study might be more reliable than using model-predicted cloud in the radiation calculations.

As for the Hampstead storm, it is clear that no description of its mesoscale meteorology is complete unless it takes full account of the effects of cloud shading and the associated areas of ascent and descent. Our forecast cannot be considered a complete explanation because of the lack of mesoscale detail in the initial conditions, the timing error and the poor comparison with Atkinson's streamline analyses. However, Miller (informal contact) has pointed out that the strong low-level convergence predicted in the forecast reported here is a useful addition to his work (Miller 1978). He found that the Crawley ascent (Fig. 2) did not lead to a storm in his model unless he increased the low-level heat and moisture, as shown in Fig. 2. His adjustment to the Crawley ascent is made more plausible by our forecast.

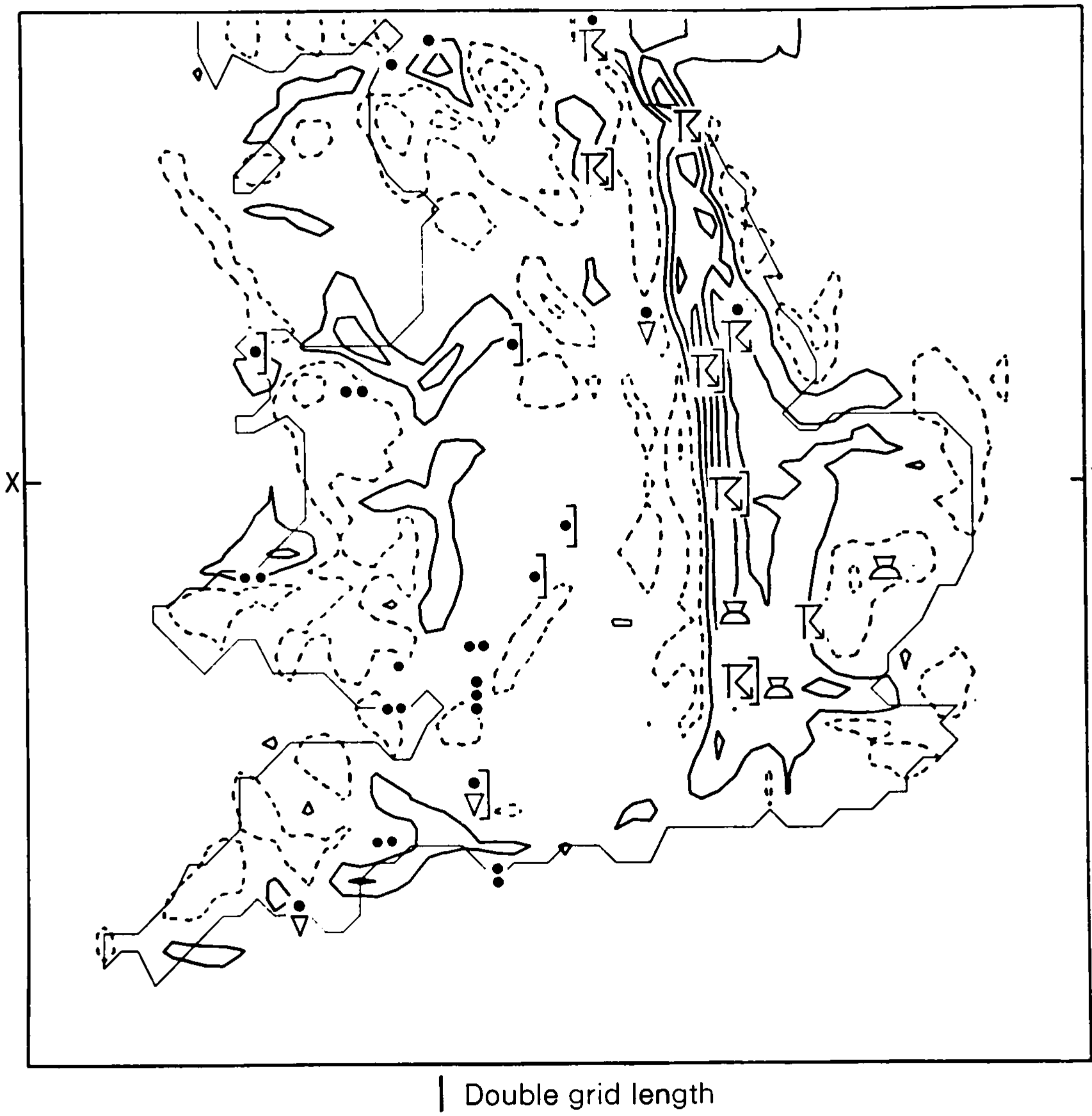

Figure 10. Forecast vertical velocity at 190 m compared with significant-weather reports, both for 18 GMT on 14 August 1975. Isopleth interval 2 cm s^{-1}; continuous lines +1, +3, . . ., dashed lines −1, −3, ... X and Y indicate the cross-section depicted in Fig. 12.

7. Conclusion

Two forecasts of the mesoscale developments on the day of the Hampstead storm have been carried out, one with and one without cloud. The comparison of the two forecasts suggests that the calculation of cloud shading is essential to good numerical forecasts of local weather. The forecast with cloud showed marked low-level convergence on the leading edge of the cloud, which moved across the country and eventually intersected the sea-breeze fronts to suggest a preferred area for convection over London.

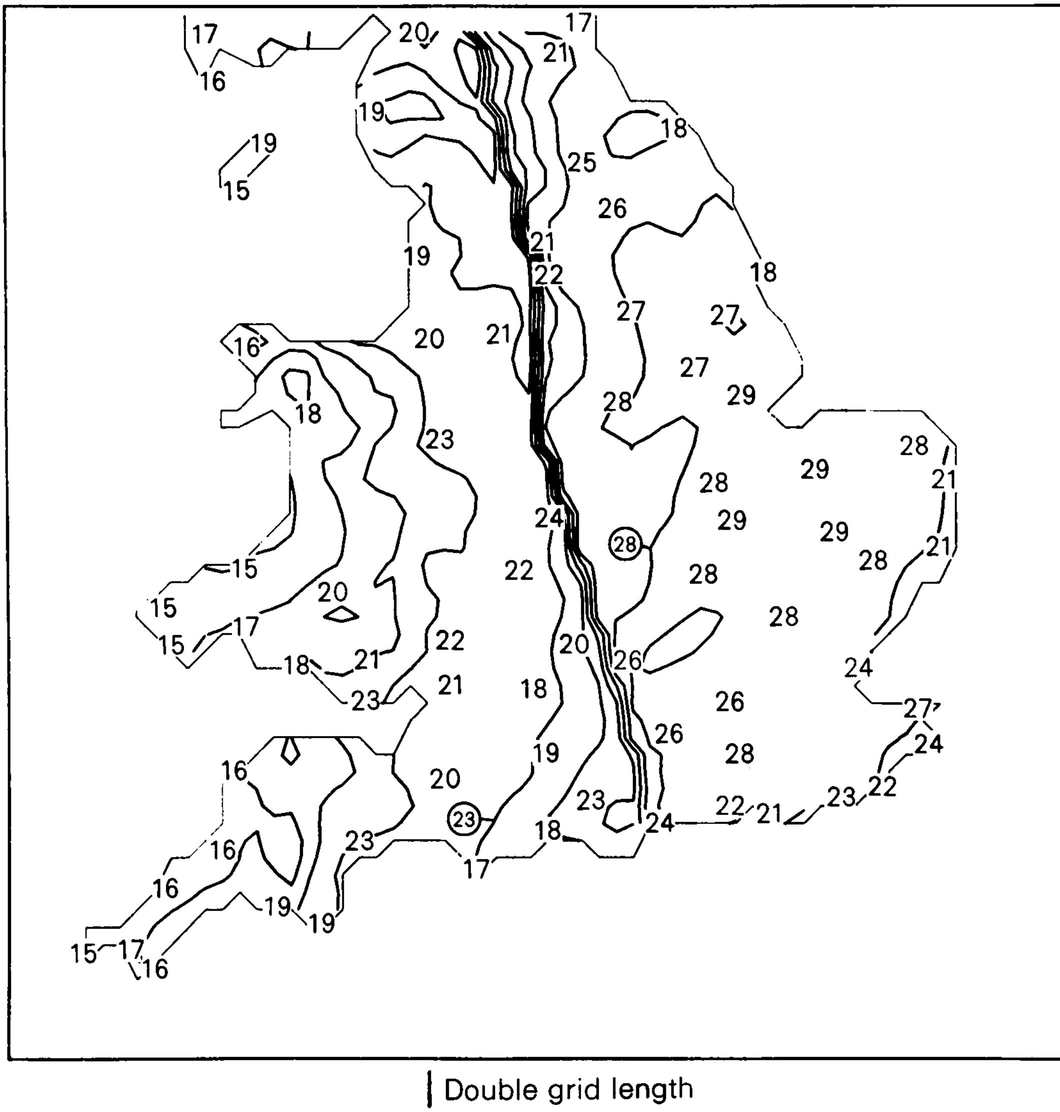

Figure 11. Forecast surface isotherms compared with observed screen-level temperatures, both for 12 GMT on 14 August 1975. Isotherm interval 1 K.

Acknowledgement

We are grateful to Drs M. J. Miller and M. W. Moncrieff for suggesting this study and for taking an interest in it.

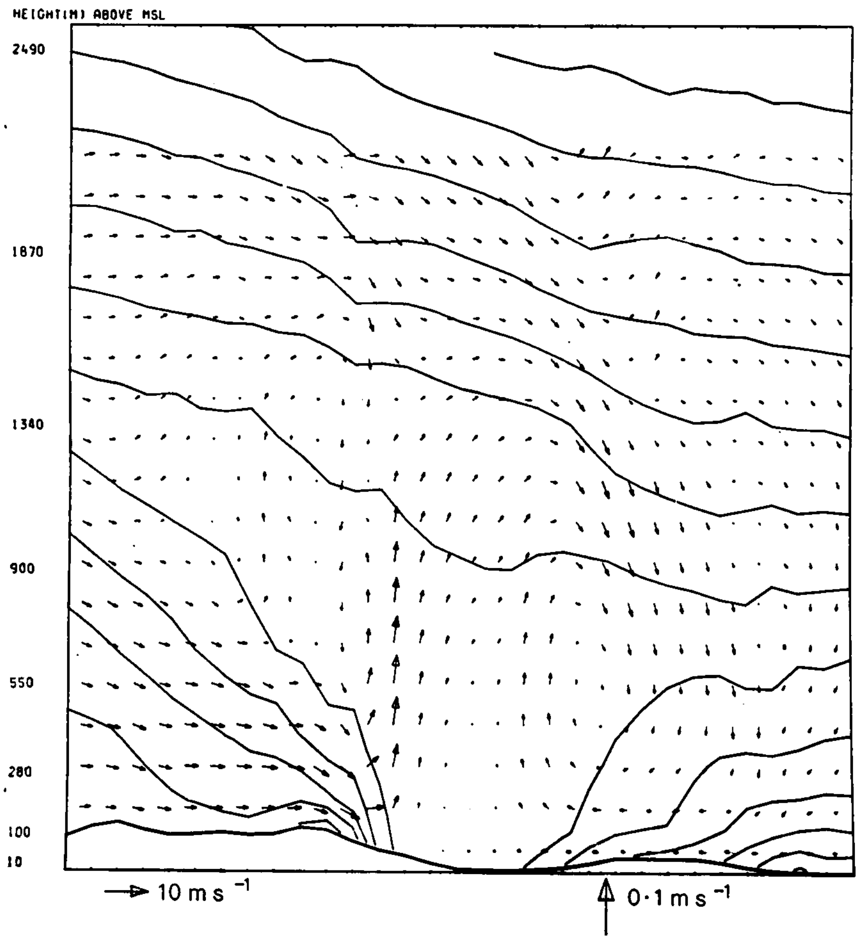

Figure 12. Vertical west–east section (X–Y in Fig. 10) through the cloud edge showing the forecast potential temperatures and components of wind velocity in the plane of the section for 18 GMT on 14 August 1975. The section is restricted to the bottom eight levels of the model and, approximately, to the eastern half of the model. Isotherm interval 1 K.

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Early meteorological observations for Sitka, Alaska

By D. E. Parker

(Meteorological Office, Bracknell)

Summary

Work has begun on the compilation of homogeneous time-series of surface data for Sitka, Alaska, where observations have been made, with a few breaks, since 1833. This note describes the solution of the basic problems of station elevation and observing times for the two series of data covering 1833–42 and 1842–67.

1. Introduction

Early meteorological data for Sitka, Alaska, remain among the untapped resources for research into climatic change. This note describes the start of efforts to render the data suitable for use in this research.

Sitka is at approximately 57° 3′N, 135° 21′W and is in that narrow coastal strip of Alaska facing west-south-west on to the Pacific north of Vancouver. It is situated partly on the south-west coast of the mountainous Baranof Island and partly on Japonski Island, which is separated from Baranof Island by a channel 300 m wide, used as a harbour. No part of Japonski Island exceeds 25 m in elevation.

The early meteorological data are summarized by the USA (Washington) *Pacific Coast Pilot* (1879), but without solving the problem of station elevation. However, following the recent discovery of evidence on the elevation of one of the two stations whose periods overlapped in 1842, it has become possible to deduce the other by comparison of surface pressures as described below.

2. Comparison of two stations operating simultaneously in 1842

From March to November 1842 there were two meteorological stations in Sitka. The four-times daily observations of the priests Veniaminoff and Cygnaeus from 1 January 1833 to 11 December 1842, new style calendar, are given by Kupffer (1846). Their station will be denoted station A. The hourly observations of the Russian Government are given by the *Annuaire Magnétique et Météorologique de Russie* from 1 March 1842 to the end of 1845, and thereafter by the *Annales de l'Observatoire Physique Central de Russie* until the station closed when Alaska was sold to the USA in 1867. This station will be denoted station B.

The individual data for a given time at stations A and B appear to disagree grossly, but this is because, according to Kupffer (1846), the times given are local time for station A, and Göttingen time (minus 12 hours because 01h etc. appear to be at night from an inspection of temperatures) for station B. Sitka is 9 hours 40 minutes west of Göttingen, so a discrepancy of 2 hours 20 minutes might be expected, but Kupffer in his conversion from the old style calendar decided to reckon time eastwards from Europe, so the discrepancy is in fact 1 day 2 hours and 20 minutes. Table I illustrates the times used. The discrepancy in the ascribed times has been verified by computing the apparent time differences for which

Table I. *Times ascribed to Sitka data*, 1842

Sitka Station A (Kupffer, 1846)	Sitka Station B (Russian vols)	Göttingen (Germany)	Greenwich
date/time	*date/time*	*date/time*	*date/time*
02/1500	01/1240	02/0040	02/0000
02/2100	01/1840	02/0640	02/0600
03/0300	02/0040	02/1240	02/1200
03/0900	02/0640	02/1840	02/1800

the variance of the pressure difference between the two stations is a minimum. This time difference was found to be about 1 day 2 hours, with variation of an hour either way according to which month of 1842 was chosen, the scatter probably arising from random errors.

When the truly simultaneous data are compared, after correcting Kupffer's observations to a barometer temperature of 13⅓° Réaumur, it is found that the mean pressure difference is 0·8 Russian half-lines = 1·4 mb, representing (at 7 °C) an elevation difference of 12 m, with station A having higher elevation (lower pressure). The USA National Weather Service (private correspondence) have found that station B had an elevation of 35 feet = 11 metres above mean sea level. Therefore station A must be taken to have had an elevation of 23 m.

De Tillo (1890) who used the Russian annals for his source, and therefore referred to station B, gives 19 m for the elevation. However, these annals, wherever they refer to the location of the station, consistently leave the elevation blank. Moreover, Washington (1879) shows a line drawing of station B which is described as being at the eastern end of the low and flat Japonski Island, and a recent Admiralty map of this island shows no elevation approaching 19 m on its eastern side (even allowing for the height of the barometer above the ground: the station building had no upper storey). Therefore the value 11 metres, and not de Tillo's value, will be used for station B.

3. Future work

Appendices 1 and 2 give further information about Sitka distilled from Kupffer (1846) and from the Russian annals. It will be necessary to check and if necessary eliminate the suspect values, and to make the early data as homogeneous as possible with later data for which the station elevation is known. A little extra insight may then be gained into the atmospheric circulation over the North Pacific in the 19th century.

References

Kupffer, A. T.	1846	Observations météorologiques faites à Sitka. In French; translation available in Synoptic Climatology Branch, Meteorological Office, Bracknell.
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	1846–67	*Annales de l'Observatoire Physique Central de Russie*. In French.
De Tillo, A.	1890	Répartition géographique de la pression atmosphérique sur le territoire de l'Empire de Russie et sur le continent Asiatique d'après les observations depuis 1836 jusqu'à 1885. St Petersburg. In Russian, but translation available in National Meteorological Library, Bracknell.
Washington	1879	Washington, US Coast and Geodetic Survey. *Pacific Coast Pilot. Coasts and islands of Alaska, 2nd series.*

Appendix 1. Notes on '*Observations Météorologiques, faites à Sitka, sur la côte N.O. de l'Amérique*' by A. T. Kupffer (1846).

1. The daily and monthly station pressures are in different units (French and English (= Russian) half-lines respectively) but the conversion factor is not given. At $13\frac{1}{3}$ °R, when the temperature correction is zero, the data give a ratio of mean daily value to given monthly value of 1·12595. One English half-line = 1/20 inch Hg = 1·6931 mb.
2. The following months contain some unlikely high daytime temperatures: January, February, March, April 1839; January 1840.
   The monthly values have been affected as a result.

Appendix 2. Surface observations at Sitka, Alaska, 1842–67. Background information in *St Petersburg, Annuaire magnétique et météorologique* (1841–45) or *St Petersburg, Annales de l'Observatoire Physique Central de Russie* (1846–67).

Year	Information
1841	(a) Magnetic and geographic [*sic*] station at 57 °3′N, 222° 15′ [*sic*] east of Paris. (b) Detailed observing instructions and tables for temperature correction of barometers, for stations in general. Wind direction is in degrees true, not magnetic.
1844, 1845 1856, 1857 1859, 1860	(a) Sun thermometer readings given. These may assist in the interpretation of some excessively high values recorded at the earlier station in 1839–40.
1844	(a) Psychrometric thermometer broken in November, so that there were no humidity data for most of the month.
1846	(a) Monthly means up to December 1845 given. (b) No Sitka data.
1847	(a) No Sitka data.
1848	(a) Gives May 1847 to December 1848 data.
1849	(a) Volume missing.
1852	(a) Observations for Jan.–June and for 2 Nov.–31 Dec. were made at the normal location at the magnetic observatory on the island called Japonne. (b) Observations for July–Oct. were made at the pharmacy of the hospital of Novo-Arkhangelsk: elevation not given. (c) 25–30 June missing.
1856 and preceding vols	(a) Göttingen time used.
1855	(a) Sitka missing from volume.
1857 onwards	(a) Local time used, with 0 = noon.
1858	(a) Volume missing.
1865, 1866	(a) Location given as 57° 3′N, 137° 49′W of Paris.
1867	(a) Observations ended on 21 October.
1853–58 1859–64 summary vols.	(a) Include 1858 means for Sitka, but not 1855. Normals for 1832–49 are given in 1854 section, where location is given as 57° 3′N, 242° 14′E.

The Groves Family

Mr Nicholas Abbott, who has for the last two years presented the L. G. Groves Memorial Prizes and Awards, has kindly lent us a copy of a privately printed history of the Groves family written by his great-uncle, the late Major Keith Groves, who with his wife Dorothy established the Memorial Fund in memory of their only son, Louis Grimble Groves. The annual presentation ceremony is always attended by a considerable number of the Groves family who take great personal pride and interest in it, and we thought our readers might like to have a short account of Major Groves's background and the connection of his family with the armed services, in particular the Royal Air Force.

The original family surname was Grimble—the late Sir Arthur Grimble, author of 'A Pattern of Islands', was a distant relative—and it was Major Groves's grandfather, born in 1817 as William Peer Grimble, who decided for personal reasons to adopt Groves as a surname. (As a young man he had been sent to study with a firm of analytical chemists in Newcastle and lived in the household of one of the partners, a Mr Groves, who treated him as one of the family.) The Grimbles had for several generations been manufacturers and tradesmen in London, usually as victuallers and distillers, and after various business ventures, including a spell in Australia, W. P. G. Groves in partnership with a Mr A. W. Whitnall established the prosperous brewery of Groves and Whitnall. He had a large family—six sons and six daughters—and the third son, James Grimble Groves (b. 1854) was the father of Major Groves.

James Grimble Groves joined the family business in 1869 as an office boy while continuing his studies at Owens College (which later became Manchester University); it is interesting that at that time a nine gallon cask of the best ale cost 13/-, i.e. 65p. He worked his way up to become Chairman and Managing Director, and also played a full part in public life, becoming a county magistrate, Mayor of Altrincham, and M.P. for South Salford. In 1878 he married Anna Eva Marsland, the daughter of a Manchester physician and his wife who was a descendant of the ancient Lancashire family of Briercliffe. Anna Marsland was an able and well-educated woman with a good business mind, and took a full share in her husband's social, political and philanthropic activities; after his death in 1914 she was elected Chairman of A. V. Roe (then a private company), one of the first women ever to hold such a position. In later life she lived in the Isle of Man where she became Chairman of the Women's Section of the Ramsey Branch of the Royal National Lifeboat Institution. She was a great traveller and was elected a Fellow of the Royal Geographical Society. In old age she used to go on voyages in cargo ships and on one such voyage on a banana boat to the West Indies was lucky to escape shipwreck in a hurricane which caused the loss of the propeller and damage to the rudder.

James and Anna Groves had seven sons and two daughters of whom Major Groves was the fifth son. The youngest son died in childhood, but the others all became men of ability, energy and character who distinguished themselves in various ways.

Listing the children of James and Anna Groves in order of date of birth we have:

1. *William Peer Groves:* Expert on the Far East. Joined Royal Naval Air Service (RNAS) in 1914 and served through the war. Appointed Assistant British Air Attaché to the League of Nations. Became Chairman of Groves and Whitnall, and Hon. Consul for Japan in Manchester.
2. *Robert Marsland Groves:* Joined Royal Navy in 1894, passing out of Dartmouth top of his term. In 1914 Flag Commander to the C.-in-C. Mediterranean Fleet and then appointed Second-in-Command in the RNAS. Commanded Naval Forces at Dunkerque. Became Director of Flying Operations (Navy) and in 1918 Deputy Chief of Air Staff in the new Royal Air Force. Held ranks of Brigadier General, Air Commodore and Captain RN; awarded the C.B., D.S.O., A.F.C. and the American Air Force Cross, and made Officier de la Légion d'Honneur. Played polo, and represented the Navy at fencing. In 1919 appointed to command the Royal Air Force in Egypt and the Middle East, but was killed the following

year in an aircraft accident. A colleague wrote in the *RAF Record* that 'the Air Force owes more to his untiring dash, loyalty and imagination than almost any other man'. His son, Hugh Marsland Groves, also joined the Royal Air Force and retired after the last war as a Group Captain.

3. *James Douglas Groves.* The sportsman of the family. A skilled horseman and first-class shot. Settled in British Columbia where he killed nearly 100 cougars. Served in the Army from 1914 to 1918. His son, Lt.-Col. J. J. D. Groves, presented the Memorial Prizes and Awards in 1978.

4. *Eric Marsland Groves:* Joined the Royal Navy and became one of the earliest submariners. In 1908, following an accident to the petrol supply of his submarine, he by great gallantry saved the lives of the entire crew thereby receiving severe injuries which caused him to be invalided from the Navy.

5. *Eva Muriel Groves:* Married her brother Robert's great friend F. C. Halahan, later Air Vice Marshal Halahan, C.M.G., C.B.E., D.S.O., M.V.O. She herself did much public work.

6. *Keith Grimble Groves:* Barrister. Director (and later Chairman) of Groves and Whitnall. Director of several other companies. Served in the Army during the first world war in France and the Middle East. Mentioned in Dispatches. Did much public work in the Isle of Man including being a J.P. and (during the last war) Second-in-Command of the Second Manx Battalion, Home Guard. Married Dorothy Moore in 1914. Their only son, Louis Grimble Groves, was killed in 1945 when a Sergeant Meteorological Air Observer.

7. *Leslie Gordon Grimble Groves:* Joined the Royal Navy and served in the Battle of Jutland. In business between the wars. Re-enlisted in 1939 and had varied war service, including being trapped for a year in Nice under the Vichy government.

8. *Eileen Norah Grimble Groves:* Married (firstly) Howard Cumming who joined the infantry in 1914 and transferred to the Royal Flying Corps in 1916. Their only son was a pilot in the Royal Air Force in the second world war and lost his life in a bombing mission over Germany.

9. *Colin Groves:* Died in childhood.

The current presenter of the Memorial Prizes and Awards on behalf of the family is Mr Nicholas Abbott whose mother was a daughter of Robert Marsland Groves, Major Groves's brother. Mr Abbott held a short-service commission with the Suffolk Regiment in Germany from 1954 to 1957, and then became a rubber planter in the Far East from 1957 to 1971. After a couple of years on a forestry project in Indonesia, he returned to this country and now works for the Fairbridge Society, a charitable organization which assists single-parent families to settle in Western Australia.

Members of the Meteorological Office probably think of the Groves family only in connection with the L. G. Groves Memorial Prizes and Awards; Major Groves's account makes it clear how wide-reaching their services to their country have been, both in peace and in war.

R. P. W. Lewis

Letters to the Editor

Comments on 'The use of analysis of variance in the assessment of rainfall variability' (by F. M. Courtney, *Meteorol Mag*, **109**, 1980, 268–271).

Courtney writes in the summary of his paper that analysis of variance may be an inappropriate technique for assessing the significance of differences between the catch of two or more rain-gauges. This statement may or may not be true; what is certain is that the evidence given in Courtney's paper does not warrant the conclusion given in his summary. I should like to make the following points:

(a) Courtney's conclusion is based on two analyses of variance of weekly rainfall data from Macclesfield Forest. Using 74 weekly rainfall totals from gauges A (ground level, 260 m altitude) and D (ground level, 365 m) he concludes that the variance ratio (between sites/within sites) was 0·0027 with 1 and 146 degrees of freedom; using 75 weekly rainfall totals from gauges B (canopy level, 345 m) and C (ground level, 335 m), his variance ratio was 0·2750 with 1 and 148 degrees of freedom. (In passing, the formula given in the paper for 'within-site' sum of squares is incorrect; this error may, however, be typographical rather than methodological.*)

The error in Courtney's conclusion stems from the fact that he has analysed his weekly totals as a one-way classification, in which all variation, apart from that ascribable to differences between sites, is classed as 'residual' or 'within-cell' variation. Since he used 74 and 75 pairs of (presumably consecutive, or near consecutive) weekly totals for his two analyses, much of the variation that he ascribes to 'within-cells' is seasonal; this seasonal variation will have grossly inflated his within-cell variance, and will largely account for the small variance-ratios of 0·0027 and 0·2750. His conclusion, that analysis of variance may be inappropriate 'in view of the very large 'within-cell' variations that can arise', is therefore unfounded.

It would be a straightforward calculation to reanalyse Courtney's data as a two-way analysis of variance, in which total variation between weekly rainfall totals would be divided into a part ascribable to differences between sites (as before), another part ascribable to differences between weeks (representing the seasonal factor), and a residual part, which would be a good deal smaller than Courtney's within-cell figure. Alternatively and equivalently, a paired-sample *t*-test would be appropriate, as described in the statistical test quoted by Courtney.

(b) Courtney's description of the analyses of variance technique is unclear. Application of the technique, he says, requires that 'the data should be normally distributed, although this requirement is not absolute and can be relaxed to a certain degree'. He also says: 'a further requirement . . . is that the variables are statistically independent. This requirement is not, however, absolute . . .'. It needs to be made clear that the analysis of variance *per se* requires neither that data should be normally distributed, nor that they should be independent; both assumptions are happily dispensed with where, for example, it is necessary to estimate the magnitudes of variance components. Normality and statistical independence are, however, prerequisites for the use of variance ratio tests of hypotheses.

(c) Newson and Clarke (1976), in the reference given by Courtney, concluded from the analyses of variance that the mean catches of ground-level and canopy-level gauges distributed over the Severn experimental basin did not differ significantly; Courtney interprets this conclusion as being at variance with results of other workers. There is, however, no inconsistency here; Newson and Clarke were making the point that differences in catch between ground- and canopy-level gauges were small relative to 'residual' or 'background' variation, which describes how differences between the catches at different sites within the catchment vary from period to period.

(d) Courtney also says 'a further argument against the use of analysis of variance (and indeed of most relatively sophisticated statistical techniques) with rainfall data is that it involves the artificial delineation of units which are analysed as if they were naturally discrete in time'. I do not believe that analysis of variance is a sophisticated technique; even if it were, it no more requires the artificial delineation of units than any other calculation based on rainfall totals.

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* Mr Clarke is correct; $\overline{Y}$ was printed instead of $\overline{Yj}$ (Editor).

To conclude, I would perhaps agree with Courtney that analysis of variance is not a perfect tool for the study of rainfall variability; before a tool is judged inappropriate, however, it should first be used correctly.

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Mr Courtney replies:

With regard to the specific points raised by Clarke:

(a) The 74 and 75 pairs of weekly totals were consecutive except that they excluded mid-winter records. It is possible that the variation is 'seasonal', except that no clear seasonal pattern was discernible: merely in some weeks it rained more than in others. Clarke is saying that the 'within-cell' variation is caused by the seasonal effect—I don't dispute that it may be. My point is simply that it exists. I agree that a paired-sample *t*-test would be appropriate—this was stated in the paper.

(b) Clarke's point is unclear to me. One *can* use any data with any statistical test, but that is not to say that it is correct to do so. The point I was trying to make was that the analysis of variance is usually considered to be a parametric technique. A parametric technique requires that data be normally distributed.

(c) This is an elaboration of the explanation in Newson and Clarke's original paper, which makes an interesting new point.

(d) I do not think we disagree. The truth of my original point that 'analysis of variance with rainfall data involves the artificial delineation of units which are analysed as if they were naturally discrete in time' does not appear to be in dispute. The significance of this point is a matter for subjective judgement and I agree with Clarke that the problem is not specific to analysis of variance.

Clarke's final statement implies that I used analysis of variance incorrectly. Unfortunately, as this correspondence amply demonstrates, 'correct' use of statistical procedures is not an absolute quality. On the 'scale of incorrectness' my use may have been lower down than his, but Clarke's reaction suggests that my original point was well made: analysis of variance and rainfall data are not happy partners.

Comments on 'Computation of vapour pressure, dew-point and relative humidity from dry- and wet-bulb temperatures' (by G. P. Sargent, *Meteorol Mag*, **109**, 1980, 238–246).

The article by Sargent (1980) on the computation of vapour pressure, dew-point and relative humidity deals with only one of the factors contributing to their 'accuracy'. In fact the calibration function aspect that Sargent deals with can be made increasingly 'accurate' but formulae with 10-digit coefficients in sixth-order polynomials are unnecessary and illusory with regard to overall accuracy.

Although modern forms of electrical sensing can give additional sources of error (Revfeim and Jordan, 1976) the simple thermometer reading considered by Sargent has three error components: the resolution of the temperature reading, the calibration function and the spatial variation of the temperature field represented by the sampled reading(s).

It is easier to consider the contribution of resolution errors using the approximate calibration formula

$$e_w = \exp\{7\cdot1-2\cdot5(1\cdot46-t/100)^2\}$$

(Revfeim and Jordan, 1976). Assuming t to be an observation of an observable value T with resolution error δT, a Taylor expansion gives

$$\begin{aligned} e_w(t) &= e_w(T+\delta T) \\ &= e_w(T) + \delta T\, e'_w(T) + \text{higher-order derivatives.} \end{aligned}$$

Now in the exponential form of calibration function the first derivative of e_w is $(1\cdot46-t/100)e_w/20$. Hence the relative error in e_w due to a resolution or reading error, of δT is $\delta T(1\cdot46-t/100)/20$. For thermometer readings δT will be of order 0·1 °C which gives relative errors between 10^{-2} and 5×10^{-3} over the temperature range −40 °C to +50 °C. Compare these relative errors with the calibration function relative error of order 10^{-5}, as calculated by Sargent, and one sees the scope for using simpler calibration functions.

The third error component from variability in the temperature field reduces the contribution from the calibration function to the point of being negligible unless it has a relative error greater than order 10^{-1} (Revfeim, 1978).

The conclusion is that in real applications, calibration functions do not need to be much more complicated than the simple exponential quadratic form given above. In particular since climatological records of vapour pressure are only maintained to 3-digit resolution (Ricketts, 1980) it would be unreal to use formulae with 10-digit coefficients. To misquote Kronecker one is tempted to say 'God created the numbers; man devised the polynomials; all the rest is the artificial accuracy of computers'.

K. J. A. Revfeim

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Ricketts, J. N.	1980	World surface climatological data—methods of quality control and archiving. *Meteorol Mag*, **109**, 325–330.
Sargent, G. P.	1980	Computation of vapour pressure, dew-point and relative humidity from dry- and wet-bulb temperatures. *Meteorol Mag*, **109**, 238–246.

Mr Sargent replies:

Revfeim goes to some trouble to show what one intuitively knows, namely that it is a waste of time and effort chasing accuracy in one part of a system if a similar accuracy is not achieved throughout the rest of the system. With a simple dry- and wet-bulb psychrometer the errors due to reading, exposure, ventilation etc. are of such magnitude as to make the use of very precise approximations to the saturation vapour pressure nonsensical and it was for this reason that simpler, less accurate approximation formulae were included in the article.

However, there may well be occasions when work is being done under very carefully controlled conditions with very accurate equipment when a high degree of precision is required. The Goff–Gratch formulations are themselves only approximations to the 'truth', albeit generally accepted as the best available, and if it is desired to make the computation simpler the closer one can get to these 'best approximations' the better. It is for the user to decide what degree of accuracy is necessary in a particular set of circumstances, but it is far easier to degrade accuracy by truncating coefficients than to regain it once the discarded digits are lost.

Reviews

Ball lightning and bead lightning: extreme forms of atmospheric electricity, by James Dale Barry. 150 mm × 230 mm, pp. x + 298, *illus.* Plenum Press, New York, 1980. $29.50 (+ 20% outside USA).

Although descriptive accounts of lightning exist in the scientific literature, there are a number of important gaps in our understanding of the physics of the discharge. The rarity of the natural phenomenon, its high energy density and the inaccessibility and rather small scale of many of the important processes, combine to present great problems for any experimental, and hence theoretical, study. These difficulties have been so severe for the subset of discharges known as bead and ball lightning, as to place them on the fringes of myth and illusion.

This book is the second in recent years to attempt a review of the evidence for ball lightning; the first was Singer's *The nature of ball lightning*, Plenum Press, 1971. Both authors, faced with a dearth of planned scientific observation, have been forced to make maximum use of serendipity. Unfortunately, the careful investigation of 200 years of accidental glimpses of the phenomena demands considerable scholarship, but the result makes rather tedious reading. With the advantage of Singer's exhaustive review before him, Barry has avoided a detailed description of the vast number of narrative reports and discussions of ball lightning and concentrated his attention on some specific topics. Nevertheless, a substantial fraction of his book is taken up with the minutiae of photographic evidence, much pored over in the past and now listed, cross-referenced, described again, and in most cases discarded as of doubtful validity and/or of little value. The bibliography occupies a third of the book. Doubtless this will be of use to a small number of researchers, but to most readers it is likely to remain a formless and indigestible list.

The author's expressed intention is to emphasize the physical aspects of the chosen discharge phenomena such as their dimensions, luminosity, motions, form of decay, and their effect on their observers and environment. From these he attempts to deduce properties such as temperature, mass and energy density. This is done very superficially for bead lightning but a comprehensive statement is provided of the observed and inferred properties of ball lightning. Much is made of the author's previously published thesis that the deduced energy density of ball lighning is normally distributed and that this suggests a single common form for the object. Neither the adopted methodology for this analysis nor its conclusions are persuasive.

The major remaining section of the book is devoted to a discussion of laboratory or field studies which have produced small-scale luminous phenomena. These include localized burning processes requiring combustible gases, the thermal emission of metal-vapour residues and the relaxation of molecules from metastable states with the emission of visible radiation. The treatment of the physical processes involved is always incomplete and usually superficial. Their relevance to bead and ball lightning remains obscure. The question of containment is avoided or, where identified, as in the case of the magnetic pinch, described only in qualitative terms. This is the closest Barry comes to an evaluation of the many theories which have been proposed to account for bead and ball lightning.

One is left with the impression of some careful and diligent detective work brought to bear on a difficult subject, but without great authority or insight. It is not possible to recommend ownership of the book to the interested non-specialist, but a few hours' reading of Chapters 3, 4 and 7 of a library copy will provide a useful guide to some current thinking.

P. Ryder

Agro-meteorology, by J. Seemann, Y. I. Chirkov, J. Lomas, and B. Primault. 240 mm × 170 mm, pp. vii + 324, *illus*. Springer-Verlag, Berlin, Heidelberg, New York, 1979. Price DM 98, US $53.90.

Agricultural yields and profits in the developed world depend upon the weather. Our very survival is determined by weather in some parts of the developing world. The sorts of agriculture that are possible at a particular place vary with climate. These facts have forced the farmer and the agricultural scientist into a wary determination to outface and overcome the weather and to understand the relations between weather, climate and agriculture.

Both climate and weather are difficult terms to define. Lamb has defined climate as comprising 'the totality of weather experienced at a given place' and has suggested that we may think of it as 'long range meteorology'. In agricultural meteorology we can think of weather as being the real atmospheric conditions experienced in a particular place at a particular time. The actual yield of a crop or the production of an animal will depend, in part, upon the direct influence of weather on the biological system and upon the influences of weather on pests, diseases and the timeliness of farming operations. Clearly, these relationships are complex and our understanding is, therefore, usually partial and often inaccurate.

However, there is a substantial body of operational achievement, including the estimation of the irrigation requirement of a crop and the forecasting of the development of a disease. There are also growing, but still insufficient, intellectual achievements, such as our understanding of the relationship between solar irradiance, canopy size and structure, photosynthesis, and the rate of growth of a crop. It was inevitable that the operational aspects have been developed by the national organizations for weather forecasting. It is unfortunate that, in general, these national organizations have not been allowed, or perhaps have not been able, to play a larger part in the intellectual development, which has generally fallen to research institutes and university departments.

This book shows the catastrophic consequences of the separation. It is the result of an initiative taken at a meeting of the Commission for Agrometeorology of the WMO. There are two parts to it, one dealing with the 'Physical and Meteorological Principles of Agrometeorology' and the other dealing

Plate I. The Main Enhancement to the Bracknell automated Meteorological Telecommunication Centre becomes operational—7 February 1981.
Seated, left to right: Mr G. Dootson, Ferranti Ltd and Mr K. W. Hathaway, AD Comms 2. Standing, left to right: Dr D. N. Axford, AD MetO(TC), Mr S. Thomas, Ferranti Ltd, Mr P. Caswell, Ferranti Ltd and Mr C. E. Goodison, Met O 5 (See facing page).

with 'Applied Agrometeorology'. The first manages to omit much that is important, such as any real consideration of the exchanges between crop and atmosphere, and to include the trivial, such as a description of a 'Weathercock without Vane (Direction)'. The authors do not separate agricultural climatology from agricultural meteorology nor do they use the scale of the processes involved in the exchanges of energy and matter to organize and simplify.

The second part, called 'Applied Agrometeorology', follows directly, without any considerations of biology, agriculture or the study of systems. It becomes an unavoidable still-birth, devoid of any possibility of intellectual life. Again, it is incomplete. In places, as in the chapter on irrigation, it is a pretentious and unscholarly assemblage of an ill-selected number of publications. In other places, as in the chapter on the 'Epidemiology of Insects and Other Diseases' (*sic*), the authors avoid all discussions of the practical and useful.

I guess that the book was written in response to the recognition of real needs, intellectual and practical. I guess that it was written, perhaps under pressure, by busy men. I am sorry that it was written and hope that it does not represent the present form or future direction of agricultural meteorology.

J. Elston

Notes and news

The Ferranti enhancement to the Bracknell automated Meteorological Telecommunication Centre (Met TC) becomes operational

The technical transfer of the Ferranti enhancement to the Telecommunication computer complex in the Bracknell Regional Telecommunication Hub took place on Tuesday 7 February 1981 (see Plate I). This Argus 700S dual computer system increases Bracknell's capacity for handling medium-speed lines from 7 to 20. Up to 13 new channels are provided at speeds ranging from 1200 bits per second to 9600 bits per second, allowing a maximum total throughput of 10×10^6 characters per hour. The Bracknell automated Met TC is now one of the most powerful message-switching complexes in the WMO Global Telecommunication System. At present there are medium-speed connections to Washington, Paris, Offenbach, De Bilt, Dublin, Oslo, and the European Centre for Medium Range Weather Forecasts, and plans are in hand for links to Belgium and Iceland in the near future.

The Ferranti Argus 700S computers are built with fast emitter-coupled logic. There is a main store of 96K 16 bit words (32K words of fast semiconductor memory and 64K words of ferrite core memory). There are three input/output sub-processors, two 80 megabyte moving-head discs and two fast access 2 megabyte head-per-track discs, with off-line spares of each type. Two visual-display units are mounted in a control-and-status console for control and reject operation, and push buttons control and display the status of the various channels and peripherals. The software consists of a comprehensive set of 130 application modules directed by a basic Ferranti operating system. These application modules carry out the specialized message-switching functions, such as queuing, scheduling, and statistical monitoring, required of the enhancement.

The contribution of marine meteorology to economic development

(based on a WMO Press Release)

The tourist enjoying the sunshine on the beach outside his fine new hotel and the port construction engineer exposed to cold and damp working conditions may seem to have little in common. Yet each is equally dependent upon weather and sea conditions, and the chances are that the changes which each would strongly dislike, rain, wind, swell and so on, would largely have their origins in ocean areas. The seas and oceans of the world cover over two-thirds of the surface area, and if the land masses were to be skimmed off at sea level, they would be easily accommodated in the ocean space available. This simplification emphasizes the dominance and potential power of the oceanic regions, and it is natural that mankind became aware many years ago of the need for scientific study of all aspects of the oceans and their behaviour. To ignore the results, often hardwon, of those long years in a world where the problems of space, natural resources and social and economic development require unstinting attention would be unsound.

Fundamental to most sciences is measurement; for the oceans, this means observations, both visual and instrumented, and, equally vital, recording of this information. Despite centuries passing since man first put to sea, few data were collected and rarely combined with other information. It was as late as 1853 before the first international agreement upon some uniformity of observation, and agreements upon exchange of data were achieved. In the subsequent years, the use of ships to collect routine and regular observations, whenever at sea, has grown tremendously, there being now some 7000 registered voluntary observing ships. The volume and density of data over the oceans, however, remains very variable—ships have their 'roads' too, and in many regions the information level is still sparse. Whilst this is the position for observations made on the surface of the sea, the situation with regard to underwater observations is very much worse. These data have only been collected routinely for some 30 years apart from scientific cruises and research, and rapid growth is now being supported. In order to apply this resource of data and the applications derived from it to development requirements, it is helpful to appreciate the foundation of the support. Today's marine meteorological and oceanographic data banks use high-speed computers to accommodate their holdings, and data are being collected steadily every day. Even though more are needed, the important feature is that many and varied services are available based on these data, and more and more highly specialized support to engineering, industrial, and social and economic development is being introduced.

As for more information services, one of the strengths is the strong liaison between the service and the user which is created, and that a contribution is made by both sides. In the same way that mariners obtain radio weather forecasts which have made use of information and weather reports from the mariner in their production, so any development study needs to be assisted in determining what further information or data must be obtained. It is only against the background of already acquired knowledge that proper and reliable judgement can be made. The early explorations and development for oil and gas in the North Sea region formed a good example of this situation. In a relatively small sea area, not far offshore with large amounts of data available from land station records, the operators were surprised to find that the detailed information and support they needed was not available. The reason, valid for many developments to come elsewhere, was that such detailed questions, as, for instance, when will the waves next be less than two feet for 36 hours, or what is the maximum rate of wind direction shift and what force will this have on a buoy, had never been posed against real operations. That the marine meteorological services were able to find the answers and establish regular support services to deal with many other complex problems as they arose, all realized in full association with the operators themselves, shows the benefits which can be achieved.

The contribution which can be made to a coastal or estuarine development is also significant. A study of past marine meteorological data can throw light on many development aspects. With computer models, hindcast techniques and forecast programming, considerations of potentially critical factors can be completed. The risks to a coastline of flooding by surge or storm effects, and the engineering requirements of dykes, harbours, barrages, the frequencies of high or storm winds for cabling, high structures and the maximum 100-year values, the probable pattern and effects of pollution in a sea or coastal chemical plant development, the choice of sites for new developments, the architectural limits and land reclamations, these are all matters for which marine meteorology and related services provide an early basis, and should play a full part in planning and studies and, later, be closely involved in continuing support.

Economic developments carry many implications for trade and food production. The marine meteorological services of today provide world-wide support to international shipping and to fishing industries. Thanks to the World Weather Watch (WWW), the international exchange of data, including all reports from ocean areas, has been established. This today also includes data from satellites scanning the oceans, aircraft and buoys at sea, combining both surface and upper-air information for the marine meteorologists to use in producing warnings, forecasts and detailed special support, as required. The costs of fishing operations, for instance, must be minimized, and services aid trawlers to choose good fishing grounds, know their predicted movement, and avoid weather which would interrupt fishing. As the need for natural resources to be carefully used increases, the support services will be called upon for more specialized and detailed advice, both for planning and operations, as is now the case for the energy industry offshore.

The capability of the WWW Global Data-processing System (GDPS) for ocean-wide analysis and forecasts, with the use of numerical prediction techniques on the marine meteorological data originating in the WWW Global Observing System (GOS) and collected by the WWW Global Telecommunication System (GTS), which supports all these marine activities, also provides for a further service of economic importance. This is 'ship routeing' for long ocean passages of passenger and cargo vessels. Vessels may need the quickest total passage time, avoiding head seas, strong winds and currents and icebergs, may need calm and dry conditions throughout to protect cargo, or to be certain to reach a port at a specific time. Specialist marine meteorological ship-routeing officers evaluate storm movements and predicted paths, waves, swell and surface currents, as they affect the particular vesssel concerned, and knowing its physical characteristics, and knowing the ship's requirements, advise the ship's master before and during the voyage. Savings of one to two days per vessel per passage can be obtained and the total benefit to the costs of operating a major vessel are highly significant. The growth of world trade can be expected to place greater demands upon this type of service over the next decade.

It is clear that the applications and services now being provided from the meteorological and oceanographic data arising from past and present marine activities are making a positive contribution to many aspects of social and economic development. In the future, these services will need to be certain that they can expand and become more specially tailored to meet demand, as the economic needs of the world are themselves established. With the ever-growing use of automated observation systems at sea and in the atmosphere, the advances foreseen in data-processing technology, telecommunications, and the techniques of prediction, there should be no doubt that marine meteorology will do so. As the oceanic regions will no doubt be unlikely ever to give up their majestic authority, so mankind must continue to look to the sea, but must ensure they have the fullest understanding and use it to the greatest possible extent.

THE METEOROLOGICAL MAGAZINE

No. 1307 June 1981 Vol. 110

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1.80 monthly
Dd 716670 K15 6/81

Annual subscription £23.80 including postage
ISBN 0 11 726283 8
ISSN 0026-1149

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

July 1981

Met.O. 942 No. 1308 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1308, July 1981, Vol. 110

551.594.221:312.26

Lightning fatalities in Singapore

By J. E. Pakiam[1], T. C. Chao[2] and J. Chia[3]

Summary

A study of the statistics of lightning deaths and the correlation with social and environmental circumstances was conducted for the island Republic of Singapore. While data were available as far back as 1922, the lack of recorded details of the circumstances of death resulted in a smaller data base for analysis.

Data were analysed for significant patterns or changes in lightning fatalities per million population, sex composition, age, monthly variation, diurnal variation, location, recreation/work ratio, elevation, severity of lightning incident, type of bodily injury, ratio of deaths to injured in an incident, and lightning fatality risk in Singapore.

The results of the analyses were compared with those of studies undertaken in temperate countries. As a result of the study, personal safety rules relevant to the Singapore environment have been proposed.

1. Introduction

Several detailed studies have been made on the statistics of lightning fatalities. In particular, Zegel (1967) surveyed lightning deaths in the USA from 1959 to 1965 and Prentice (1972) conducted a 25 year study (1945–69) on fatalities in Australia. Other countries with statistical studies include Republic of South Africa, German Federal Republic, Austria, Hungary and United Kingdom.

With its high thunderstorm frequency, the island Republic of Singapore seemed a good choice for a study of lightning deaths in an equatorial location. Data sources were (a) Meteorological Services Singapore, (b) Coroner's Courts, (c) Report on Registration of Birth and Deaths, (d) Department of Pathology, Ministry of Health, (e) daily English and Chinese newspapers. Individual deaths due to lightning could be traced back as far as 1922, but details of cases were only available from 1956 onwards. However, even from 1956, not all relevant data in each case were available. This lack of data showed up in the various forms of analysis attempted.

2. Thunderstorm and lightning frequency and distribution

Singapore experiences an average of 181 thunder days and 229 lightning days per annum (1961–78 average). These numbers may vary quite substantially from year to year (Fig. 1). The annual number of thunder days has varied from 150 to over 200, and that for lightning days from 150 to close to 300.

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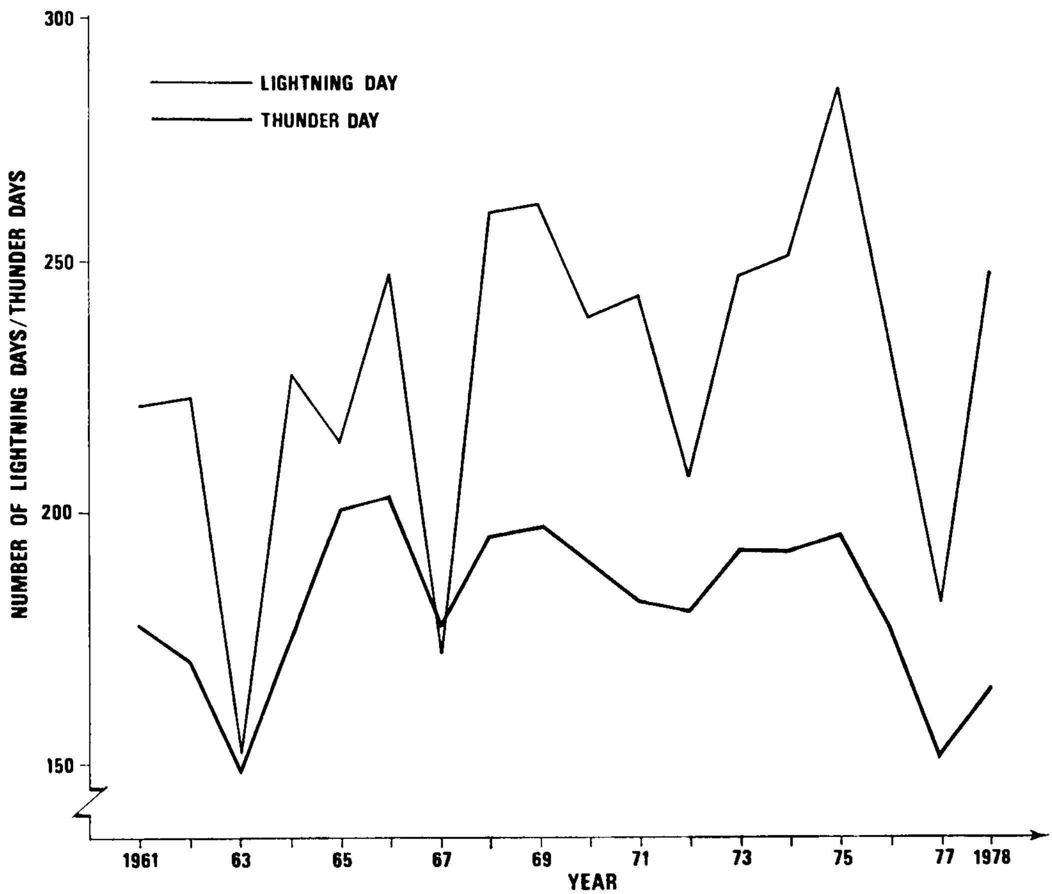

Figure 1. Variation of annual lightning days and thunder days in Singapore, 1961–78.

The seasonal distribution of the number of thunder days and thunderstorms is bimodal (Fig. 2). Two peak periods in April and November with about 20 thunderstorm days/month are separated by minima of 5 and 15 in January and July.

As might be expected, most of the thunderstorms occur in the late afternoon (Fig. 3).

3. Lightning fatalities/million

Lightning fatalities/million population were calculated for the period 1922–79 and are plotted in Fig. 4. Data for the year 1938 were not available. A unitary filter of order 4 (0·125, 0·250, 0·250, 0·250, 0·125) was also plotted (Craddock, 1968).

The graph shows a gradual decrease in lightning deaths/million over the 58 year period. This can be more readily concluded when the means for the periods 1922–1941, 1942–1960 and 1961–1979 are calculated. The mean number of deaths/million for these periods is 2·6, 1·8 and 1·7 respectively. These values show that, in recent years, the number of lightning fatalities has remained constant at about 1·7/million.

Other countries such as USA, Australia and the U.K. (Zegel 1967, Prentice 1972) show a similar

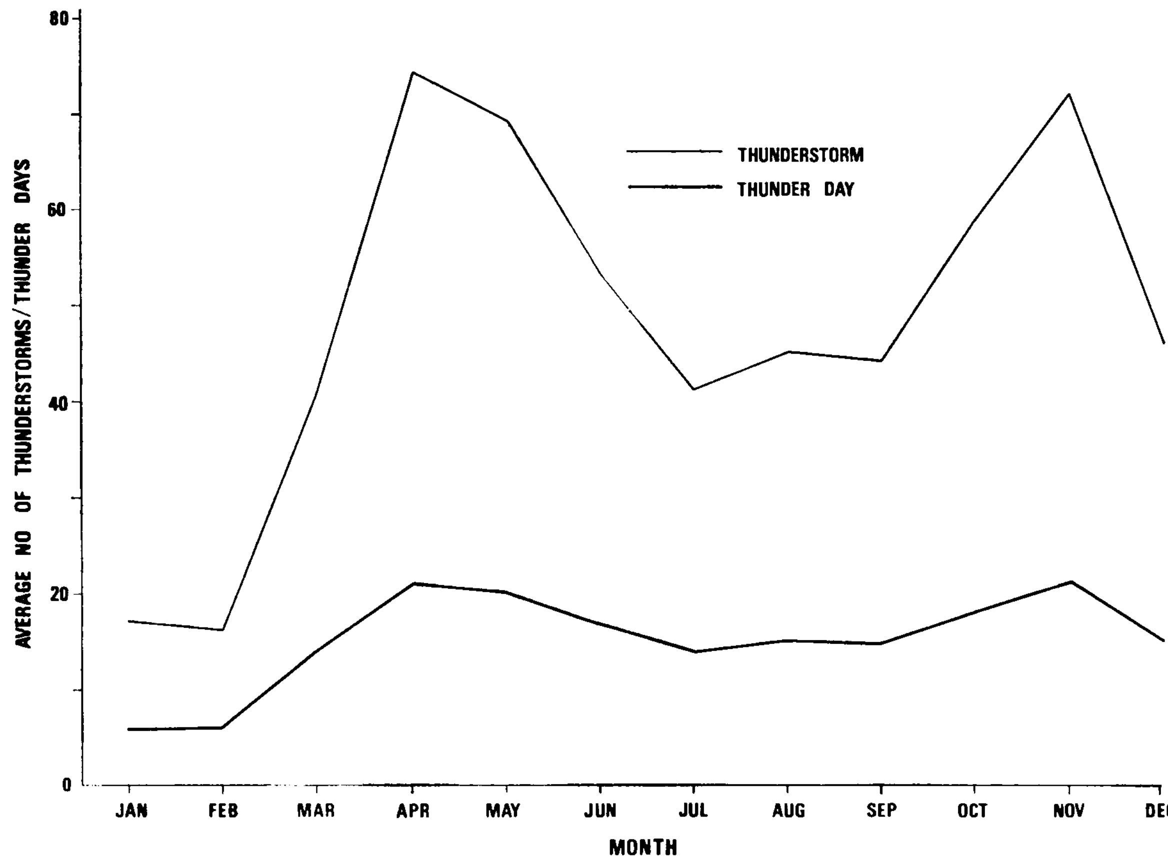

Figure 2. Average number of thunderstorms and thunder days per month in Singapore, 1961–78.

declining death rate, owing to better public education and increasing urbanization. Values of death rates for other countries and a comparison with Singapore are given in Table I.

The table shows that Singapore has the highest death rate of those countries examined. This may be attributable to the year-round high thunderstorm frequency.

Table I. *Comparison of death rate/million for various countries*

Country	Period	Death rate/million per annum
United Kingdom	1951–60	0·2
Australia	1950–60	0·4
United States of America	1959–65	0·6
German Federal Republic	1952–60	0·8
Austria	1964–68	1·3
Republic of South Africa	1963–69	1·5
Republic of Singapore	1961–79	1·7

4. Sex composition

For the years 1956 to 1979, there were 80 deaths, of which 66 were male and 14 female. The male/

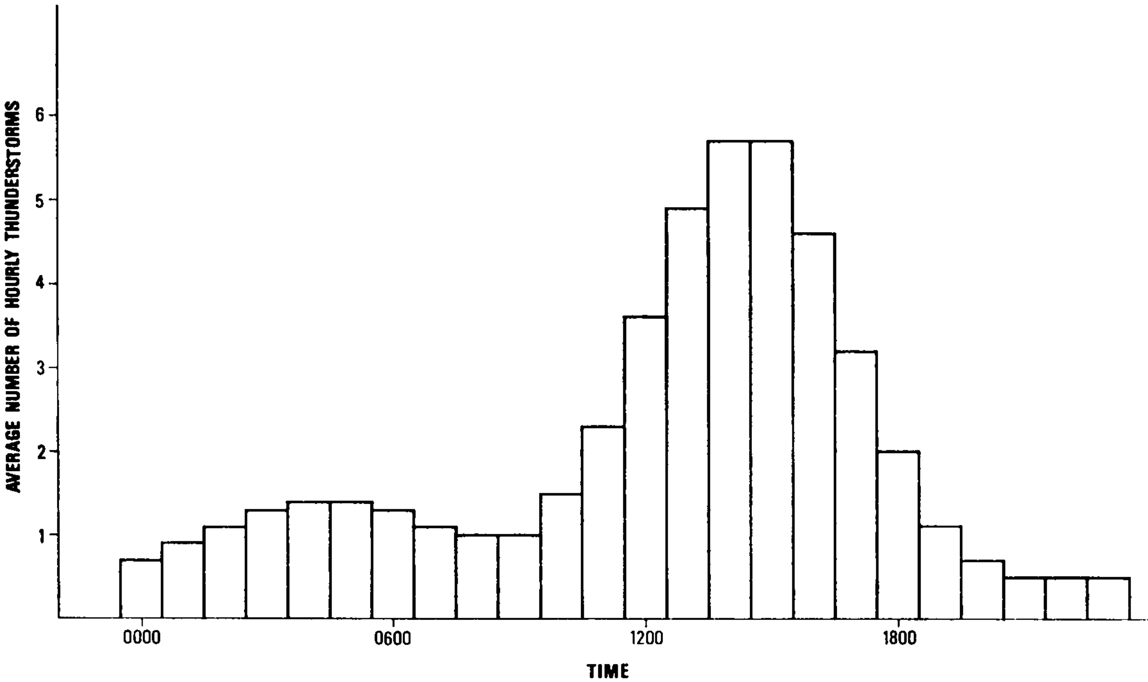

Figure 3. Diurnal distribution of hourly thunderstorms in Singapore (local time).

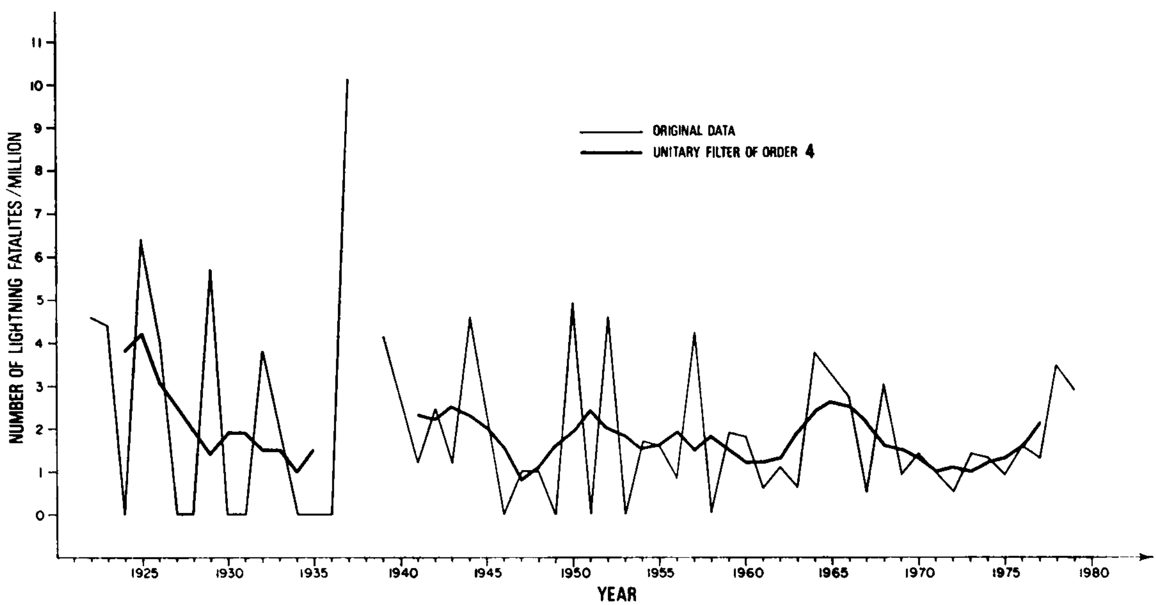

Figure 4. Annual variation of the number of lightning fatalities per million population.

female ratio is 4·7. Females only accounted for 17½% of the total fatalities, though the female sex composition for the whole population in 1967 was 48%.

The disproportionate number of female deaths can be attributed to the nature of work, with most outdoor activities being performed by males.

Similar high male/female ratios have been recorded in Australia (4·5) and USA (death and injury, 3·0–5·7).

5. Age

Table II gives the distribution of deaths caused by lightning accidents by age group for the 24 years of record. The greatest number of deaths occur in the age groups of 10–19 and 20–29. A comparison with the age distribution of Singapore's population for 1967 shows that about 58% of the deaths occur in these age groups, representing 38% of the population.

Young people are prone to lightning accidents because of their ignorance of dangers involved when lightning is nearby. The age group of 20–29 would also include those able-bodied workers who could be working in the open and who probably did not exercise the necessary precautions.

Comparison with other countries shows similar statistics. In the USA, 22% of those killed by lightning were under 18, whilst in Australia, 23% were between 10 and 19 and 30% between 20 and 29.

Table II. *Distribution of lightning deaths by age composition for* 1956–79.

Age group *Years*	Number of fatalities	Percentage of total number of deaths	Percentage of age group of total population for 1967
0–9	7	8·7	29·5
10–19	25	31·3	24·5
20–29	21	26·3	13·9
30–39	12	15·0	11·8
40–49	13	16·3	8·6
50–59	1	1·3	6·7
60–69	1	1·3	3·6
70+	0	0	1·4
Totals	80	100	100

6. Monthly variation of lightning deaths

Fig. 5 shows the distribution of the number of lightning fatalities by month for the period 1956–79. The maximum number of deaths due to lightning occurs in the month of November. This is 20 times more than the minimum which occurs in July. The second highest monthly death toll occurs in April.

The peak monthly periods of death correlate well with the peak monthly periods of thunderstorm activity (Fig. 2).

7. Diurnal variation of lightning deaths

Only 47 cases out of 80 had times of death recorded. The diurnal variation of these times of deaths is shown in Fig. 6.

A maximum is observed at around 1500–1600 hours local time. No deaths are recorded after 1830 hours and before 0500 hours. About 65% of deaths occur between 1330 and 1630 hours.

A comparison with the diurnal variation of thunderstorm (Fig. 3) shows good correlation of peak hours.

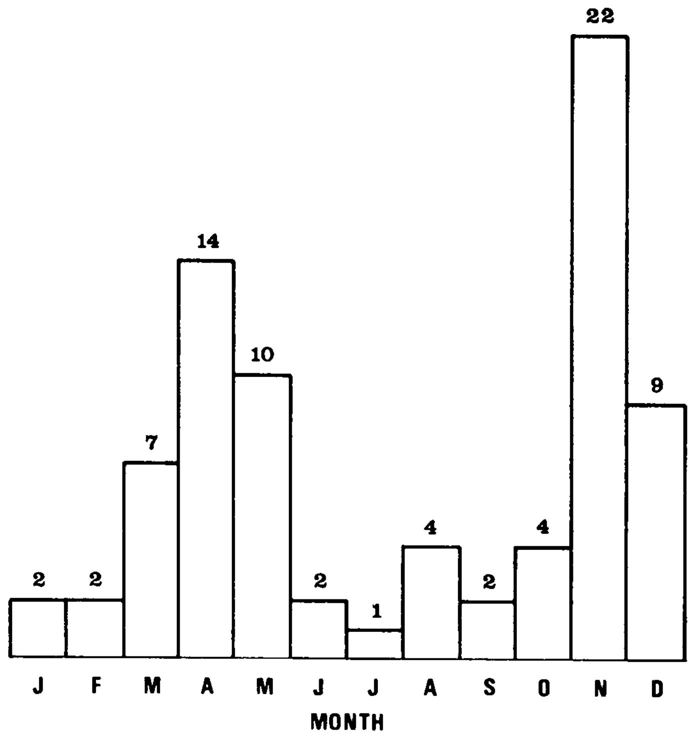

Figure 5. Number of lightning deaths per month for 1956–79.

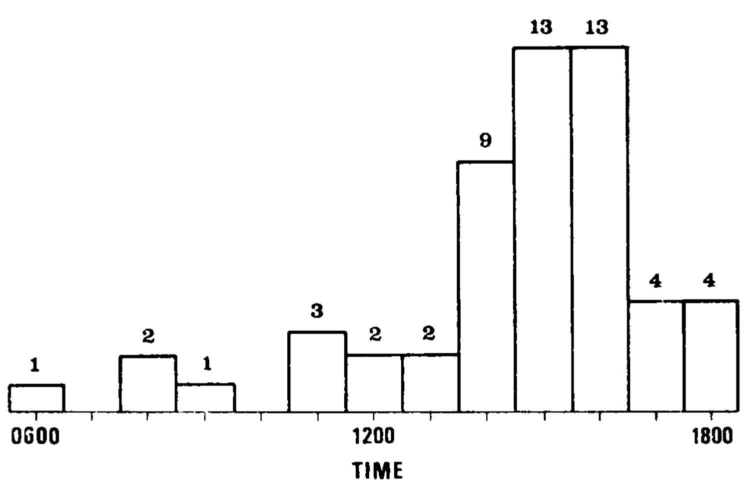

Figure 6. Number of lightning deaths by time of day.

Comparison of times of death with other countries shows good agreement. Table III gives the percentage of deaths in different time periods for USA, Australia and Singapore.

Table III. *Percentages of deaths in different time periods for different countries*

Country	1200–1800	Time of day 1800–0000	0000–0600	0600–1200
USA	70	20	1	10
Australia	85	4	11	
Singapore	80	7	0	13

8. Location of lightning fatalities

Data were categorized into two broad groups—sheltered and open areas. From a study of the records, sheltered areas were found to be either (a) wooden huts and sheds, typically with a galvanized iron roof (or, in earlier times, an attap* roof) or (b) trees. No deaths were recorded when sheltering in substantial, protected buildings. Open areas comprised (a) small, open or partly covered, wooden boats, (b) sea or beach areas, (c) rooftops, (d) golf courses, (e) football fields, (f) animal-feeding areas, (g) other, including hilltops and slopes.

Table IV shows the fatalities classified into the different categories.

Table IV. *Location of lightning deaths.*

Location		Number of fatalities	Percentage of total
Sheltered	Hut, Shed	13	24
	Tree	5	9
Open	Boat	7	13
	Sea or beach	8	15
	Rooftop	3	6
	Golf course	1	2
	Football field	3	6
	Feeding animals	2	4
	Other	12	22
Total		54	

Thirty-three per cent of those killed were sheltering while 67% were killed in the open. The highest number of fatalities (13) were those sheltering in huts or sheds. These are low unprotected shelters, usually sited close to trees or in open areas. A significant number of fatalities (8) occurred on beaches or in shallow water and a comparable number (7) occurred while travelling on boats.

Other countries show similar statistics. Australia (Prentice 1972) recorded 63% of deaths in exposed areas and 32% in sheltered areas. The USA (Zegel, 1967) recorded 11% of deaths under trees (Singapore, 9%) and 8% in open water (Singapore, 13%).

A location map of all lightning fatalities with a recorded location is given in Fig. 7. The total number of data points is 72. The map shows that urban built-up areas with high population densities are much safer than rural, open areas.

9. Recreation/Work ratio

A study was carried out on the activity undertaken by a person while struck and killed by lightning.

* Attap (also spelt atap) = the nipa palm, the leaves of which are used for thatching.

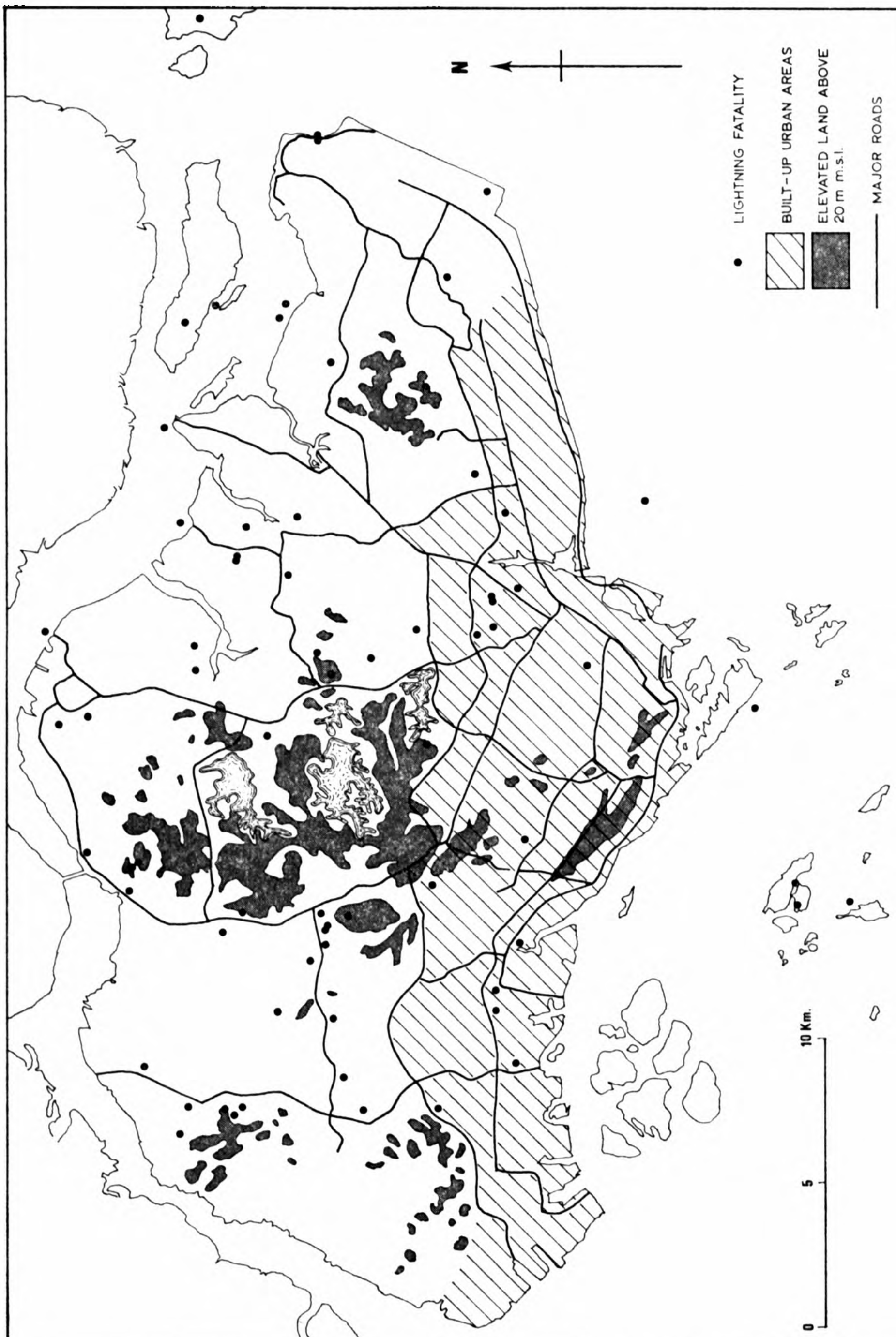

Figure 7. Location map of lightning fatalities in Singapore, 1956–79.

Activities were classified into the three categories of 'Work', 'Recreation' and 'Indefinite'. A working definition of each category is given below:

(1) Work category: Any person who is exposed to lightning injury risk by being compelled to remain outdoors, and shelter under trees or in huts by nature of his work. Besides workers, this category also includes workers running for shelters, people travelling to work, etc.

(2) Recreation category: Any person who is exposed to lightning injury risk by his own volition.

(3) Indefinite category: Any person whose circumstances of death are unknown.

Data were further subdivided as to whether the person killed was on foot, on bicycle or in a boat. Analysis was first carried out for exposed locations and then for sheltered locations. The results are presented in Tables V and VI.

Table V. *Activity undertaken while in exposed location.*

	Work	Recreation	Indefinite	Total
On foot	14	12	2	28
On bicycle	0	0	1	1
On boat	4	2	1	7
Totals	18	14	4	36

Table VI. *Activity undertaken while in sheltered location.*

	Type of location							
	Trees				Huts/sheds			
	Work	Recreation	Indefinite	Total	Work	Recreation	Indefinite	Total
On foot	0	2	2	4	10	1	2	13
On bicycle	0	0	1	1	0	0	0	0
On boat	0	0	0	0	0	0	0	0
Totals	0	2	3	5	10	1	2	13

The tables show that the majority of people killed were on foot (45 or 83·4% of total deaths), 28 (51·8%) were in exposed locations and 17 (31·6%) were in sheltered locations. Two (3·7% of total) were killed while travelling on bicycle while 7 (12·9% of total) deaths were recorded while travelling in a boat. The number killed in the work category was 28 and the number killed in the Recreation category 17, giving a Recreation/Work ratio of 0·61.

To determine whether there were any changes in Recreation/Work ratio patterns over the years, the study period was divided into two eight-year periods, 1965–72 and 1972–79, and the Recreation/Work ratios calculated (Table VII).

Table VII. *Recreation/Work ratios for* 1965–72 *and* 1972–79.

	Work		Recreation		Indefinite			
Period	No.	Percentage of total	No.	Percentage of total	No.	Percentage of total	Total No.	Recreation/ Work ratio
1965–72	16	64	7	28	2	8	25	0·44
1972–79	14	44	11	34	7	22	32	0·79

The Table shows a notable change in recent times to higher Recreation/Work ratios (0·79) from earlier years (0·44).

Comparison with Australia shows that 34% (Singapore 51·8%) were killed while on foot in the open, 31% (Singapore 31·6%) while sheltering and on foot, while 22% (Singapore 16·6%) were killed while on horseback or in an open vehicle. In terms of Recreation/Work ratios, Australia in recent times (1957–69) had a ratio of 1·0 compared to only 0·43 for the period 1945–57 (average over entire period was 0·60). Such trends towards higher Recreation/Work death ratios in recent years have also been noted in the USA.

10. Elevation of site of fatality

A topographic map was used to determine the elevation of the site of fatalities. A graph of the number of deaths against elevation was plotted (Fig. 8). Most of the deaths occur in low-lying areas with very few fatalities at higher elevations. The reason can be deduced from Fig. 7. The areas with elevations exceeding 20 m above m.s.l. are either catchment or reservoir areas which are sparsely populated.

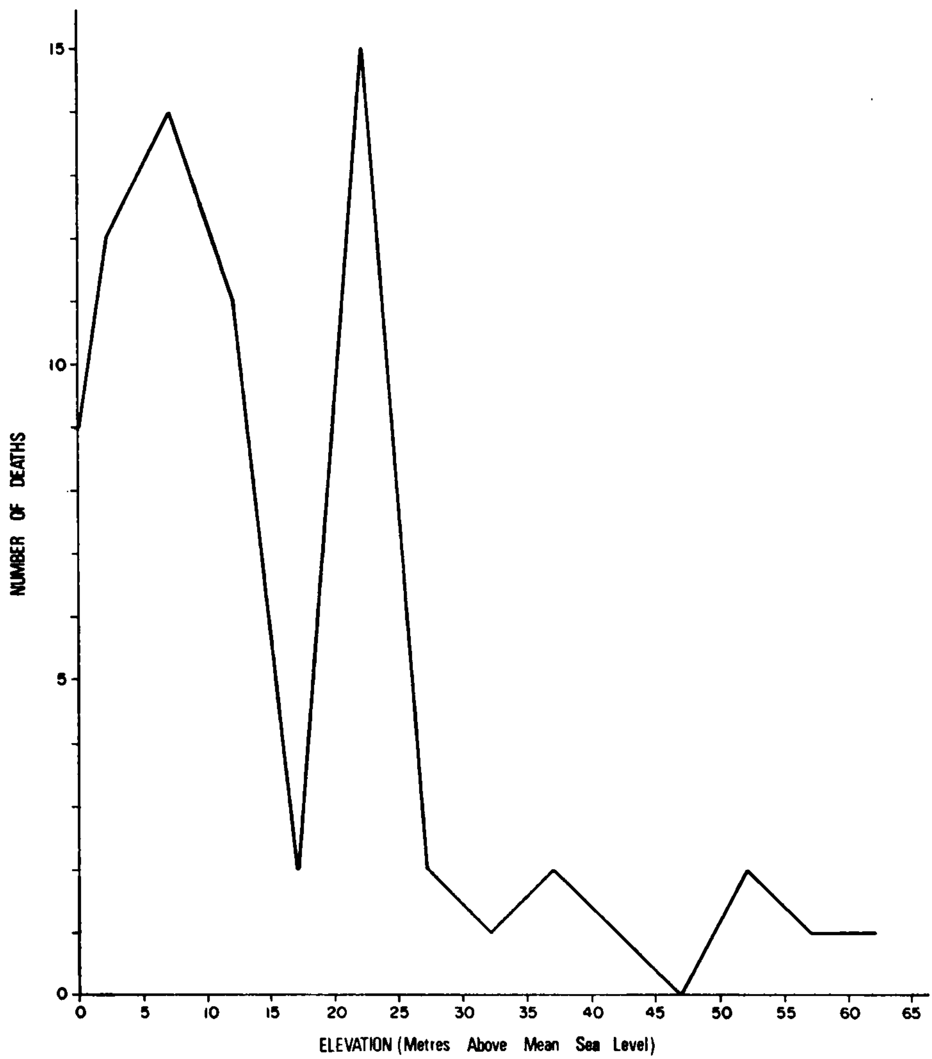

Figure 8. Relationship between lightning fatalities and elevation.

11. Severity of lightning accident

Of 54 fatalities investigated, 46 incidents resulted in single deaths (85% of total deaths) and 4 incidents resulted in 2 deaths (15% of total deaths). Of these 4 incidents, one occurred on a boat, one inside a hut, one on a beach and the last on a football field. If the criterion for most severe incident is taken as the most number of deaths followed by the most number of injured, then the most severe lightning incident occurred when a group of school-children, having a picnic on the beach, were struck, resulting in 2 deaths and 5 injured.

Compared with the USA, Singapore experiences about the same percentage of double deaths as the USA (15%), but the USA has 15% of fatalities occurring with 3 deaths or more and a smaller number (70%) of single deaths. The literature also reports a number of instances in other countries with multiple deaths. Singapore, in the 24 year period of study, has been fortunate in not having such severe incidents.

12. Type of bodily injuries

Only 39 cases had postmortems available for study. Injuries were classified and their relative frequency calculated. The results are given in Table VIII.

Table VIII. *Frequency of types of injury associated with lightning death.*

Location of injury	Number	Percentage of total
Head, face, neck	29	74
Chest	4	10
Abdomen	3	8
No external injuries	3	8

From the table, it can be noted that a direct strike, with current passing through vital organs (brain or heart) accounted for 84% of deaths. So far as has been documented in recent years in Singapore, only one person has been known to have survived a direct strike to the head. This investigation will be documented in a separate paper.

13. Ratio of injured to dead

It is not known how many people receive minor injuries or shocks due to lightning and either recover at home or are treated medically and discharged. The information that is available is the number of people injured and treated at hospital as a result of association with a lightning incident resulting in death. The total number of injured associated with 54 lightning fatalities has been ascertained to be 54, distributed in the following manner (Table IX). The ratio of injuries to death for Singapore is therefore 1·0.

Table IX. *Number of injured associated with a lightning fatality*

Number of persons injured in an accident	Number of incidents resulting in deaths	Total number injured	Comments
0	28	0	
1	12	12	
2	3	6	
3	2	6	
4	1	4	Timber loading, open area, low-lying.
5	1	5	Schoolchildren, picnic on beach.
7	3	21	Two incidents involving groups of people on hilltop. One incident involving a wooden boat.
Totals	50	54	

As far as other countries are concerned, evidence presented by Golde (1976) for Austria and Hungary showed a ratio of 2 injuries for every fatality.

The Singapore ratio is lower than for other countries, perhaps because there are fewer group activities, especially recreational ones, where large groups of people may be affected by a single lightning flash.

14. Lightning fatality risk in Singapore

The average number of deaths per annum in Singapore over the last 24 years is 3·3.

The number of lightning strokes to earth per annum may be deduced from a number of studies. Stanford Research Institute has estimated the number of ground strokes per km^2 per thunderstorm day per annum for different latitudes (Pierce *et al.* 1962). For Singapore, the upper limit is about 0·06. The number of lightning strokes to earth is therefore 0·06 × 600 km^2 × 200 thunderstorm days = 7200/annum.

Another study by Müller-Hillebrand (1965), corrected for latitude, gives the number of ground strokes per 100 km^2 per 10 thunderstorm days as about 100 for Singapore. The total number of strokes is 100 × 6 × 20 = 12 000/annum.

From these two studies, an estimated value of the number of strokes can be taken as 10 000/annum. This implies that 1 in 3000 ground strokes in Singapore results in a fatality.

15. Personal safety in Singapore

Taking into account the nature and location of lightning fatalities in Singapore, a simple set of rules for personal safety may be drawn up.

(a) *Time of commencement of precautionary measures.* The major personal protective measure taken by the layman against the vagaries of the thunderstorm is to avoid getting wet. However, a downpour may drench but will not kill a healthy person as may a lightning flash. Since lightning activity in an area does not necessarily correlate with the heaviest rainfall in that area (very often, lightning occurs when rain is not falling and it may still continue when the rain has ceased), precautions against being struck by lightning should be taken independently of the fear of getting wet. A good procedure in a lightning storm is to count the interval between a lightning flash and the accompanying thunder. An interval of three seconds implies that lightning is about one kilometre away. It is suggested that precaution be taken when the time interval is 20 seconds and shorter, whether the storm is approaching or receding.

(b) *Target audience.* The age group to be educated on lightning hazards is mainly the 10–29 year old group who comprise 58 % of all deaths. Thus, schoolchildren appear to be the target audience. In view of increasing recreation/work death ratios in recent years, emphasis must be placed on hazards due to recreation.

(c) *Precautionary measures*

(i) Seek shelter in a substantial well-grounded building or within a metal-bodied vehicle (e.g. a motor vehicle). Urban, built-up areas are safe. If one is forced to seek shelter in an unprotected wooden shed or building, keep away from metal objects, metal pipes, electrical wiring and wooden beams or walls that are wet. Crouch on the floor, with feet together and away from all extended objects.

(ii) Do not stay out in an open area, such as beaches, the sea, rooftops, tops and slopes of hills, recreation fields, etc. Do not carry tall metal objects such as metal umbrellas or golf clubs. If caught on open ground, crouch down in the lowest point or depression in the area with feet together.

(iii) Avoid standing close to the trunk of tall isolated trees or touching or standing close to tall metal structures, wire fences or pipes.

Conclusions

1. Lightning fatalities occur at a rate of 1·7/million. This is the highest rate reported in the literature to date and may be attributable to the high year-round thunderstorm frequency.
2. The male/female death ratio is 4·7, which is about the same as for other countries.
3. Fifty-eight per cent of the fatalities occur in the 10–29 year age group. This is a finding similar to that of other countries.
4. The distribution of lightning fatalities through the year correlates well with the distribution of thunderstorms. Peaks occur in November and April, with minima in July and January–February.
5. The diurnal distribution of lightning fatalities correlates well with the diurnal distribution of thunderstorms. A maximum is observed between 1500–1600 hours local time. About 65% of deaths occur between 1330 hours and 1630 hours.
6. Of all the deaths investigated, 33% were killed in open areas and 67% in sheltered areas. Other countries report similar results.
7. The recreation/work death ratio averages 0·60, with a value of 0·44 in earlier times and 0·79 in modern times. The prevalence of recreation deaths in recent times is similar to that in other countries and may be attributed to rising affluence and increasing leisure periods.
8. Most of the deaths occur in low-lying areas. Higher-elevation areas in Singapore are sparsely populated.
9. Eighty-five per cent of deaths are single events and 15% are double deaths. The most severe incident occurred at a picnic when two were killed and five injured.
10. Direct strikes with current passing through brain or heart account for 84% of deaths.
11. The ratio of dead to injured is 1·0 in Singapore. Other countries report ratios of about 2·0. This may be due to fewer group activities, especially recreational ones, in Singapore.
12. Lightning death rate in Singapore is 3·3/year. From the estimated number of lightning strokes in Singapore, it can be calculated that about 1 in 3000 ground strokes in Singapore results in a fatality.
13. Personal safety should be emphasized to schoolchildren, especially those recreating.

Acknowledgements

The authors gratefully acknowledge the relevant information supplied and the help rendered by the various Government departments and the daily newspapers.

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551.501.9:551.508.54:533.6.07

The problems of anemometer exposure in urban areas—a wind-tunnel study

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Summary

The problem of defining a mean wind speed which reflects the general characteristics of the surrounding terrain is examined for the particular case of the area around Sheffield University. This problem has arisen in connection with the data analysis procedures for a full-scale wind force measurement project where a reference wind speed is required for data presentation. Wind-speed data are available on the site from three separate buildings. Data from one of these anemometers are supplied to the Meteorological Office. Initial attempts to establish a single vertical relationship between the outputs of these three anemometers were not successful, and a wind-tunnel study of the wind structure over the area was therefore undertaken. This study enabled the response of each of the three anemometers to be examined for dependence on wind direction and roof location.

The results of this project imply that considerable uncertainty is associated with any mean wind-speed definition whose reference height is comparable with the size of the objects which compose the surrounding terrain. It follows from this that representative mean wind speeds for urban areas can only be defined for heights considerably in excess of 10 metres.

1. Introduction

This paper presents some of the results of an investigation into the relationship between the wind velocity measured at three points on the site of a full-scale wind-loading test. These investigations were initiated in order to assist with the data analysis program associated with the wind-loading experiment. The building concerned, the 20 storey Arts Tower at Sheffield University, has been the subject of an extensive program of research whose aim has been to determine the dynamic wind loads which act on the structure. The method of determination of these dynamic wind loads is fully described by Jeary, Lee and Sparks (1979).

It is important that during the measurement of the wind loads simultaneous records of the wind speed and direction are made, in order to determine the levels of load which are associated with various combinations of wind speed and direction and, for a given wind direction, how the dynamic load and the wind speed are related to each other. Ideally it would be preferable to be able to relate the dynamic wind-force data to a wind velocity measured at a height of 10 m above open, level ground which properly reflected the general characteristics of the terrain in the vicinity of the test site. Such a definition of the reference wind speed would then conform to the definition of the basic wind speed for a particular geographical location as defined in the BSI Code of Practice for wind loading (1972) and might facilitate a straightforward application of the project's results.

2. Sources of wind data

The wind-speed recordings, used as a reference for calculating building response to given levels of wind activity have, in the past, been obtained from two sources. The principal source, i.e. the wind speed which is recorded together with building acceleration levels, thus providing the basic data for modal force analysis, has been obtained from a Casella cup anemometer mounted on a 6 m mast located on the roof of the Arts Tower (see Plate I). The height of this anemometer is 84 m above street level. The positioning of the anemometer is well within the 'building-induced' interference to the wind flow, the magnitude of this interference being strongly directional. This necessitates the inclusion of an incident wind-direction correction factor for the wind speed during data analysis. The correction used

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Plate I. University Arts Building (right) and Geography Building (left). The anemometer heads are encircled. (See facing page.)

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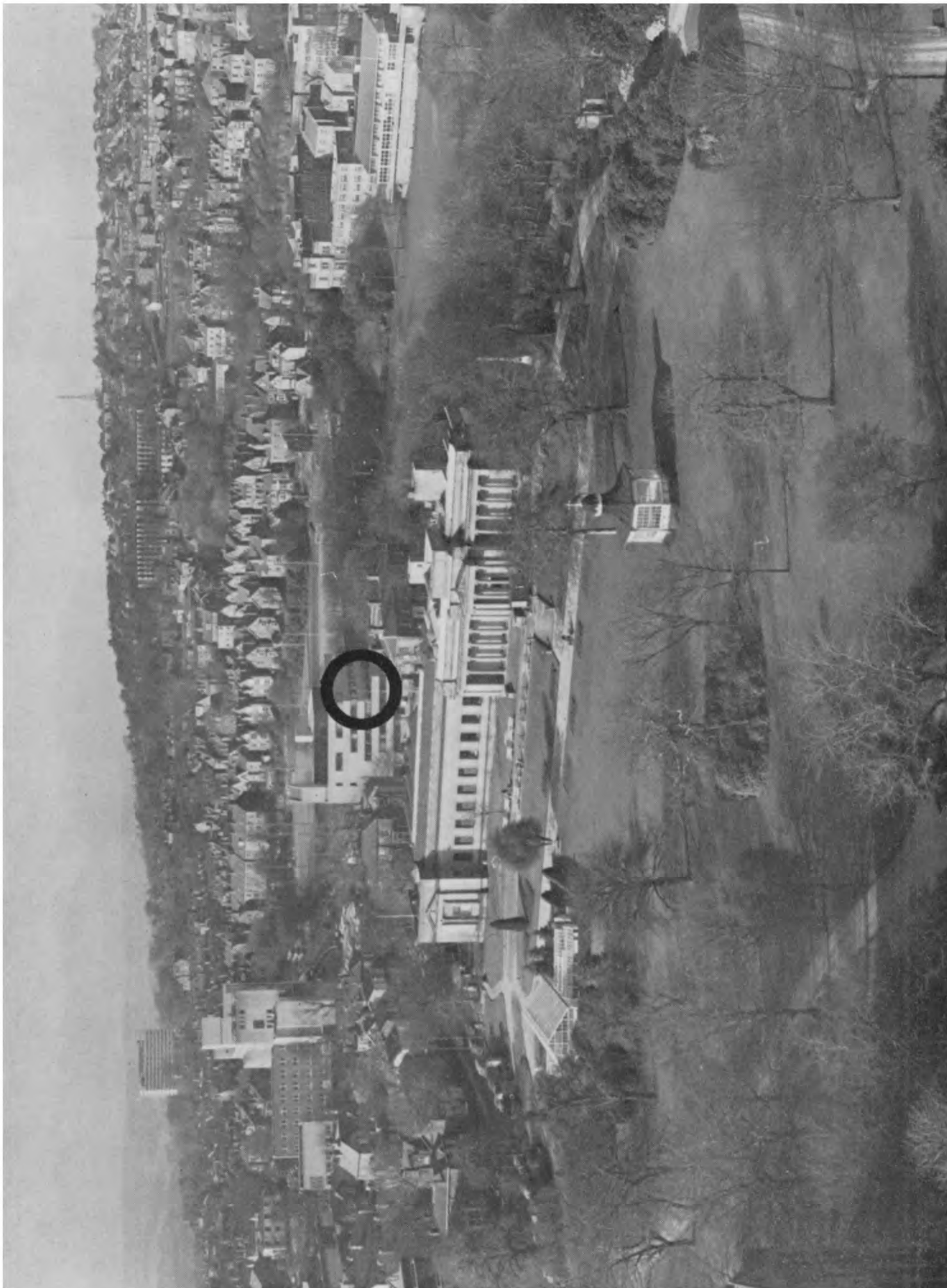

Plate II. Weston Park Museum viewed from the University Arts Tower. The anemometer head is encircled. (See facing page.)

in the past was determined by a wind-tunnel investigation of the variation of mean wind speed with direction, measurements having been made on a 1 : 400 scale model of the isolated building, with no modelling of other buildings on the surrounding site. One of the aims of the present investigation is to attempt to identify and measure any significant site-induced wind-speed variations which should be included in the correction factor.

Wind-direction data are obtained from recordings available from the Weston Park Museum (Plate II), which had, until December 1979, a Dines pressure-tube anemograph mounted on a 10 m mast on the roof, at a total height of 22 m above street level. This instrument has since been replaced by a Munro cup anemometer, which started its operation in February 1980. It is worth noting here that although the Weston Park anemometer station has been superseded by that situated on the University's Geography Building (Plate I), as the official source of Meteorological Office data for Sheffield, it nevertheless possesses long-term recordings for the area which may prove a useful data source.

The instrument situated on the Geography Building is a Munro three-cup anemometer on a 6 m mast and is 31 m above street level. The relative horizontal dispositions of the three instruments are shown in Fig. 1.

Investigations into the relationship between the wind velocity measured at the three anemometers on the site (Arts Tower, Geography Building and Weston Park Museum) of the full-scale test have therefore, been initiated in an attempt to characterize any major peculiarities of the site in so far as they may affect the full-scale wind-loading tests and to provide a means of normalizing the force data with respect to a reproducible characteristic wind-velocity parameter. The general aims of this investigation are then:

(a) To determine the variation in mean wind speed with incident wind direction measured by the Arts Tower anemometer and, by comparing this with the undisturbed free wind speed at that height, attempt to separate 'building-induced' variations and 'site-induced' variations. The undisturbed free wind speed at a point is the wind that would blow at that point if the surrounding terrain were open and level. By 'open terrain' is meant an area no part of which is nearer to an obstruction than ten times the height of the obstruction; such obstructions can be either natural, for example trees, or artificial, for example buildings. In a wind tunnel the free wind is known fairly precisely; in the real world, whilst it has been found to be a useful concept for wind engineering design purposes, it is a concept difficult to quantify accurately in practice. The free wind as defined here is to be distinguished from the gradient wind just above the atmospheric boundary layer, a wind which is closely related to the large-scale pressure field.

(b) To compare this information with the mean wind speeds measured at the two other anemometer stations in an attempt to identify the major flow characteristics of the site, and to define a law of variation with height of the mean wind speed.

A series of investigations to satisfy these aims has been carried out using wind-tunnel techniques in which both the local terrain and the characteristics of the atmospheric boundary layer have been modelled.

3. The wind tunnel and models

(a) *The wind tunnel.* The experiments were carried out in the Sheffield University 1·2 m × 1·2 m Boundary Layer Wind Tunnel. The simulation of the dominant characteristics of the natural wind flow over the suburban/urban area was achieved by the inclusion of flow-mixing devices and roughness sheets in the forward part of the working section. Both the wind tunnel and the method of atmospheric boundary layer simulation are fully described by Lee (1977). The majority of the tests were performed at a scale of 1 : 1000, in order to include the maximum site area on the wind-tunnel turntable. However,

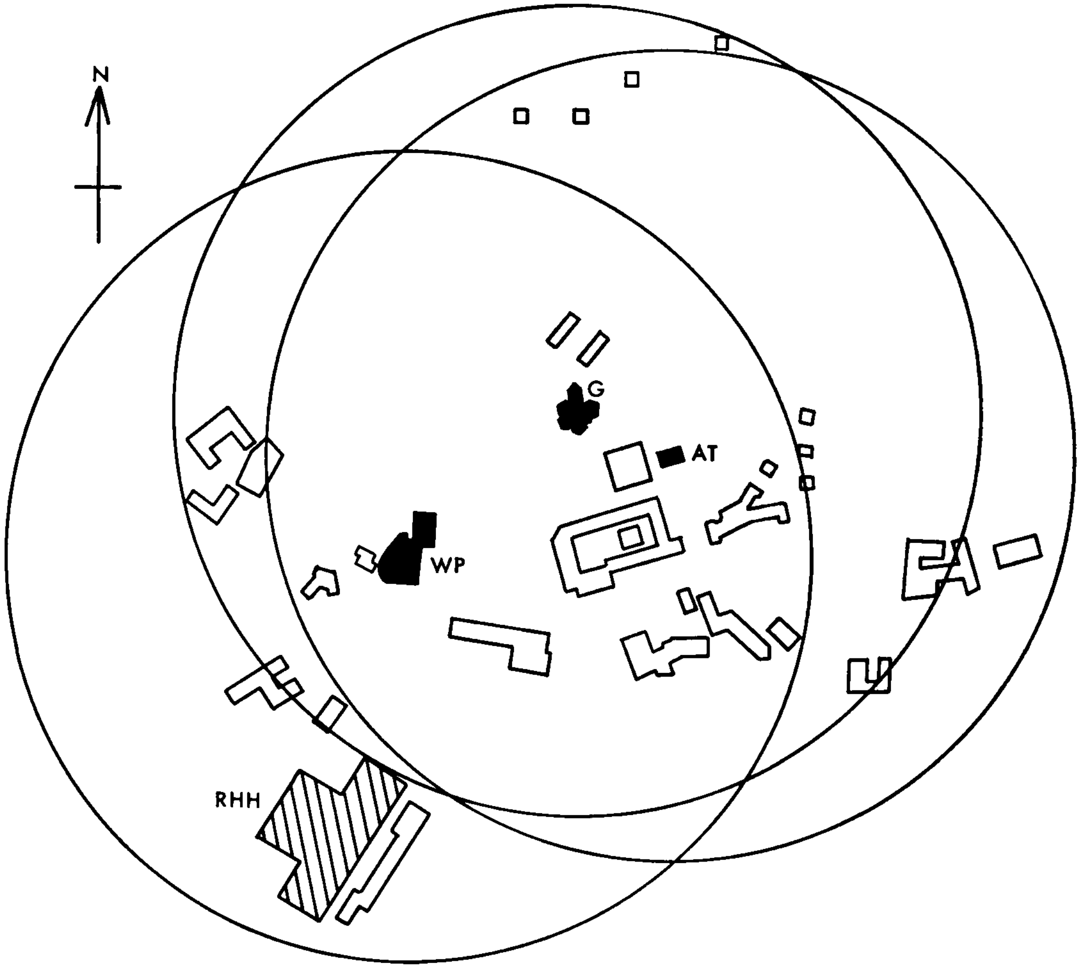

Figure 1. The wind-tunnel site model. AT = Arts Tower; G = Geography Building, RHH = Royal Hallamshire Hospital; WP = Weston Park Museum.

in order to examine the influence of roof detail and anemometer location on the measured wind speed, some tests were performed with larger models, at a scale of 1 : 350.

The modelled anemometer speed measurements were made with a miniature NPL type pitot–static tube connected to a Betz manometer. These measurements were all checked using a linearized Disa hot-wire anemometer fitted with a straight wire probe. The wind-tunnel reference speed was monitored by a further NPL type pitot–static tube connected to a Betz manometer and located at the modelled gradient height, 900 mm above floor level.

(b) *The models.* A linear modelling scale of 1 : 1000 was used for the majority of the tests in order to accommodate the extent of the relevant site on the 1·1 m diameter wind-tunnel turntable. This scale enabled all major buildings within a radius of 550 m of any of the anemometer stations to be modelled.

Fig. 1 shows a plan of the major buildings on the site, modelled as level ground. All other buildings, usually less than about 15 m in height, were modelled as simple scaled blocks and, for the sake of clarity, are not shown here. The site model was not contoured.

The desirability of presenting each of the three anemometer stations, in the absence of any surrounding modelled buildings, with nominally identical wind patterns (i.e. so that the effect of tunnel variables was minimized) dictated the use of a sectional model layout. This was constructed in such a way that each of the measuring stations in turn could be positioned in the centre of the turntable and still be surrounded with an accurate representational model of all major buildings within a scaled radius of 550 m. The model sections are indicated by the circles in Fig. 1. The lettering on Fig. 1 indicates the buildings as follows: AT (Arts Tower), WP (Weston Park Museum), G (University Geography Building) and RHH (Royal Hallamshire Hospital). This last building referred to, the Royal Hallamshire Hospital, is a major site feature whose height is comparable to that of the Arts Tower. The RHH building was only modelled on the turntable for the model section centred on the Weston Park Museum anemometer, since for the other two sections it lay outside their 550 m radii. For these two sections of the model the RHH building was positioned in the wind-tunnel working section at the appropriate distance and orientation upstream of the turntable rotation.

Whilst the authors are aware of the difficulties of using wind-tunnel models to represent the real world, some justification for presuming that the model results can be applied to full scale do exist. A comparative full-scale and wind-tunnel model survey of the environmental wind conditions around the base of the Arts Tower has been carried out (Lee and Hussain 1979) and good agreement between both sets of results was obtained. Additionally the full-scale dynamic wind-loading project results have been compared with those obtained by corresponding wind-tunnel models (Evans and Lee 1981) and again good agreement has been achieved.

4. Results of wind-tunnel measurements

(a) *The Arts Tower anemometer—speed measurements.* In Fig. 2 a number of sets of data are presented which depict the variation of wind speed with direction, for different test conditions, all measured using the 1 : 1000 site model. The wind speeds U_A, are all shown non-dimensionalized by U_O, which is defined as follows: U_O is the value of the mean wind speed at the height of the anemometer, determined from the characteristics of the simulated atmospheric boundary layer incident flow and represents a mean speed unaffected by any particular building geometry or site detail modelled on the turntable. It should be noted that the anemometer is not centrally located above the building's roof and so a degree of asymmetry will arise from this source, amongst others which may be due to the site.

Referring first to the measurements taken with the anemometer in its normal position, a number of characteristics of this graph are worth noting:

(1) The peaks of the graph appear to correspond to the wind flow being incident on the building corners. In this case the angular separation between the peaks calculated from the distances of the anemometer position from the building corners predicts angular separations of approximately 55°, 120°, 75°, and 110°. These values compare favourably with the experimentally observed values of 55°, 110°, 80°, and 115°, the differences being well within the limit of expected experimental error.

(2) Minima in the graph correspond to the wind flow being incident normally on to the building faces. The difference between the true compass direction shown in Fig. 2 and the direction of the nominally north face of the building is 20°, with the building 'north' facing 340°.

(3) The minimum at about 350° is of particular significance to the wind-loading program since wind force is proportional to the square of wind speed. This direction corresponds to the wind being incident normally on to the northerly broad face of the building and also corresponds with a frequent wind direction. With the wind in this direction the speed measured by the anemometer on the Arts Tower would indicate only approximately 50% of the undisturbed, free wind speed at that height.

When the Arts Tower building was removed from the 1 : 1000 site model and the test was repeated it

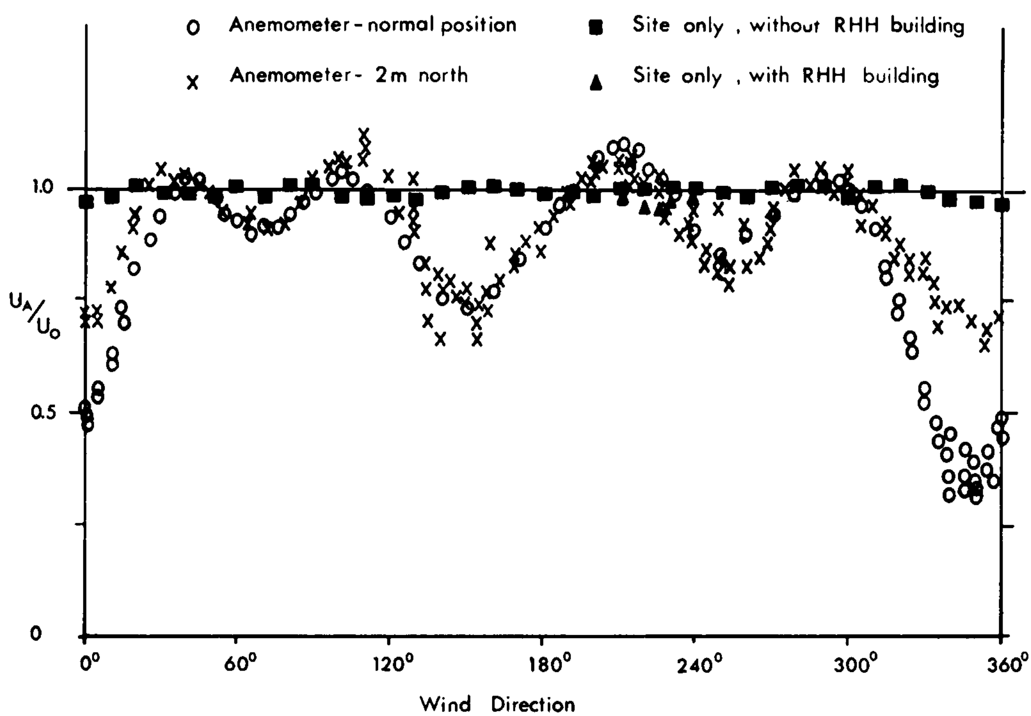

Figure 2. Variation of mean wind speed with wind direction for the Arts Tower anemometer, from wind-tunnel tests with a 1 : 1000 scale model.

was found that the measured wind speed at the anemometer height remained approximately constant with wind direction. An examination of this set of data in Fig. 2 shows that the inclusion of the RHH building, located 600 m away from the Arts Tower on a bearing of 225°, in the working section produces only a barely discernible effect. Thus, a comparison of the variation of mean wind speed with incident direction made at the modelled location of the Arts Tower anemometer, both with and without the Arts Tower model in position, indicates this variability to be almost entirely building-dependent. Very little contribution to the mean wind variation is considered to be generated by the surrounding site.

Clearly small errors in the positioning of measuring devices at a modelling scale of 1 : 1000 are likely to introduce significant errors in the magnitudes of measured speeds in regions of high wind shear such as exists near the roof of the Arts Tower. In order to illustrate this, the anemometer position was moved 2 mm north (on the model scale) and the variation of mean wind speed with direction re-examined. Fig. 2 also shows the effect of this movement of the anemometer position on the measured wind speed and may be compared with the original position data. The measurement shows that whilst the general shape of the curve remains similar, the magnitude of the minimum at 350° changes dramatically. This would seem to indicate that whilst the general properties of the graph may be confidently accepted, the actual magnitudes of all the peaks and troughs require more careful examination.

Further tests have been conducted on a model of the Arts Tower at a scale of 1 : 350, the larger model enabling a more accurate anemometer positioning to be maintained. These tests at the larger scale have not been performed in the presence of a site model, following the conclusions reached from Fig. 2. The initial 1 : 350 Arts Tower model had a flat roof, unlike the actual building whose roof surface is a complex group of small shapes housing lift-motor rooms, water tanks, flue housings, etc.

The influence of small changes in anemometer height, or mast height, is shown in Fig. 3, where the directionally dependent speed variations are shown for mast heights of 4 m, 6 m and 8 m full scale. The very large speed differences at 170° and 350° caused by reducing the 6 m mast height to 4 m imply that very small errors in vertical positioning on the 1 : 1000 model tests could be responsible for large errors in their results.

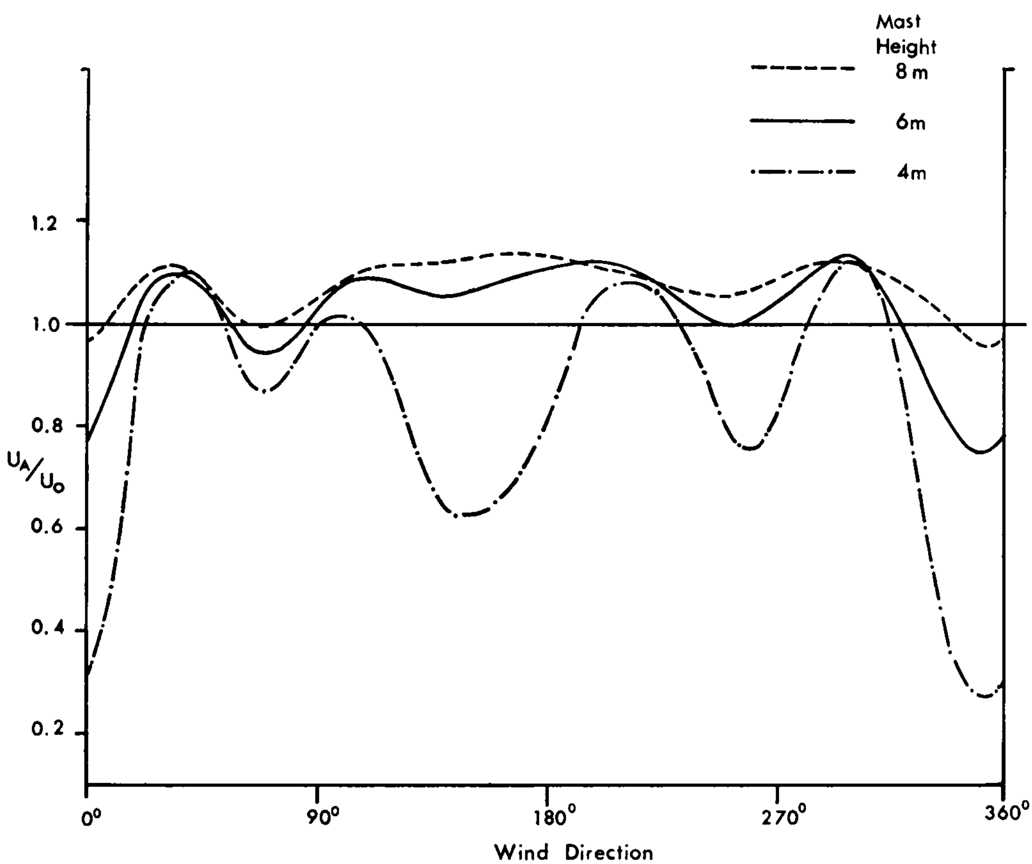

Figure 3. Influence of mast height on the variation of wind speed with direction, from wind-tunnel tests with a 1 : 350 scale model of the Arts Tower.

The last test with the 1 : 350 model was to inspect the influence of the actual roof structure as opposed to the flat-roof model used so far. The results of this test are shown in Fig. 4 where the true roof structure model and the flat-roof model are compared. With the exception of the minimum at 70° the two models produce very similar results.

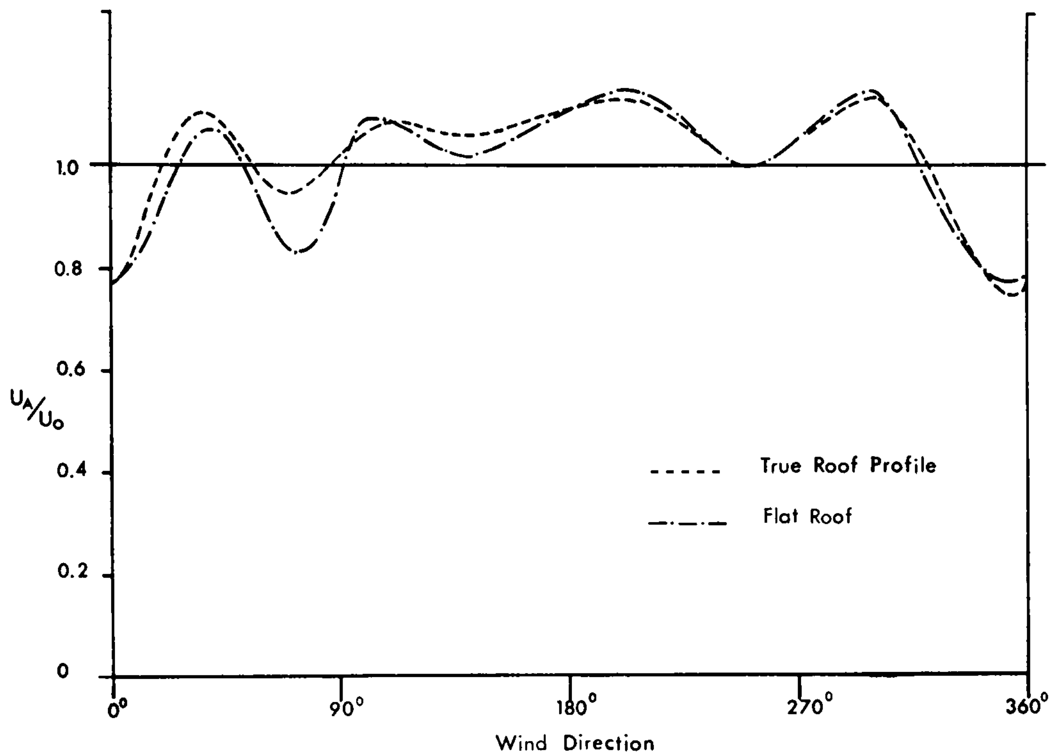

Figure 4. Influence of modelled roof shape on the variation of wind speed with direction. Arts Tower model, 1 : 350 scale.

This final data set, i.e. of the 1 : 350 true-roof-structure model, is recommended as the basis for the directionally dependent wind speed correction factor to be applied in the analysis of the full-scale experimental data. The application of a set of correction factors, based on these data, will convert the measured wind speed at 84 m above street level to an equivalent undisturbed free wind speed at a height of 84 m which reflects the general terrain characteristics of the area.

(b) *The Arts Tower anemometer—direction measurement.* Some preliminary tests have been conducted on a 1 : 1000 model of the Arts Tower in order to estimate the accuracy of the full-scale wind direction vane. In these tests a small vane, approximately 3 mm square, was mounted on a jewel watch bearing on the model roof and the direction of the vane relative to the tunnel axis, and hence wind direction, was monitored for different building orientations. It was found that for some directions, notably those for which a roof corner lay upstream of the vane position, large angular differences existed between the vane indication and the tunnel axis. The tentative conclusion drawn from these preliminary tests is that the full-scale vane indication is unlikely to be a reliable source of information and that it is not possible at present to produce a vane measurement correction factor.

(c) *The University Geography Building anemometer.* The University Geography Building anemometer is a Munro three-cup anemometer mounted on a 6 m mast attached to the 25 m roof and is thus 31 m above street level. The output data from this instrument are supplied to the Meteorological Office as a source of wind data for the Sheffield area.

Tests, carried out using the 1 : 1000 site model, have been conducted in a manner similar to those described in the preceding sections. The variations of measured wind speed with wind direction are shown in Fig. 5, where the speed, U_G, is shown non-dimensionalized by the average undisturbed free wind speed at that height for all wind directions, U_O. In order to distinguish between wind speed variations due to the proximity of the building itself and, separately, those due to the characteristics of the site, the 1 : 1000 model of the Geography Building was removed from the site model and the measurements were repeated. From the two sets of results shown together in Fig. 5 it can clearly be seen that all the major features of wind speeds measured above the building are due to the site features alone and not to the proximity of the building itself. This conclusion is the reverse of that found in the case of the Arts Tower anemometer.

Figure 5 shows a number of interesting features:

(1) The minimum at 120° corresponds to the Geography Building being downstream of the Arts Tower. This proximity effect is dramatically visualized in Plate I.

(2) A small, but measurable, reduction in the indicated wind speed may be attributable to the presence of the RHH building, situated 600 m away on a bearing of 210°.

(3) The minimum seen at 170° occurs when the building is downstream of the fairly high-density University complex which is nominally 30 m high and 100 m away from the Geography Building (see Fig. 1).

(4) The trace maximum at 270° corresponds to the wind incident across Weston Park, just west of the site.

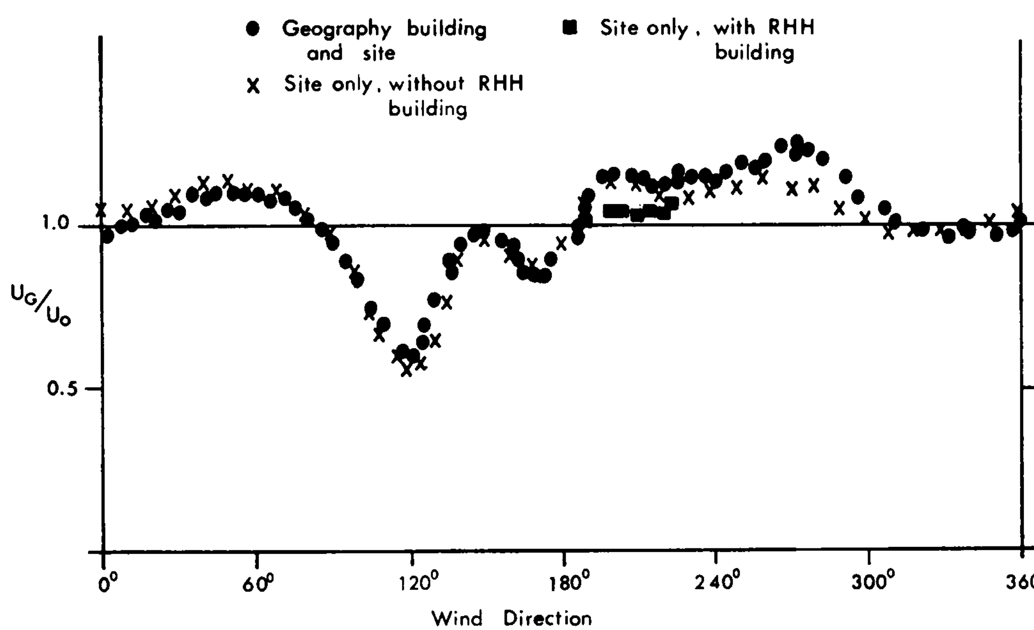

Figure 5. Variation of mean wind speed with wind direction for the Geography Building anemometer, as deduced by rotating a 1 : 1000 scale model of the building and surrounding site in the wind tunnel.

In order to check the main conclusion of the comparison shown in Fig. 5, i.e. that the directionally dependent speed variation of the Geography Building anemometer is dependent on the site rather than on the building, a further test at 1 : 350 scale was performed. This test utilized a larger-scale model of the building without the site features being present. The results, shown in Fig. 6, demonstrate the validity of the earlier finding. However, Fig. 6 should not be interpreted as indicating that the site for this anemometer is acceptable, in that it provides a good estimate of what the wind would be if the building were not there, since this is shown not to be true by Fig. 5. What Fig. 6 does indicate is simply that the ratio of the anemometer mast height to building height, for a building of that particular shape, is sufficiently large for the anemometer to be clear of flow effects above the building's roof.

(d) *The Weston Park Museum anemometer.* The Museum viewed from the Arts Tower is seen in Plate II, where the anemometer head, 10 m above the 12 m high building roof, is shown circled. The tests carried out on the 1 : 1000 model of the Weston Park Museum anemometer complete with its surrounding site, including the RHH building, were performed as described in the preceding sections. Fig. 7 shows the variation of mean wind speed, U_W, with direction. Two large minima are easily identified on bearings of approximately 80° and 180°. The first of these appears when the high-density University complex is upstream, whilst the second minimum, slightly more extreme than the first, is associated with the RHH building 300 m away (see Fig. 1).

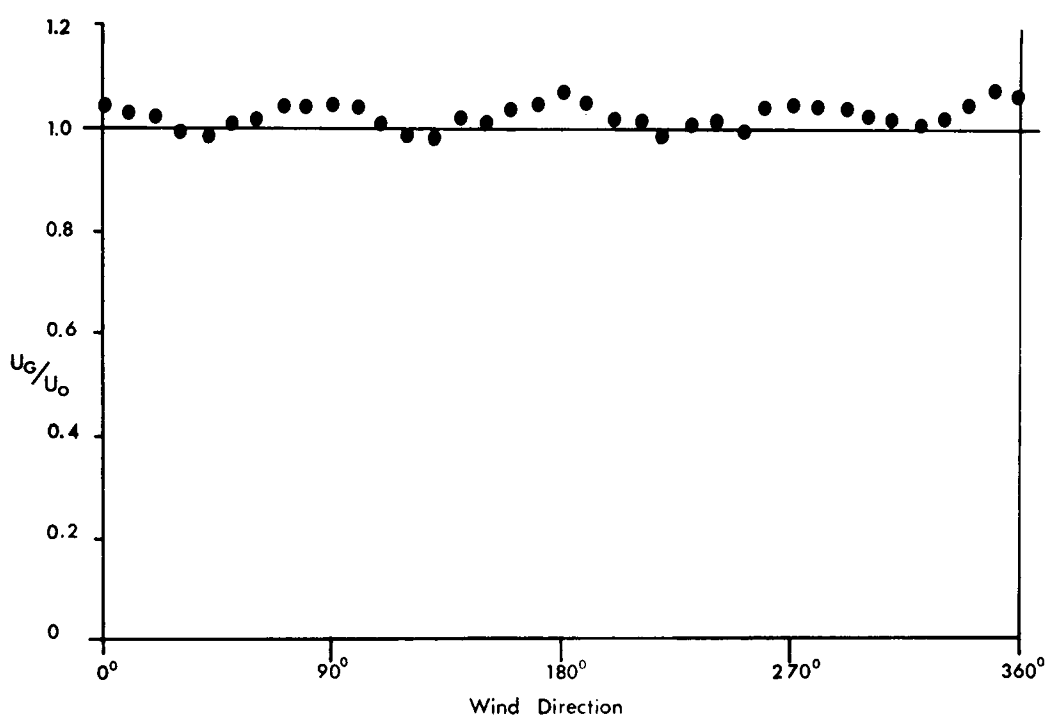

Figure 6. Variation of mean wind speed with wind direction for the Geography Building anemometer, as deduced by rotating a 1 : 350 model of the building without the surrounding site in the wind tunnel.

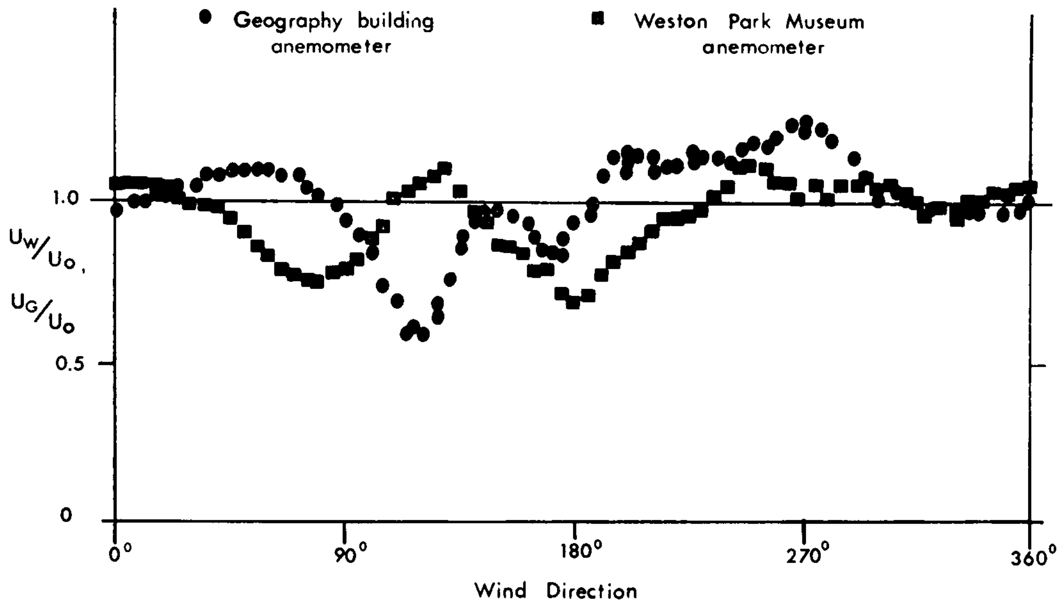

Figure 7. Variation of mean wind speed with wind direction for the Weston Park Museum anemometer compared with that for the Geography Building anemometer, from wind-tunnel tests with a 1 : 1000 scale model.

Although no separate test on a 1 : 350 model of the Museum has been carried out it seems most likely to the authors that the major features of Fig. 7 can be explained with reference to the site details and that the directionally dependent variations are unlikely to be building-dependent to any significant extent. This conclusion has been reached in view of the tests carried out on the Geography Building anemometer where the anemometer was shown to be sufficiently far above the building to escape its influence. In the case of the Weston Park Museum the ratio of anemometer mast height (10 m) to building height (12 m) is even greater than for the Geography Building. In view of this the authors did not consider that any useful purpose would be served by a 1 : 350 model test of the Weston Park Museum. It is, therefore, worth commenting on the statement by J. S. Hopkins (1979), 'The museum roof above which it [the Dines anemograph] is mounted has a 'zig-zag' profile and so can be expected to create more turbulence than a roof of conventional shape. This defect of exposure contributed to the Meteorological Office's decision to cease publication of the Weston Park anemograph data in the *Monthly Weather Report* with effect from January 1975 and to replace it with data from an electrical cup instrument mounted on a nearby university building [the Geography Building]'.

The conclusions drawn from Fig. 7 seem to suggest that Hopkins's unsupported estimate of the effect of the 'zig-zag' roof is a significant overestimate. An inspection of the Museum roof reveals the 'zig-zag' profile to consist of an irregular array of north-facing roof lights, light-wells, access stairways, store chambers, etc. having height variation of approximately 1 m above and below the façade roof level, which, since the anemograph mast is 10 m high, might be considered negligible, particularly in comparison with the new Meteorological Office data source which is only on a 6 m mast.

In general, the wisdom of the removal of the Meteorological Office data source from the Museum building to the Geography Building can be judged from Fig. 7 which compares the corresponding velocity variations. The overall directionally dependent speed variation of the new data source is seen to be slightly larger than that of the old one. Incidentally it must not be forgotten that the construction of the RHH building took place during the decade prior to change of data source location and so Fig. 7 cannot be used as the single correction for all Weston Park Museum data prior to 1975.

5. A wind speed relationship with height

From the wind-tunnel tests the following relationships between the wind speeds measured by the three different anemometers have been evaluated:

$$U_A/U_G = 1{\cdot}28, \sigma = 0{\cdot}30$$
$$U_A/U_W = 1{\cdot}39, \sigma = 0{\cdot}25$$
$$U_G/U_W = 1{\cdot}10, \sigma = 0{\cdot}20$$

These ratios have been averaged for all wind directions and have the standard deviations, σ, as indicated.

It is required, then, to produce a relationship from the available information which will enable a directionally corrected 84 m wind speed from the Arts Tower to be reduced to a corresponding wind speed. The power-law equation is the most convenient form for establishing such a vertical wind-speed relationship, and states in its general form

$$V_H/V_{10} = (H/10)^\alpha.$$

For areas with sizeable obstructions in the terrain this equation can be amended to read

$$V_H/V_{10} = ((H-d)/10)^\alpha,$$

where

V_H is the wind speed at any height H in metres,
V_{10} is the 10 m wind speed
d is the zero-plane displacement, and
α is the power-law exponent.

The values of V_{10} obtained from this relationship are critically dependent on the value of d chosen to represent the adjacent terrain. The BSI Code of Practice for wind loading (1972) gives some guidance in making this choice, suggesting a value of average roof height of 10 m for terrain described as surfaces covered by numerous large obstructions, such as towns and their suburbs and the outskirts of large cities. Whilst such a description may be considered appropriate to the sites of the three anemometers, it would be useful to know of the effect of using values of d both greater and smaller than 10 m, since there is known to be a degree of uncertainty associated with the value given implicitly in the BSI Code of Practice. Using values of d of 7 m, 10 m and 15 m, the power-law equation has been used, together with the results of the wind-tunnel study, which gave three relationships between the speeds measured by the three anemometers, to yield a set of values of the power-law exponent α. These values varied from 0·116 to 0·212.

Applying the values of the power-law exponent given in the preceding paragraph to a real situation has the following results. If a mean wind speed measured by the Arts Tower anemometer has a value, corrected for wind direction, of say 50 kn, this may then be translated into a velocity at 10 m, thought to be representative of the site terrain, which varies between 32·4 kn and 40·1 kn, depending on the values chosen for α and d.

It is clear to the authors that this degree of possible error in the stipulated normalizing velocity renders the use of a nominal 10 m wind speed inappropriate for the purposes of the experiments being carried out in this instance. In a wider context the authors would question the validity of any nominal 10 m wind speed which might be considered to be representative of the terrain characteristics in suburban or urban areas in which the average obstruction height is itself of the order of 10 m.

6. Conclusions and recommendations

(a) A standard height of 10 m is in use as a reference point for the definition of mean wind speeds by some compilers of climatic data bases, used in building design, though not necessarily by the Meteorological Office for this particular purpose. In the light of their findings the authors recommend that the use of such a reference height for the determination of mean wind speeds intended to be representative of a particular area should cease where that area includes terrain features whose average height is of the same order. Wind-tunnel experiments have demonstrated that mean wind speeds measured at low levels in urban areas can be significantly influenced by the immediate locality of the measuring point.

(b) It is recommended that all who use mean wind speed data from anemometers mounted on masts on buildings in urban areas should familiarize themselves with the probable influence of surrounding objects on the recorded wind speed. Consideration should be given by those who supply such data to the application of corrections which take account both of the directional characteristics of the wind and also of the height of the instrument, since it is the supplier who is responsible for the choice of site.

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The effects of inadequate sampling and of circulation pattern on real and apparent zonal mean temperature

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Summary

It is shown to what extent the restriction of meteorological observations to land is likely to cause overestimation of climatic variability of zonal mean temperature. The effect is particularly marked if circulation changes induce temperature changes having a low zonal wavenumber.

1. Introduction

During the past few decades it has become customary to express estimated changes of the temperature of the earth in terms of global, hemispheric or at least zonal averages. These parameters are the focus of frequent debate because they are among the most obvious indicators of changes in the earth's heat balance, for instance as a result of carbon dioxide, volcanic dust, or other man-made or natural influences. However, the supporting data have until very recently been mostly limited to land areas—and even to a small selection of these areas.

This paper includes examples of possible sampling errors of estimated climatic changes based on zonal mean temperature when the input data are for land only or for those limited land areas for which observations are available. The basic thesis is that reported changes of global, hemispheric or zonal mean surface air temperature may arise from three sources:

(a) Real changes in the total heat content of the atmosphere plus ocean.

(b) Redistribution of heat between atmosphere and ocean.

(c) Systematic sampling error caused by preferential siting of land stations in the ridges or troughs of a low-wavenumber pattern of temperature changes.

It is clear that (b) and (c) above are linked, because low-wavenumber patterns of temperature change will systematically affect the air temperature over the oceans, and therefore alter the heat fluxes across the sea surface so as to tend to cancel the air temperature changes there. Therefore, the true zonal mean air temperature will change in the same sense as the mean change over land, but the observations, restricted to land, will overestimate this zonal mean change because the air temperature changes in oceanic regions, though reduced, will still be in the opposite sense. Observed variances of land and oceanic monthly mean surface air temperatures are used to quantify the damping effect of the ocean.

Monthly mean data are used throughout because they smooth the effects of individual atmospheric disturbances and are commonly employed in studies of climatic change.

2. Procedure and results

At each point the temperature change over a period may be expressed as $T' = A \cos n(\phi\text{-}\phi_x)$ where n is zonal wavenumber, ϕ is longitude, ϕ_x is the longitude of maximum warming, and A is the amplitude of the field of changes, differing between land and ocean. Note that, because $A_{\text{land}} > A_{\text{ocean}}$, T' does not necessarily average zonally (or globally) to zero, even if it results entirely from internal circulation changes. When most of the warming is over land the true zonal mean $[T']_{\text{true}} > 0$ because the changes have greater magnitude over land. Similarly $[T']_{\text{true}} < 0$ for cooling over land. But it is intuitively obvious that when the warming is mainly over land, the value $[T']_{\text{land}}$ averaged over land only, commonly used as an estimate of $[T']_{\text{true}}$ especially for the earlier years of instrumental data, in fact exceeds $[T']_{\text{true}}$ because there is cooling over the oceans. Again the converse applies when the cooling is over land.

This note attempts to quantify the discrepancy between $[T']_{true}$ and $[T']_{land}$ using observed standard deviations of monthly mean air temperature over land and ocean.

Monthly mean upper-air data have recently been collected for nearly 50 stations in the northern hemisphere, mainly at middle or high latitudes. In the process of quality-control, statistics for generally 15 to 30 years ending at about 1978 have been computed, and these include standard deviations as well as normals of monthly data, for the surface and for levels aloft. Because of the application of this note to the earlier years of instrumental data, only the surface will be considered. It is found that the standard deviation of January monthly surface temperature is 1·1 °C at OWS 'M' and OWS 'P' but about 3·2 °C in interior Canada and at Verhojansk in Siberia. At Sable Island off south-east Canada it is 1·3 °C and at Vancouver 1·7 °C. Corresponding July values are 0·8 °C at the weather ships, and 1·5 to 2·0 °C far inland. Now the local standard deviation resulting from a sinusoidal curve of amplitude A of random phase is $A/2^{\frac{1}{2}}$: therefore values of $A_{land} = 4{\cdot}5$ °C, $A_{ocean} = 1{\cdot}5$ °C will be considered, representing winter, and the computation of mean T' over land, over ocean, and over all longitudes will be made for 50 °N for various ϕ_x, and $n = 1$ to 8, assuming that A_{land} applies over all land and A_{ocean} over all ocean.

The results for $n = 1$ to 3 are shown in Tables I to III. For wavenumber 3 (Table III), possibly the most applicable to winter, it is seen that if the maximum warming is at 20 °E the true zonal mean warming is 0·5 °C but the mean warming over land is 1·1 °C. When the maximum warming is at 80 °E (cooling at 20 °E) these values become −0·5 °C and −1·1 °C respectively. Thus measurement restricted to land has the potential to yield values of zonal mean climatic variation about double (actually 1·1/0·5 = 2·2) the true values at 50 °N in winter.

This factor of about two applies also to wavenumbers 1 and 2 (Tables I and II), but for wavenumbers $\geqslant 4$ the total and land-only variations in T are small, possibly a situation applicable to summer. The ratio r of apparent to true standard deviation tends to

$$\sigma_{land}/\{(\sigma^2_{land} \times p^2_{land}) + (\sigma^2_{ocean} \times p_{ocean} \times p_{land})\}^{\frac{1}{2}},$$

ignoring spatial coherence, as wavenumber becomes large so that phase bias is eliminated: here σ is standard deviation and p is the proportion of total longitude, p_{land} being 0·68 and p_{ocean} 0·32 at 50 °N. For $\sigma_{land} = 3\,\sigma_{ocean}$ (winter) we have $r = 1{\cdot}44$: for $\sigma_{land} = 2\sigma_{ocean}$ (summer) we have $r = 1{\cdot}39$. These limiting minima of the factor of overestimation of zonally meaned air temperature change if the cause is redistribution of heat between atmosphere and ocean. If $\sigma_{land} = \sigma_{ocean}$, $r = (p_{land})^{-\frac{1}{2}} = 1{\cdot}21$.

For combinations of wavenumbers the ratio may be estimated by taking

$$r = (\Sigma A_n r_n^2/\Sigma A_n)^{\frac{1}{2}},$$

where r_n is the ratio for wavenumber n.

At 60°–70°N the proportion of ocean is smaller and the problem is reduced. Even at 50 °N, inclusion of the Aleutians (which are not far north of 50 °N) would ameliorate the situation but this would not benefit mean temperature estimates for periods before about 1900 because the stations were not yet founded. At 40 °N the very wide Pacific without islands is a severe problem.

In the tropics, east–west variations in temperature will be far less marked than in a mid-latitude winter, although it is difficult to guarantee complete freedom from the problem.

3. Comments on existing northern hemisphere temperature series

(a) Budyko's (1969) series is based on maps of temperature anomalies compiled at the Main Geophysical Observatory in Leningrad. Only to the extent that the maps cover the ocean, with realistic interpolation where observations are lacking, will the bias caused by irregular sampling of thermal troughs and ridges have been avoided.

Table I. *Estimates of actual and measured surface temperature change at 50 °N for data over land only, assuming that the real temperature change is a wavenumber 1 of amplitude 4·5 °C over land, 1·5 °C over ocean.*

Phase of maximum warming (°East)	Mean temperature change (°C) land	sea	all	land minus all
0	0·7	−0·5	0·3	0·4
30	0·9	−0·6	0·4	0·5
60	0·9	−0·6	0·4	0·5
90	0·6	−0·4	0·3	0·3
120	0·2	−0·1	0·1	0·1
150	−0·3	0·2	−0·1	−0·1
180	−0·7	0·5	−0·3	−0·4
210	−0·9	0·6	−0·4	−0·5
240	−0·9	0·6	−0·4	−0·5
270	−0·6	0·4	−0·3	−0·3
300	−0·2	0·1	−0·1	−0·1
330	0·3	−0·2	0·1	0·1

Table II. *As Table I but for wavenumber* 2.

Phase of maximum warming (°East)	Mean temperature change (°C) land	sea	all	land minus all
0	−1·2	0·9	−0·6	−0·7
20	−0·8	0·6	−0·4	−0·4
40	0·0	−0·0	0·0	0·0
60	0·9	−0·6	0·4	0·5
80	1·3	−0·9	0·6	0·7
100	1·1	−0·8	0·5	0·6
120	0·4	−0·3	0·2	0·2
140	−0·5	0·3	−0·2	−0·3
160	−1·1	0·8	−0·5	−0·6

Table III. *As Table I but for wavenumber* 3.

Phase of maximum warming (°East)	Mean temperature change (°C) land	sea	all	land minus all
0	0·6	−0·5	0·3	0·4
10	1·0	−0·7	0·5	0·6
20	1·1	−0·8	0·5	0·6
30	0·9	−0·7	0·4	0·5
40	0·5	−0·3	0·2	0·3
50	−0·1	0·1	−0·0	−0·1
60	−0·6	0·5	−0·3	−0·4
70	−1·0	0·7	−0·5	−0·6
80	−1·1	0·8	−0·5	−0·6
90	−0·9	0·7	−0·4	−0·5
100	−0·5	0·3	−0·2	−0·3
110	0·1	−0·1	0·0	0·1

(b) Willett's (1950) paper includes diagrams giving contours of 20 year surface temperature change, based only on land stations but with some spatial interpolations and extrapolations based on meteorological flow patterns, thus reducing the thermal sampling problem. However, his world trend graph weights all stations equally and takes no account of developments over the oceans, though his restricting the data to 1 station per 10° square reduces the over-emphasis on Europe and North America, so there may be serious sampling error.

(c) Mitchell's (1961) series, unlike Willett's, corrects for the northward decrease of the size of 10° squares. However, like Willett, he has not taken account of oceanic areas, so serious thermal sampling errors may have taken place.

(d) Köppen's (1914) series is also for land only, though he includes a limited study of Atlantic shipping routes.

(e) Angell and Korshover (1977, 1978) used radiosonde land stations, distributed as evenly as possible, and including an Aleutian station. They also used ship 'P' in the Pacific (50 °N, 145 °W). However, the oceanic coverage was still sparse. There were 12 stations altogether between 40 °N and 60 °N.

(f) Harley (1978) used grid-point data which avoid the sampling problem (or sweep it under the carpet, introducing other difficulties (Parker 1980)). Harley's paper includes a table comparing different authors' results. Unfortunately the different workers have used different sets of levels, e.g. surface only; surface–500 mb; surface–100 mb; mean sea level–75 mb; so exact comparison is impossible.

(g) Painting (1977) also used mean charts, whose reliability will suffer from the same shortcomings as grid-point data.

(h) The present computations may explain positive correlations between central England temperature (Manley 1974) and the average of the Mitchell and Budyko series used by Miles and Gildersleeves (1978). Wavenumber 3 (Table III) gives true mean warming (cooling), which is overestimated by the data network, when the maximum warming (cooling) is near Greenwich. The deduction of hemispheric trends from scattered early instrumental data may be impossible.

4. Final remarks

This note does not disprove the possibility of net hemispheric or global warming or cooling, but emphasizes that movement of mean trough and ridge positions can give the impression of changes of global mean temperature if the data are irregularly distributed, especially in mid-latitudes. Apparent changes may be superimposed on real ones. The position of the two sharpest winter-time thermal troughs near the east coasts of the northern hemisphere continents is such that slight longitudinal shifts could have a considerable effect on mean temperature over these land masses, even if the true zonal means were unchanged.

It has also been demonstrated that movements of mean trough and ridge positions will eventually result in changes of true mean temperature in the same sense as the apparent changes. Thus if the troughs are more over the ocean than usual, transfer of sensible and latent heat from ocean to atmosphere will be enhanced because of increased (ocean minus air) temperature difference, and the atmosphere will be warmed. At the same time the thermal sampling error will be more positive than usual (warmth being more over land than usual). Also, external factors being unchanged, the ocean will cool and the system (ocean + atmosphere) will have constant heat content. Other factors such as changes in albedo have not been considered.

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Notes and news

100 years ago

The following extracts are taken from *Symons's Monthly Meteorological Magazine*, July 1881, **16**, 112 and August 1881, **16**, 128.

REGULAR OBSERVATIONS UPON THE TOP OF BEN NEVIS

We have not space upon the present occasion to express fully our views respecting mountain stations, but we should be sorry for this number to go forth without chronicling the laborious undertaking commenced on June 1st by Mr. Clement Wragge, whose station on the Weaver Hills, in Staffordshire, we have already noticed.* Mr. Wragge having left Farley, opened communication with Mr. Buchan respecting the efforts of the Scottish Meteorological Society to establish an observatory at Ben Nevis, and the final result briefly is, that a complete set of instruments is fixed upon the top of Ben Nevis, the highest point in the British Isles, 4,406 feet above sea level. Mr. Wragge has gone into residence at Fort William, and has commenced the somewhat alarming task of rising between 4 and 5 a.m., and after making a low level observation, climbing to the summit in readiness for observations at 9, 9.30 and 10 a.m., *every day*. If this be not devotion to Meteorology, we should rather like to know to what that term should be applied.

OBSERVATIONS ON BEN NEVIS

To the Editor of the Meteorological Magazine

SIR.—In your last number it is stated that I ascend Ben Nevis *every* day. Kindly allow me to say that a trained assistant usually relieves me at the rate of twice a week. It is certainly hard and trying work, especially so in bad weather; but it must be remembered that, through the kindness of the Scottish Meteorological Society, I take a horse half-way, and this is a great relief to me.

Yours faithfully,
Clement L. Wragge, F.M.S.

Fort William, August 2nd, 1881

* *Meteorological Magazine* Vol. XV, p. 98 (August, 1880).

Correction

Meteorological Magazine, **110**, 1981, p. 17, line 10. After '. . . the ratios of' insert 'wet rainfall-day incidence for other thresholds to'.

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1.80 monthly
Dd 716670 K15 7/81

Annual subscription £23.80 including postage
ISBN 0 11 726284 6
ISSN 0026–1149

THE METEOROLOGICAL MAGAZINE

August 1981

Met.O. 942 No. 1309 Vol. 110

HER MAJESTY'S
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METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1309, August 1981, Vol. 110

551.509.311: 551.515.41: 551.577.37(420)

Synoptic aspects relating to the development of widespread heavy rainfall over southern England on 30 May 1979

By M. R. Woodley
(Meteorological Office, Upavon)

Summary

A small low moving north-north-eastwards across the English Channel and south-east England on 30 May 1979 brought heavy and prolonged rain to much of southern England, accompanied by thunderstorms and a tornado. Synoptic aspects of the development are now examined, with emphasis on the contribution of low-level convergence.

Introduction

May 1979 was a wet month over much of southern England, and in a number of areas the soil moisture deficit for grassland was at or close to zero near the end of the month. On 30 May a small low moved north-north-east from near south-west France, reaching the Channel Islands by midday, where for a time it became multi-centred, with the main depression crossing south-east England in the evening. The associated fronts brought prolonged heavy rainfall to western areas, with falls exceeding 50 mm in some places and flooding, notably around the Dorset, Wiltshire and Somerset border area. A well-marked line-squall and tornado was observed, and thunderstorms developed over southern and eastern England during the afternoon and evening. In this paper the synoptic factors are considered in some detail, in order to explain the apparent rapid development of an area of heavy rain and thunderstorms.

Synoptic developments

A major upper trough developed in mid-Atlantic towards the end of May and a deepening surface low moved north-eastwards to become centred near western Ireland. A warm and moist airflow was advected over the British Isles and near-continent with dew-points of 17 °C being reported in parts of western France. During 29 May the surface fronts moved east across the country, giving only occasional light rain over southern England. The upper trough continued to move slowly east and by 00 GMT on 30 May, the surface fronts had become quasi-stationary over south-east England and the near-continent with a marked baroclinic zone extending from the Bay of Biscay, through Cornwall, to south-west Norway. An analysis of wet-bulb potential temperature (θ_w) at 850 mb (Bradbury 1977), Fig. 1, showed the fronts to be well marked, with a gradient of 1 °C in 50 km. The places used for this analysis or subsequently mentioned in this paper are given in Fig. 2. On the morning of 30 May, the surface anticyclone over central Europe began extending a ridge westwards across central Britain as the upper trough became disrupted by upper-air developments over mid-Atlantic. The corresponding decline of Low P created an easterly geostrophic component of about 10 m s^{-1} along the surface fronts, some 150 km to 450 km ahead of the low, and gave a westward movement of around 6 m s^{-1} to the fronts.

Isolated outbreaks of rain occurred early in the day over southern counties of England, the Channel Islands and Brittany. This rain area expanded quickly into a wide band of moderate or heavy precipitation, which moved north-north-eastwards at about 6·5 m s^{-1}, reaching the Manchester area around 12 GMT. Some areas of western England experienced almost 12 hours of continuous rain, much of

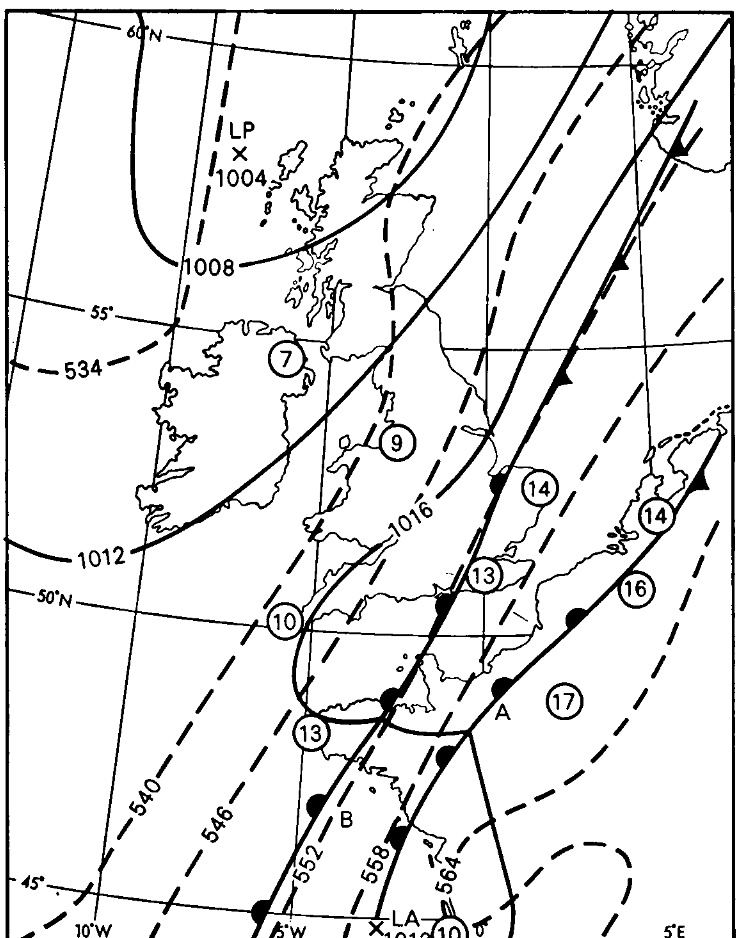


Figure 1. Surface and 1000–500 mb thickness analysis at 00 GMT on 30 May 1979. Figures within circles are wet-bulb potential temperatures at 850 mb. Pressures in millibars. Thicknesses in decageopotential metres.

it heavy, and by early afternoon, telephone inquirers from parts of eastern Somerset were speaking of rivers overflowing and flood water threatening property. The Wessex Water Authority, to whom the Main Meteorological Office at Upavon is responsible for rainfall warnings, later reported that rainfall totals in their area exceeded 30 mm in a number of places, with Yeovilton (Somerset) recording 57 mm. It will be seen later that the main area of rain was closely related to the surface fronts and the area of easterly geostrophic wind flow, whereas the precipitation close to the main low centre was generally caused by thunderstorms triggered by daytime heating.

The principles of the use of radar data for determining rainfall rates over a wide area have been reported in several publications, and the development of a system of linked radars is described by Taylor and Browning (1974). A rainfall radar system was installed at Upavon early in 1979 as part of the Meteorological Office short-period weather forecasting pilot project (Browning 1979), and the system proved invaluable on this occasion. The first indication of thundery activity came from a

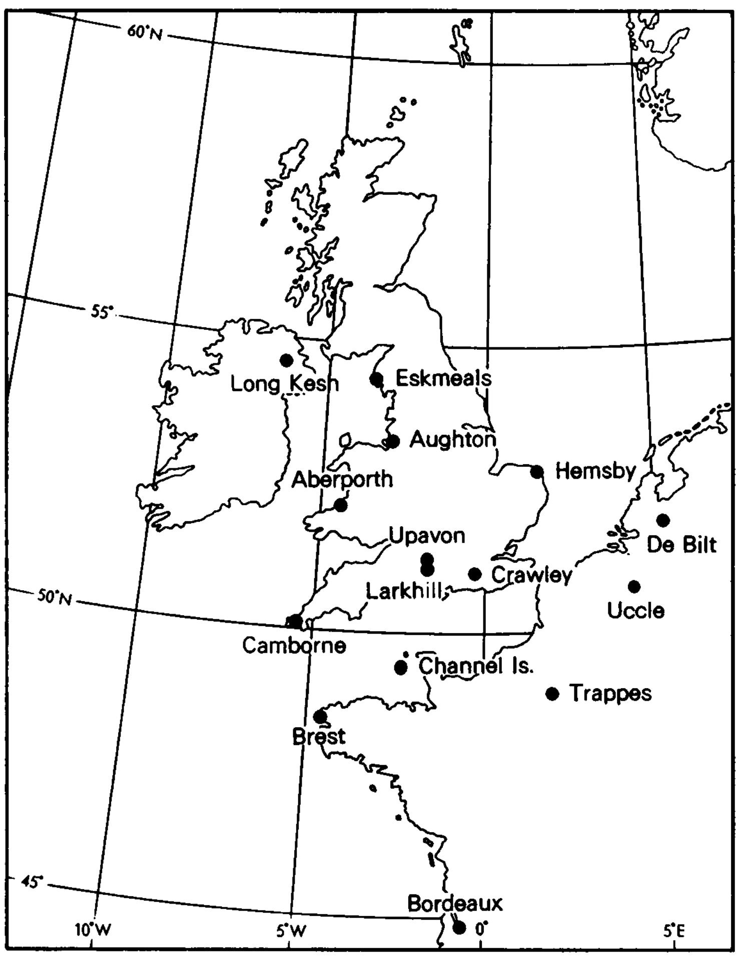


Figure 2. Location of places mentioned in article.

SFLOC report over central Brittany at 0800 GMT. Subsequent reports showed the area of activity moving north-north-eastwards at 17 m s^{-1} with thunder being heard at the Portland Bill Coastguard station at 11 GMT. This storm weakened as it moved inland, but a further thunderstorm reported at Portland Bill the following hour was later identified as part of a developing system which moved inland across east Dorset and Wiltshire to give a particularly active line-squall and tornado over Salisbury Plain (Smith 1980) between 1315 and 1330 GMT.

Fig. 3 shows the areas of precipitation, nominally* 1 mm h^{-1} and 4 mm h^{-1}, within a 50 km radius of Upavon, and derived from the computed raw radar data. The sequence of patterns shows clearly the south-west to north-east movement of the thunderstorm/squall front at about 50 degrees to the right of the backing mid-tropospheric wind flow (Figs (4a) and (b)). Plate I shows clearly the rainfall pattern depicted by the Upavon radar over a 210 km radius at 1403 GMT with its two distinct bands. The cellular cluster just to the north of Cherbourg is probably a newly formed thunderstorm cell, which moved into east Hampshire about one hour later. Further thunderstorms occurred during the afternoon over south-east England, later becoming widespread as the low moved north-north-east across the home counties. Drier weather which spread into south-west England behind the second rainfall band later extended to most parts of southern England by midnight.

Factors relating to the development of heavy rain

The development of the widespread heavy rainfall on the 30th was not, even with hindsight, immediately apparent from a study of the synoptic situation. Though the data at 00 GMT pointed towards cloud and rain moving from the south, none of the available data suggested the likelihood of copious rainfall.

The 00 GMT upper-air ascents from Crawley, Hemsby, and Camborne showed layers of cloud between 8000 ft and 18 000 ft, some of which were unstable, but the ascent for Brest, however, was rather more stable with moist layers to at least 24 000 ft. The radiosonde ascents from De Bilt, Uccle, Trappes, and Bordeaux, (see Fig. 2), revealed marked potential instability between 3000 ft and 20 000 ft, and infra-red pictures taken by the METEOSAT and NOAA 6 satellite systems showed this cloud belt to extend north-north-east from north-west Spain, across south-west England, and then, with breaks, to south-west Norway. A sequence of METEOSAT photographs covering part of 29 and 30 May has previously been published (Moore 1980).

Fig. 5 shows the 00 GMT analysis of the 14 °C θ_w surface following work by Harrold and Nicholls (1968), and Browning and Harrold (1969), and vertical motion (w) of about + 30 cm s^{-1} at Brest may be deduced from the diagram, although without upper-wind data from Bordeaux, the analysis over northern France is in some doubt. The absence of reports of moderate or heavy rain in Brittany at midnight supports the view that the deduced value of w at Brest is too high. Two further methods were therefore used to calculate the vertical motion more accurately.

The first used the sharp increase in θ_w—where the radiosonde sounding intersects the frontal zone—and the vertical wind shear to obtain the height of the frontal surface and hence the slope from the position of the front at the surface. A rate of vertical motion may thus be calculated using a simple formula (Appendix 1). This method will not give a detailed description of the bands of ascending and descending motion, but it will provide an indication of the activity of the front. Table I shows an analysis of the frontal surfaces at various radiosonde stations and the calculated rate of vertical motion.

* At that time the radar had not been calibrated against the check rain-gauges: the best available estimate was that the radar was under-reading by a factor of 2.

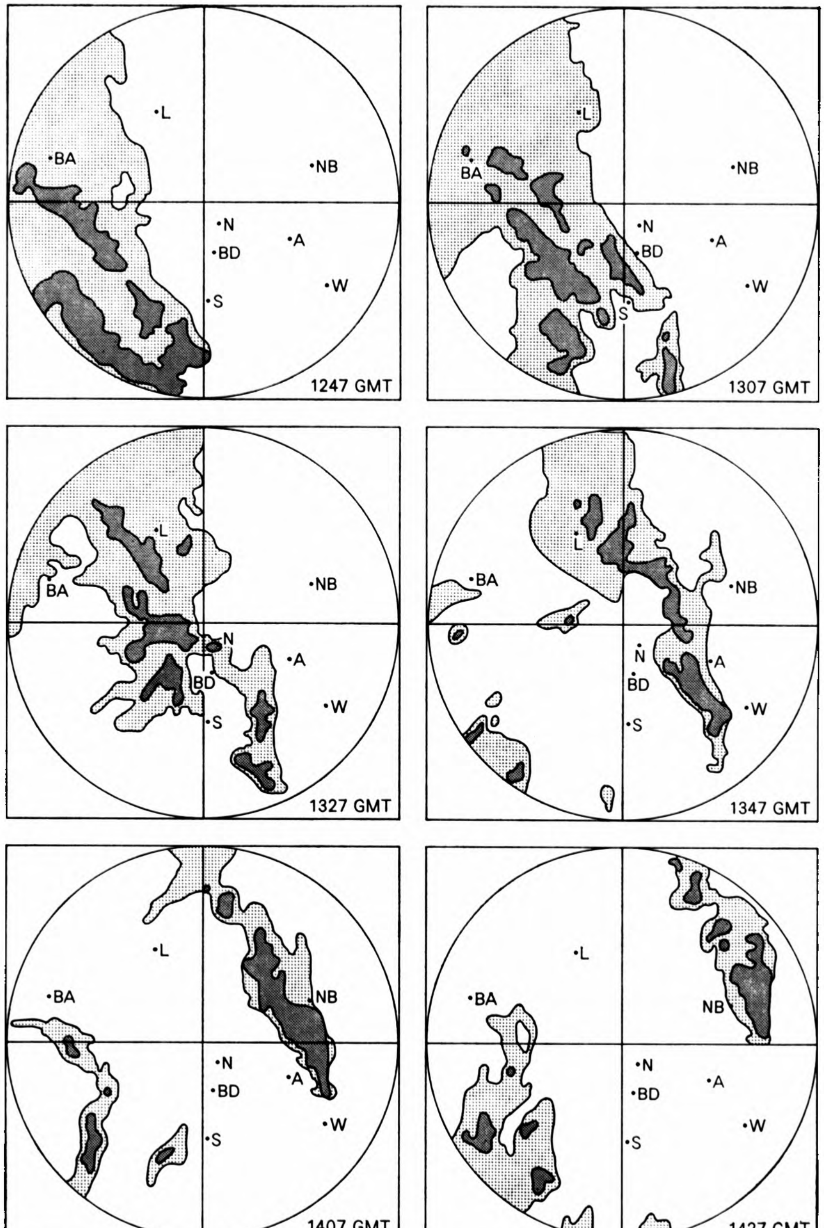
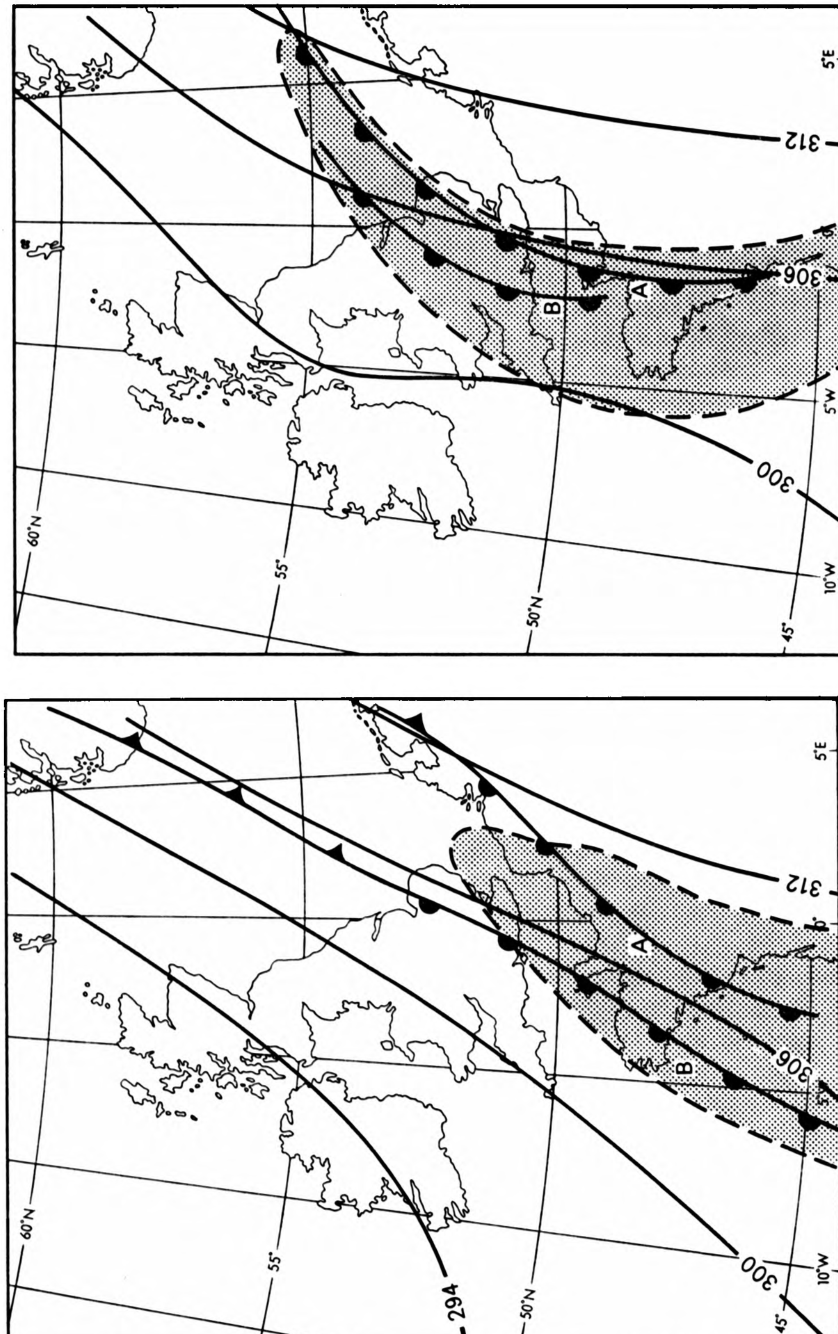


Figure 3. Precipitation patterns within a 50 km radius of Upavon at elevations of 0·5° or 0·9°. Light stipple indicates areas with precipitation nominally equalling or exceeding 1 mm h⁻¹, and dark stipple areas with nominal precipitation ⩾ 4 mm h⁻¹.

Key to locations: BA = Bath, L = Lyneham, NB = Newbury, N = Netheravon, BD = Boscombe Down, A = Andover, W = Winchester, S = Salisbury.



00 GMT

12 GMT

Figure 4. 700 mb geopotentials in decageopotential metres. Surface fronts shown conventionally. Shaded area indicates dew-point depression $\leqslant$ 2 °C. (a) 00 GMT, (b) 12 GMT.

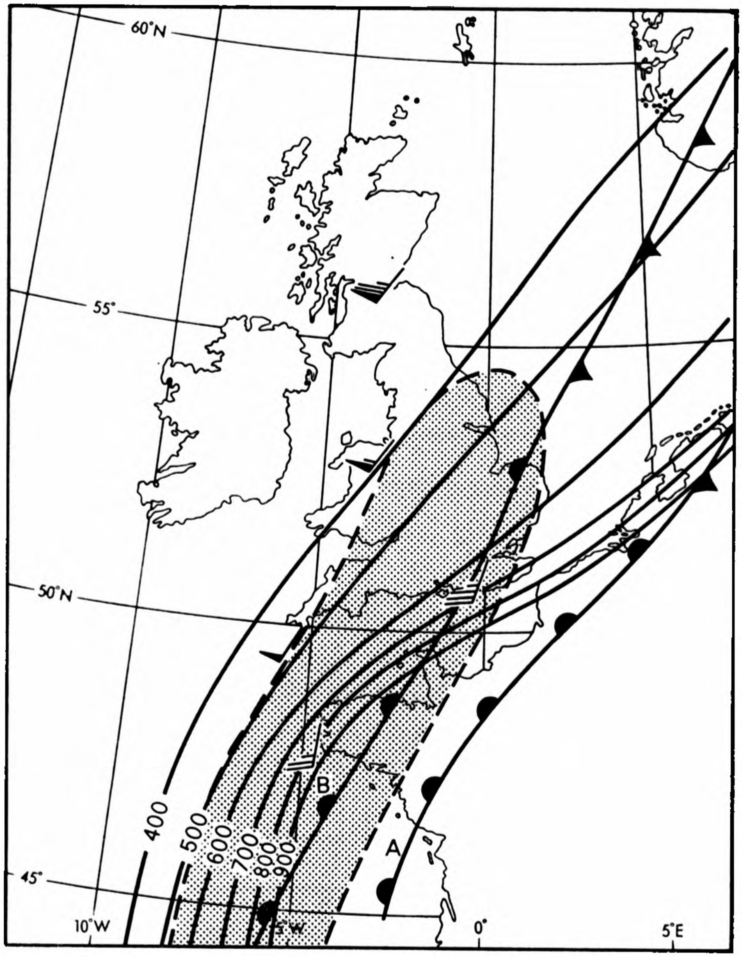
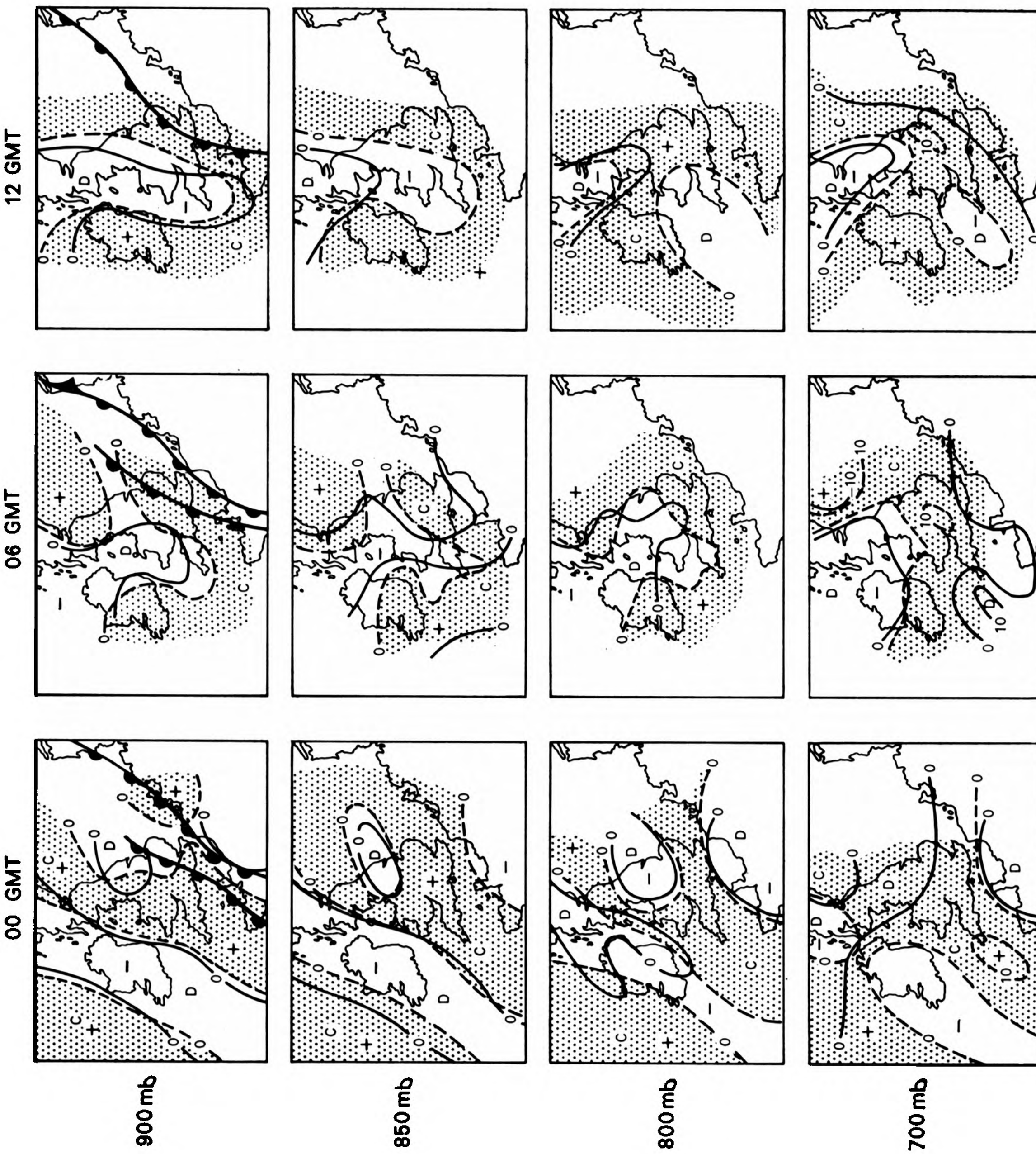


Figure 5. Analysis of 14 °C wet-bulb potential temperature surface at 00 GMT on 30 May 1979. Solid lines are isobars. Relative winds indicated by wind arrows: each full feather denotes 5 m s^{-1} and triangles 25 m s^{-1}. Shading indicates area with dew-point depression $\nless$ 5 °C.

No assessment was made for warm front B at Brest, because the front was within the surface friction layer.

The second method was based on the technique used by Bellamy (1949) and Poulter (1949). Briefly, a triangular system is devised between radiosonde stations, and by calculating the line integrals around the triangles, the horizontal divergence fields are calculated for the centroid of each triangle for each upper-air level, including an initial divergence field at the surface. From these values w may be computed using the method described by Holton (1972), for an incompressible fluid. Here the difference in w at the top and bottom of a column may be determined by multiplying the mean horizontal divergence of that layer by the thickness of the layer. Therefore with $w = 0$, at the surface of the earth, w may be computed for sequential layers in the vertical. The results for seven layers are shown in Fig. 6. The data are incomplete because upper-wind information was missing or unavailable at some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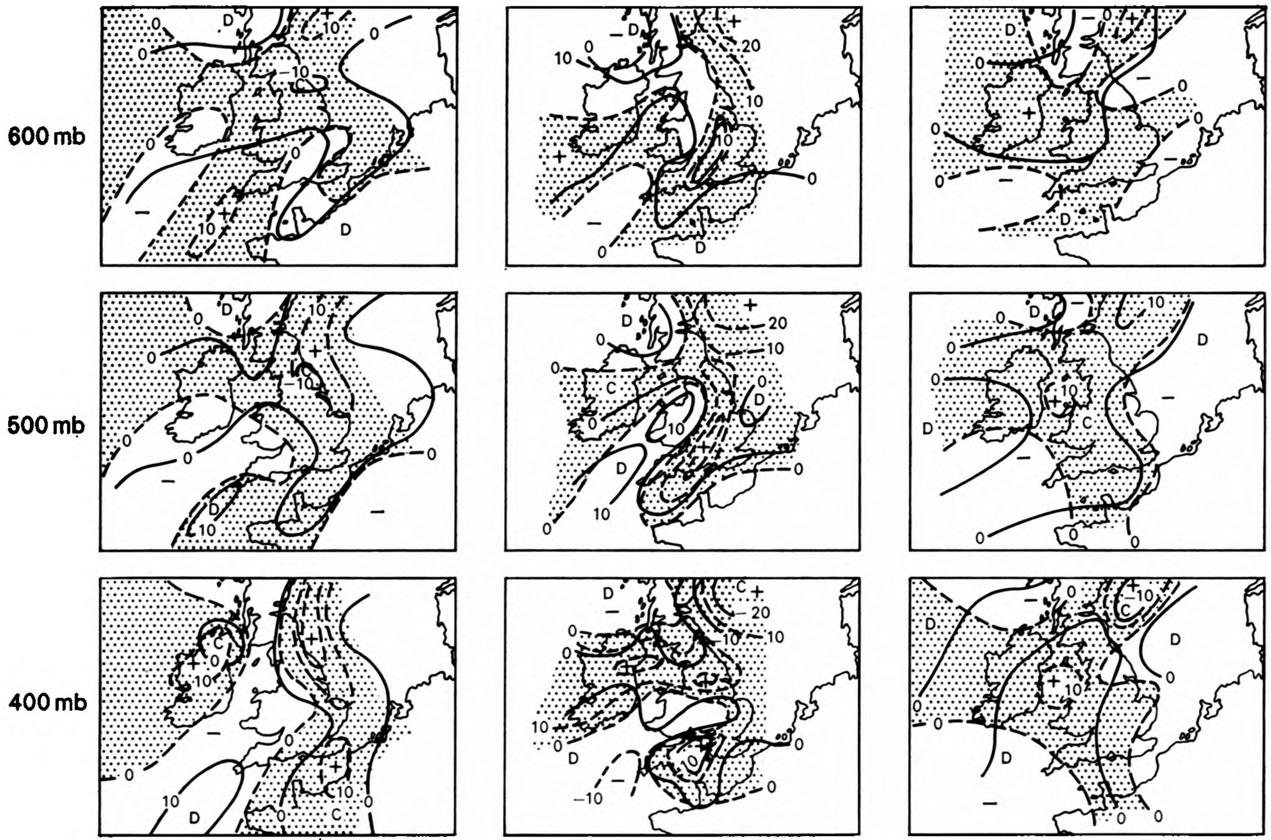

Figure 6. Divergence and vertical velocity on 30 May 1979. Divergence in full lines in units of 10^{-6} s^{-1}. Vertical motion in dashed lines in units of 1 cm s^{-1}. Areas of ascent are shaded and indicated by +; areas of descent are indicated by —. D = Divergence, C = Convergence. Surface fronts are superimposed at 900 mb level.

Table I. *Analyses of frontal surfaces on 30 May* 1979

(a) Warm Front A

Details of frontal zone (top T and bottom B)

Station	Time GMT	Height mb	Height km	θ_w °C	Wind degrees/m s^{-1}	Resultant wind degrees/m s^{-1}	Horizontal distance from surface front km	Slope degrees	Orientation of surface front degrees	w cm s^{-1}	ω mb h^{-1}
Camborne	00	T 535	5·06	14	210/40*	205/27·5	315	0·92	210	3·85	—9
		B 550	4·86	12	205/35*	200/23		0·88			
Brest	00	T 805	1·91	14	200/16	195/13·5	185	0·59	210	3·60	—13
		B 850	1·46	11	230/6·5	210/08		0·46			
	12	T 700	3·01	15	170/14·5	180/11	189	0·91	190	3·03	—9
		B 745	2·52	13	—	—		0·76			
Crawley	00	T 595	4·43	15	220/24	210/17	149	1·70	210	0·0	0·0
		B 605	4·24	13	215/20	205/16		1·62			
Larkhill	05	T 460	6·23	15	205/32	200/22	203	1·75	210	11·67	—30
		B 475	6·10	13	205/26	200/19		1·72			
	09	T 540	5·06	14	180/29	185/20	102	2·84	200	25·6	—68
		B 625	3·95	12	180/20	185/15		2·21			
(b) Warm front B											
Long Kesh	12	T 560	4·69	11	185/20	190/15	463	0·58	230	9·75	—28
		B 575	4·49	8	185/12·5*	190/11		0·55			
Aughton	00	T 620	3·91	11	205/29	200/21	231	0·97	210	6·17	—17
		B 680	3·22	9	210/14	200/12		0·80			
	12	T 700	3·02	12	170/12	180/11	212	0·82	230	12·05	—38
		B 720	2·80	8	Calm	190/05		0·76			
Aberporth	07	T 575	4·53	12	200/27·5*	195/19	315	0·82	210	7·04	—19
		B 600	4·21	10	205/21·5	200/16		0·76			
Camborne	00	T 640	3·70	12	205/27·5	200/20	250	0·85	210	5·15	—15
		B 720	2·78	10	200/16·5	195/14		0·63			
	12	T 730	2·66	12	190/10*	190/10	198	0·77	190	0·0	0·0
		B 850	1·44	9	140/03	180/06		0·42			
Larkhill	05	T 780	2·17	12	195/14*	190/12	93	1·33	210	9·53	—35
		B 810	1·87	10	205/08	195/09		1·15			
	09	T 855	1·41	12	155/13	160/11	22	3·36	200	41·44	—145
		B 930	0·72	10	070/09	150/05		1·71			

* Wind values are 'best estimates' at that level assuming the continuation of a marked shear in speed above the frontal surface.

Note. The height (in kilometres) of the frontal surface was obtained from the WMO table of geopotential altitude as a function of pressure and proportionally adjusted to fit the reported height of the standard reporting level above the frontal surface. Geometric height was assumed equal to geopotential altitude.

stations, at some or all levels. This method of calculation can be used with advantage where upper-air stations are fairly close together; however, small errors in the reported winds, or marked wind shears, can cause large errors in the horizontal divergence values.

Discussion of results

The diagrams in Fig. 6 show clearly the effect of increasing convergence along warm front B, with the largest values of w occurring over central southern England, at 06 GMT. Comparison of the results of Table I with these diagrams show a reasonable measure of agreement. The value of $w = 41{\cdot}44$ cm s^{-1} at Larkhill at 855 mb gives a clear indication of the marked increase in the convergence effect by 0900 GMT: it is consistent with the intensification of the main rain area over south-west and western England, and also with the probable values of w ahead of a developing line-squall and tornado system. The apparent decrease in values of w for midday is also consistent with the main squall front being confined to parts of Wiltshire, Hampshire, and possibly parts of west Berkshire.

The radiosonde soundings (Fig. 7) at Larkhill for 0500 GMT and 0920 GMT are of particular interest. If the ascents are modified to take account of w, the air mass becomes potentially unstable with considerable entrainment of moist air to high levels. This modification will also enable the analyst to calculate a new precipitable water content. Using the method developed by Benwell (1965), the precipitable water content, was, chronologically, 19 mm and 18 mm, for Larkhill. Modified, these figures become 22 mm and 24 mm respectively. Though Larkhill itself experienced less than 10 mm precipitation, the revised figures are nearer to the general level of rainfall in the area.

The criteria associated with the development of the tornadic storm are similar to those reported at the time of the Wokingham storm (Browning and Ludlam 1962) and the 1973 tornadoes (Whyte 1974). They are:

(a) a frontal zone across southern England, with south-south-westerly upper winds;

(b) development of the first storm over Brittany, probably over the Côtes du Nord where the land rises in places to over 350 m;

(c) movement of the storm to the right of the mid-tropospheric wind flow (Fig. 8);

(d) a marked vertical wind shear, i.e. a wind veer with height;

(e) a surface wind directly opposed to the path of the storm;

(f) a marked squall or gust front ahead of the storm; and

(g) a sharp veer in the surface wind behind the main storm.

Clearly these events demonstrate that the storm system contained a supercell, and can be classified as a 'severe right local storm' (see Browning 1968). It was unusual in that severe storms generally require θ_w values of around 20 °C. An analysis of the computer printout of the rainfall radar data, plus SFLOC reports, show that the thundery system could be tracked from 0800 GMT to 1450 GMT, and that from 1150 GMT onwards it probably consisted of a supercell with other smaller cells nearby. The rainfall radar system proved to be of considerable value to the forecasting staff at Main Meteorological Office, Upavon in showing the cellular structure of the rainfall pattern and the well-defined boundary marking the spread of clearer weather from the south-south-west.

Conclusions

The frontal storms were triggered off by the forced ascent of moist air over Brittany, and in moving across the English Channel encountered increasingly favourable conditions for development. The

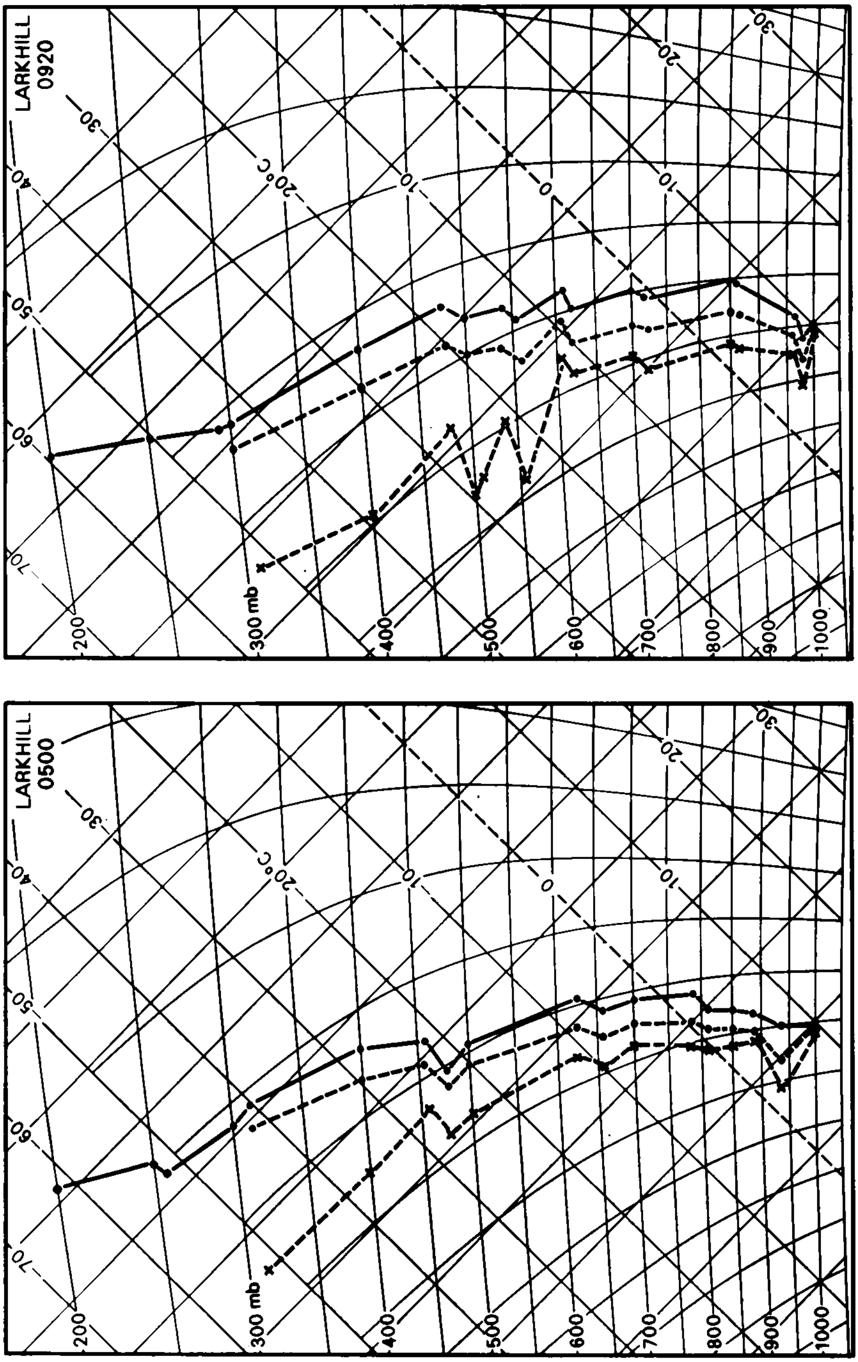

Figure 7. Radiosonde ascents at Larkhill on 30 May 1979. ●——● Dry bulb ●- - -● Wet bulb ×- - -× Dew point.

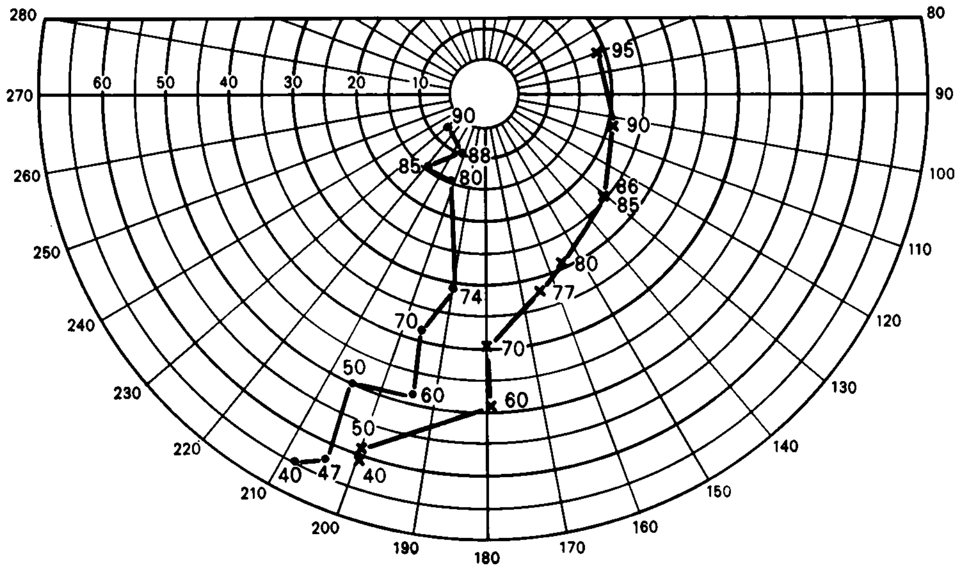

Figure 8. Hodograph of upper winds at Larkhill on 30 May 1979. ● —— ● 05 GMT, × —— × 09 GMT. Speeds in knots. Pressure levels in tens of millibars.

convergence, associated with the warm fronts, was responsible for the intensification of the rain area over western Britain, and the development of a supercell near the Dorset coast. Other storms were brought about by the effects of daytime surface heating over France, and the backing of the upper winds advected the storms across south-east and east England. Undoubtedly the key factor was the development of a surface ridge some 400 km to the north of Low A, brought about by a combination of anticyclonic disruption of the mid-Atlantic upper trough, and favourable dynamic factors in the baroclinic zone. This was responsible for the increased convergence over Britain.

Acknowledgements

Thanks are due to the staff at the Meteorological Office, Royal Signals and Radar Establishment, Malvern for supplying the rainfall radar printout, and to Mr J. D. Perry, Principal Meteorological Officer, 38 Group, for many helpful comments.

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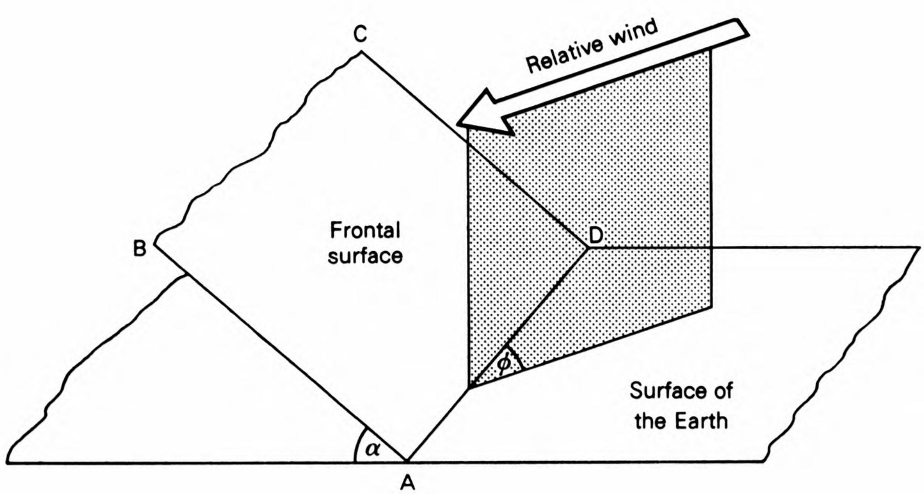
Appendix 1

Let ABCD represent a frontal surface intersecting the surface of the earth at an angle α. Then if the wind relative to the frontal surface is calculated and has magnitude V, the vertical motion can be assessed. If the (relative) wind is blowing parallel to AD (i.e. if $\phi = 0°$ or $180°$) then there is neither ascent nor descent. If the wind is blowing *into* the surface there is ascending motion, and if *away from* the surface there is descending motion. In general, the value w of the induced vertical velocity is given by

$$w = V \sin \phi \sin \alpha.$$



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The founding of the Meteorological Office, 1854–55

By R. P. W. Lewis
(Meteorological Office, Bracknell)

Summary

An account is given of the steps leading to the establishment of the Meteorological Department of the Board of Trade and the appointment of Captain R. FitzRoy, RN as its head in so far as they are ascertainable from contemporary sources.

The present account is intended to amplify, and in certain minor respects to correct, previously published accounts of the history of the Meteorological Office in so far as they are concerned with the actual foundation of that institution in 1854–55 and the appointment of Captain (later Admiral) Robert FitzRoy to be its head. The Office was founded as a department of the Board of Trade, and it is unfortunate that a large number of Board of Trade papers were destroyed towards the end of the last century so that it is possible that some primary documentary sources have disappeared forever; certainly, very little relevant material can be traced today, either in the Public Record Office or elsewhere. However, enough remains for the general course of events to be described clearly enough.

In 1853 the first international marine conference was held in Brussels as a result of the work of Lieutenant M. F. Maury of the United States Navy. (Following an accident which rendered him unfit for further active service, Maury had in 1842 been put in charge of the Depot of Charts and Instruments where he organized a remarkable survey of winds and currents, distributing logbooks to captains and plotting and analysing the results.) As a result of this conference, at which Maury represented the United States, a strong feeling developed in scientific and shipping circles that the British Government should co-operate with the Americans by setting up their own office to collect oceanic and other scientific observations and to tabulate the results. On 26 April 1853 Lord Wrottesley, a senior Fellow of the Royal Society (of which he was to become President in November of the following year) and an expert on astronomy and the observational sciences, made an eloquent speech in the House of Lords; this speech was later reprinted as a pamphlet entitled 'On Lieut. Maury's plan for Improving Navigation, with some remarks upon the advantages arising from the pursuit of abstract science' and makes good reading even now. In February 1854 Captain FitzRoy (as he then was) wrote the following letter[1] to Colonel Sabine*, the Treasurer of the Royal Society:

Febr. 3 1864

My dear Colonel Sabine,

I send a copy of the paper to which I referred yesterday. For the first year it would not be too *difficult* to carry on without a *draughtsman*, but *time* would be lost.

I have made no special allusion to magnetic observations because you are the Magnetic Chief who will say what and how much should be done—and because my "Outline" for Lord Wrottesley was to bear on Maury's plan alone. The more I think about the subject, the more interested I feel in it—and I shall forthwith prepare for regular work—by going to a convenient house—where I shall have air, *room*, and light—and shall be able to work *at home*, as well as in *other* places.

Mr Heywood, in a note *just received* by me, says—"On Monday, I intend to ask Sir James Graham, in the House of Commons, whether an Office will be established to co-operate with Lt Maury, and if the records of surveying ships,

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*General Sir Edward Sabine, K.C.B., F.R.S., 1788–1883; astronomer and geodesist; President of the Royal Society 1861–71.

preserved at the Admiralty, may be rendered accessible to the person in charge of that Office. I am glad to hear, from Lord Wrottesley, that the Office will probably be under the Board of Trade, as it will thus be more easily in communication with the Mercantile Marine".

I remain always
Sincerely and respectfully
Yours
Robt. FitzRoy

(I reserve *other* topics and *private* feelings).

At the same time, FitzRoy wrote a memorandum[2] of eight foolscap pages entitled 'Mode of proceeding in Office' which is reproduced as Appendix 1. The Parliamentary Question referred to in the letter was duly put by Mr Heywood on 6 February 1854 (Appendix 2).

On 3 June 1854 the Board of Trade addressed a letter[3] to the Royal Society in the following terms:

Office of Committee of Privy Council for Trade
Marine Department, 3rd June, 1854.

Sir,—I am directed by the Lords of the Committee of Privy Council for Trade, to acquaint you, that, with the concurrence of the Lords Commissioners of the Treasury, My Lords have determined to submit to Parliament an estimate for an office for the discussion of the Observations on Meteorology which it is proposed shall be made at sea in all parts of the globe in conformity with the recommendation of the conference held at Brussels last year; and they are about to construct a set of forms for the use of that office, in which it is proposed to publish from time to time, and to circulate such statistical results as may be considered most desirable by men learned in the Science of Meteorology in addition to such other information as may be required for the purposes of navigation.

Before doing so, however, they are desirous of having the opinion of the Royal Society as to what are the great desiderata in Meteorology, and as to what forms that Society consider the best calculated to exhibit the great atmospheric laws which it may be most desirable to develope.

I herewith inclose a form of Log which will contain all that it is proposed to execute at sea; but it may possibly happen that observations on land upon an extended scale may hereafter be made and discussed in the same office, and in framing your reply it is desirable that such a contingency should be borne in mind and provided for.

I am, Sir, your obedient Servant,
James Booth

To the Secretary, Royal Society

The Royal Society acknowledged this letter on 24 June in a communication[4] signed by Colonel Sabine which informed the Board of Trade that the President and Council of the Society had 'addressed a letter...to several of the most eminent meteorologists in foreign countries' asking for their comments and advice. (The final reply of the Royal Society was sent to the Board of Trade on 22 February 1855, and is of considerable length. It is reprinted as an Appendix to FitzRoy's Report[5] for 1857 in which it is oddly and probably mistakenly described as a reply to a letter from the Board of Trade dated 15 January 1854, not 3 June; I have not been able to trace any letter for this earlier date, but there was probably a misreading of 15 June (date of Royal Society Council meeting).)

The next undoubted fact is the appointment of Captain FitzRoy to a position in the Board of Trade on 1 August 1854.[6] In the article on FitzRoy written for the 9th Edition of the *Encyclopaedia Britannica* not long after FitzRoy's death it is stated that '...when in 1854 Lord Wrottesley, the President of the Royal Society, was asked by the Board of Trade to recommend a chief for its newly forming meteorological department, he, almost without hesitation, nominated FitzRoy...'. I have not been able to trace any contemporary evidence for this statement, and the Librarian of the Royal Society has informed me that there is no documentary support for it in the Society's archives. However, the article in the *Britannica* was written by John Knox Laughton (1830–1915) who served in the Royal Navy from 1853 to 1885 and then became Professor of Modern History at King's College, London; he was President of the Meteorological Society from 1882 to 1883 (his Presidency covering the time

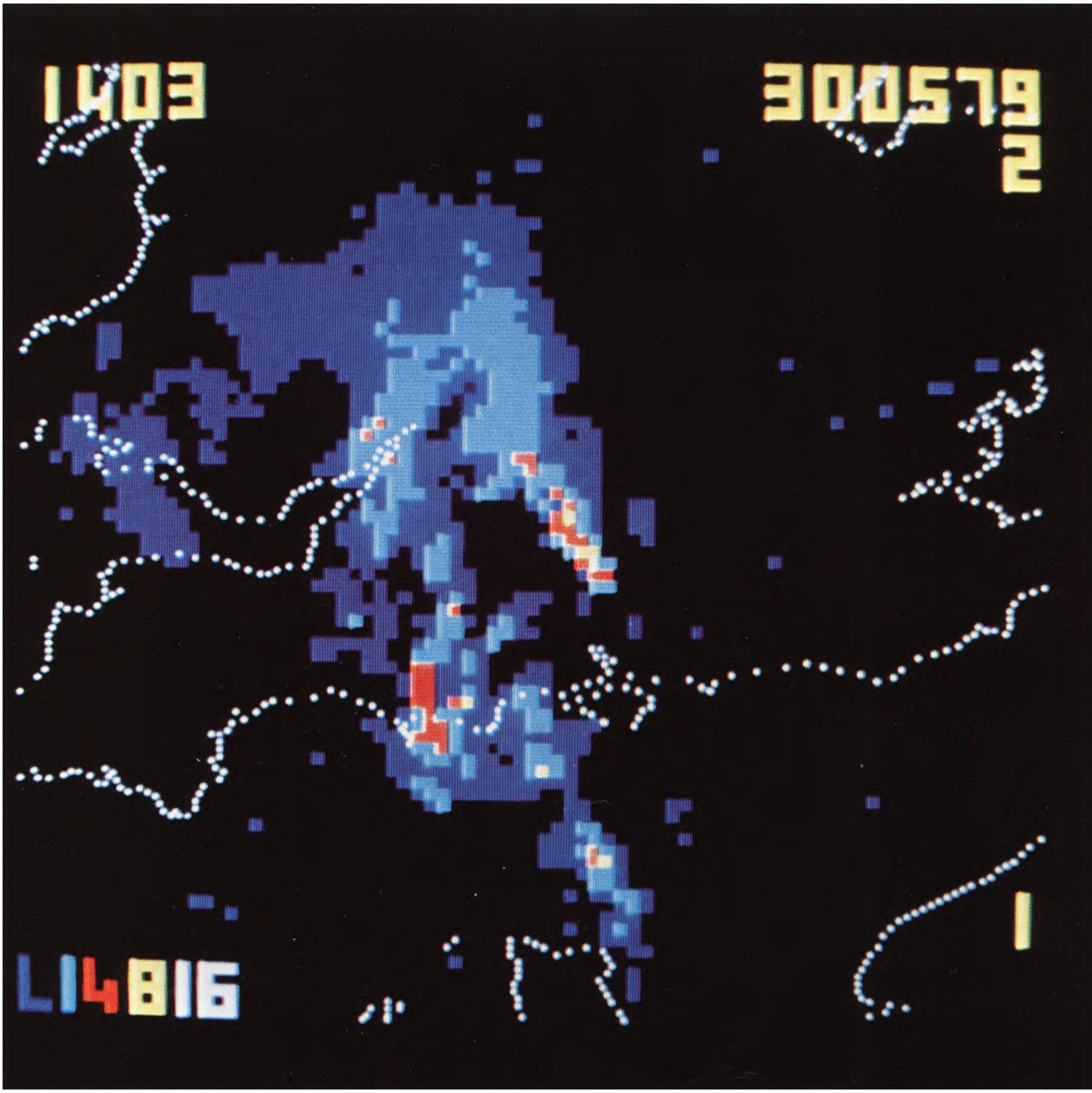

Plate I. Photograph of rainfall radar display at 1403 GMT on 30 May 1979, in 210 km radius of Upavon. (See page 210.)

Plate II. A new river bed caused by the avalanche of rainwater down the hillside on 1 August 1980 at Orra Beg, Co. Antrim. Note the car on the original road location. (See page 227.)

Plate III. Section of road hurled some 200 to 400 metres down the hillside at Orra Beg on 1 August 1980.

Plate IV. Hillside stripped cleanly to bedrock by force of water at Orra Beg on 1 August 1980.

Plate V. Picture shows 'fissures' approximately 3 m deep immediately above old road at Orra Beg on 1 August 1980.

Plate VI. Sunrise at Wokingham, Berkshire at 0718 GMT on 21 November 1980.

Photographs by D. J. Creasy

Plate VII. Sunrise at Wokingham, Berkshire at 0724 GMT on 21 November 1980. These photographs show the effect of the sunrise on the base of a spread of medium cloud in a ridge of high pressure ahead of a weak warm front over the South-west Approaches. Observations from Beaufort Park, Easthampstead around these times gave a light south-westerly wind and medium cloud between 10 000 and 12 000 ft.

that the Society obtained its Royal Charter) and was knighted in 1907. Although a very young man at the time of FitzRoy's appointment, Sir John Knox Laughton would later have been in a position to hear a good deal about it and may have had the opportunity of seeing papers that have since disappeared. (A minor error in the *Encyclopaedia Britannica* article is the description of Lord Wrottesley as the President of the Royal Society, an office he did not assume until several months after FitzRoy's appointment.) It is nevertheless clear from FitzRoy's own letter that he himself, Lord Wrottesley, and Colonel Sabine were in close touch on the matter. FitzRoy's own account,[7] dated 8 February 1855, is uninformative as to the precise steps leading up to his appointment, and is as follows:

> The importance of accumulating meteorological observations, and tabulating them methodically, for the purpose of future, rather than immediate investigation, having been urged by the Royal Society, while the practical benefits arising from such collections, even at the present time, were proved by the direct consequences of Maury's extensive labours, Her Majesty's Ministers agreed to establish an office under the Board of Trade for receiving and tabulating all such observations made at sea.
>
> It was considered that much information might be compiled with respect to currents, as well as winds, which might be made more generally known to those interested in the passages of ships across the ocean; and that the sooner such authentic compilations could be made generally available, the greater would be their value. It was, moreover, pronounced to be necessary that instruments of a reliable and understood nature should be alone employed; that they should be carefully tested and vigilantly guarded from accidental causes of error.
>
> To meet these objects, an estimate of probable expenses was submitted to Parliament, and the sums proposed were voted, namely, 200*l*, for the Mercantile Marine and 1000*l* for Her Majesty's ships.
>
> Soon afterwards an officer was appointed to execute the duties of the Meteorological Office, to be subsequently assisted by a few subordinates; but some time elapsed before instruments of the peculiar kind deemed proper by a Committee of the Royal Society could be finished, and an office appropriated for the object in view. Now the preliminary arrangements are made, and the Meteorological Office of the Board of Trade is open at No 2 Parliament Street...

FitzRoy's official title, as Head of the new office, seems to have varied somewhat, according to the entries in the *Imperial Calendar*. The first mention is in the 1856 edition where he is listed as 'Meteorological Statist', in the 1859 edition this is changed to 'Chief of Meteorological Department' and in 1864 to 'Chief of Meteorological Division'. Nowhere is there any reference to his being called 'Superintendent', which is the title given him in the list of names of Heads of the Meteorological Office inscribed on the wall of the entrance hall of the Meteorological Office Headquarters at Bracknell. The same list also has the letters 'C.B.' (Companion of the Order of the Bath) inscribed after his name. This is a mistake; FitzRoy never received any official honour or decoration for his work.[8]

The staffing and financing of the Office was on a modest scale. FitzRoy's first Report[9] to the President of the Board of Trade contains the following passage:

> The Meteorological Office being but recently established, and not having yet received a large supply of records, only four* persons are at present engaged in it, including the officer in charge.
>
> The sum estimated for 1854–5 was £3,200; but, as no expenses were incurred till half the financial year had expired, a balance remained in hand which may diminish the estimate necessary for 1855–6.

Despite the small number of staff, it is clear from a perusal of FitzRoy's early reports that a very large amount of work was carried out, consisting not only of routine office work and the regular tabulation of data, but of meteorological research and investigation. For example, Appendix No. 6 to the 1863 Report lists 54 'charts, books and pamphlets' published up to 1 April 1863. Although some were brief, and some were merely new editions, others were of considerable length, e.g. the '*Eleventh Number of Papers*' with 280 pages; indeed, the '*Papers*' series averaged 95 pages each.

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*In 1862 the number had risen to ten, but by that time FitzRoy had instituted the collection of daily reports by telegraph, and the issue of storm-warnings.

As to the name of the office, the first four Reports (1855, 1857, 1858 and 1862) called it the 'Meteorological Department of the Board of Trade', and the next two (1863 and 1864) the 'Meteorologic Office of the Board of Trade'; in the body of his first Report FitzRoy occasionally referred to it as the 'Meteorological Office'. The name 'Meteorological Office' was not officially agreed and made permanent until some time after FitzRoy's death. An interesting account of the way the Office worked and of the financial arrangements is given in FitzRoy's Report for 1862 which is reproduced as Appendix 3.

Acknowledgements

I should like to acknowledge the help of Mr R. E. Anslow of the Public Record Office, Kew, and of the Librarian of the Royal Society, Mr N. H. Robinson, who have provided me with copies of certain documents and other useful information. My thanks are also due to Mr David Stanbury who has made a detailed study of the whole life and career of Admiral FitzRoy.

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1. London, Public Record Office, BJ 3/61.
2. London, Public Record Office, BJ 7/2.
3, 4. Copies in Minutes of the Council of the Royal Society (meeting of 15 June 1854).
5. *Report of the Meteorological Department of the Board of Trade*, 1857.
6. London, Public Record Office, BT 3/50.
7. *Monthly Notices of the Royal Astronomical Society*, **15**, 1855, 165–158.
8. Communication from the Secretary to the Central Chancery of the Orders of Knighthood (Major General P. B. Gillott, C.B., C.V.O., O.B.E.).
9. *Report of the Meteorological Department of the Board of Trade*, 1855.

Appendix 1

On Maury's plan—Ocean Statistics—Mode of proceeding in Office R.F. Feb. 3/54

MEMORANDUM

With reference to Lieut. Maury's project,—It may be assumed that the oceans should be represented by charts or maps, as fully as may be practicable, consistently with clearness. Such charts should shew all the oceanic statistics that can be expressed, at a synoptic view, either by letters, or numbers, or symbolically.

Such statistical information if not all *immediately* useful to Navigation, will be hereafter, if not now, of value to Science.

The following may be a practical method of combining, obtaining and utilising Ocean Statistics.

Employ some nautical man who is interested in such subjects—whose character will guarantee his proceedings, and who will give full time and thought to their pursuing.

Assist him by a draftsman and a clerk. Appropriate an office. Fit it with tables and shelves.

Publish notices of an office being opened by the Government for the reception of Journals, logs, remarkbooks, and other records of nautical information. Issue skeleton forms, and popular instructions, gratuitously, to all proper persons, on condition of the forms being returned, more or less filled.

On the return of each such form, or on the delivery into office of any other acceptable document—a receipt should be given—for the same expressing its character and value, as estimated according to a scale.

Some mode of reward—by honorary distinction,—such as a testimonial, or diploma, or decoration, may be devised—to encourage those who contribute the more valuable observations.

These oceanic charts, in which meteorological facts should be combined with all others affecting the atmosphere, or the bed of the sea, or the ocean itself—these charts should be subdivided into Squares, more or less extending according to the nature of each tract of sea.

For every such space, or square, there should be twelve, or twenty four or even fifty two minutely (48?) subdivided charts—(for the separated data of each month, fortnight, or week) less or more according to the special importance and (varying) natures of each tract, or region. The original drawings should be projected on a large scale, and copied by lithography.

Reduction, and any kind of compilations may be subsequently effected. All factors recorded on the charts should likewise be registered in books, under letters, and numbers, that would correspond to similar distinctions on the squares of the charts (and places of deposit on the shelves of the office?).

While new information is being gathered, and duly entered, as it is received, (with as little delay as may be)—research should be made in every available repository of nautical information—in all the Voyages of every nation that are accessible—in each log, journal, and remarkbook that may contain useful factors bearing on this subject. Such gleanings, when combined, will contribute largely towards this important branch of hydrography—well termed, by Colonel Sabine, "Ocean Statistics".

Much research will be necessary, on the part of the individual charged with the extensive work of which an outline is here sketched. General results should be given by him annually, or from time to time, to [be] subsequently revised as increased knowledge may render advisable.

Libraries—Archives of nautical information, such as those at the Admiralty and India House—and private collections, should be examined, as far as may be practicable, and all facts extracted from such sources, or indeed, from any source, should be forthwith entered in a book—with the particulars necessary for reference to them hereafter, if requisite and for enabling other enquirers to verify any part of the work.

Meanwhile the routine duties of the office, namely receiving, issuing, and copying documents—drawing charts, and entering, or laying down observations, should proceed during the usual, and distinctly specified, hours daily.

From the person charged with these duties will be expected, from time to time, such practical Sailing Directions as may be the earliest return to the Public for their money appropriated for this service.

R.F. Feby 3/54

Appendix 2

Extract from *Hansard's Parliamentary Debates* for 6 February 1854

IMPROVEMENTS IN NAVIGATION—CAPTAIN MAURY'S PLAN—QUESTION.

MR. HEYWOOD said, he begged to ask the right hon. Baronet the First Lord of the Admiralty whether it was probable that an office would be established to co-operate with Captain Maury and the American Government in oceanic and other scientific observations; and whether the important collections of observations on currents, winds, and temperature, already in possession of the Admiralty, would be rendered accessible to the head of the proposed office?

SIR JAMES GRAHAM said, he was happy to inform his hon. Friend that, amidst more pressing and less peaceful occupations, the subject to which he had adverted had not failed to attract the attention of the Government. The President of the Board of Trade and he (Sir J. Graham) sent Captain Beechy to the Conference at Brussels, and in consequence of his report, it was the intention of the Government to appoint an officer to whom the observations made both on board merchant ships and Queen's ships would be referred. A Vote for this purpose would be taken in the Navy Estimates; and orders had been issued to the commanders of Her Majesty's ships, directing that meteorological observations should be made every four watches—that was, once every four hours—in every part of the world where Queen's ships were employed. An opportunity of making similar observations would also be furnished to a select number of merchant ships—not fewer than one hundred—and the result of all these observations would be returned to the Board of Trade, where they would be digested. They would then be communicated to Captain Maury, as would also the reports already received.

Appendix 3

Extracts from Chapter IX of the '*Report of the Meteorological Department of the Board of Trade*' for 1862, by Admiral FitzRoy.

28. The attendance here is necessarily continuous—between ten and six o'clock daily, for some—from eleven to five for others—of the ten persons employed; only two of whom are yet on the regular establishment of the Board of Trade, namely, Mr Pattrickson and Mr Babington, my zealous and able assistants.

Specially scientific duties are taken principally by the latter, whose Cambridge education and aptitude for meteorology have enabled him to render good public service. General management in the office, with financial business, correspondence, and much valuable aid in drawing and calculating, are Mr Pattrickson's particular business.

29. Meteorological telegraphy is satisfactorily attended to by Mr Simmonds and by Mr Symons, who, also, are assiduously engaged in extracting and reducing various meteorological observations, collected on an extensive scale, therefore needing much time for discussion and preparation for printing.

Mr Harding and his son attend to records, stores, correspondence, and translation. Mr Strachan has charge of the instruments and optician's duties, aided by Mr Gaster. Two youths carry out our weather reports, or telegrams, and are otherwise actively employed in searching for papers, extracting, and copying.

30. Consequent on the progress made, and the results gradually developed, arrangements for weather reporting increased in extensiveness, as has been shown, but the actual time now occupied by meteorological telegraphy is comparatively small, although we are in daily communication with twenty home stations—and with Paris, for six on the Continental coasts.

32. Kew verified instruments were intrusted to the care of clerks in charge of selected telegraph stations, by arrangement with the Directors of the Electric, the Magnetic, and the Submarine Telegraph Companies. Gradually and well those telegraphists acquired the duties asked for, then perfectly new, which are now continued with extremely creditable regularity and precision.

33. From the commencement in September 1860, no break, or interruption, not only of telegraphic but harmonious written intercourse, has occurred. The directors of those great companies have liberally reduced their tariff charges by one-third—in favour of our public communications, and have authorized reasonable precedence for our messages along their lines.

34. Being fully convinced that the importance, nationally considered, of this system of weather reporting—hitherto experimental—deserves support as a permanent institution—I ventured to submit to you, Sir, the following financial estimate.

35. In 1860—for the financial year 1861–2 the sum proposed to be voted by Parliament for "Meteorological Observations" was 2,800*l* which, with 900*l* provided for salaries and printing, under other heads (Board of Trade and Stationery Office), made a total or gross sum of 3,700*l*—for all purposes of this office—including an experimental commencement of meteorological telegraphy.

36. The expense of this new undertaking was first estimated at 100*l* monthly—and that estimate was found to be sufficient until the last quarter of the financial year 1860–1.

37. Nearly at that time (February 1861) the *cautionary signals* were first employed—and so well were they found to answer even on the very limited scale tried during the next few months—that in August following an extension of the system was organised by telegraphic communication from outlying stations—by more extended telegraphic *cautions*, and by daily "*forecasts*" of weather, regularly sent—entirely at the expense of the Board of Trade—to all the principal newspapers—which asked to be supplied with them, besides Lloyd's, Liverpool, and Glasgow Underwriters' associations. Since that time the Admiralty have directed the Coast-guard to co-operate whenever practicable—adding thus about eighty places of storm warning to the fifty previously in communication.

38. These important additions have not caused nearly so great an additional expense as might have been anticipated, because the Telegraph Companies have very liberally reduced their charges on meteorological telegrams for Government, by one-third, in general (and—in the case of Heligoland—one-half), while authorizing procedence on the wires, of all ordinary *private* telegraphy.

39. The result is that the system, at present considered to be working *satisfactorily*—can be continued in a similar manner—without asking for a larger increase to the meteorological vote than 100*l* above *last* year; or 4,600*l* instead of 3,700*l*.

40. The gross sum for meteorological observations in 1862–3 being thus estimated at — — —	£4,600
of which is provided for salaries at Board of Trade, 440*l*, and by Stationery Office, for printing forms, books, papers, tables, charts, &c., 360*l* — — — — — — — — — — — — — — —	800
Leaves to be provided — — — — — — — — — — — —	£3,800
Which will be required for–	
Salaries — — — — — — — — — — — — — —	£800
Agencies — — — — — — — — — — — — — —	50
Special printing — — — — — — — — — — — — —	150
Opticians — — — — — — — — — — — — —	100
Carriage, packing, and all contingencies — — — — — — — — —	100
	£1,200
Meteorological telegraphy — — — — — — — — — — —	2,600
1 February 1862 Total —	£3,800

41. This estimate shows the heads under which this sum may be divided; but it is to be said that the great expense of supplying *sets of instruments*, gratis, to merchant ships, has almost ceased; because ample results of that judicious annual expenditure, first authorized in 1854, are now in this office, sufficient to occupy all at present employed here during several years. To continue accumulating would tend to overwhelm.

42. Many of these instruments are now employed at telegraph stations—others are still on board a gradually diminishing number of selected ships, and a few are at maritime positions.

43. In addition to these scientific results, the stimulus that has been given to careful observation and record, the information that has been diffused in the mercantile marine—and the consequent direct advantage—in a national point of view—are now well known to have been very beneficial.

44. But having thus shown the way—and demonstrated its advantages—it may remain for others to follow, for their own advantage chiefly, by supplying themselves similarly with instruments, books, and forms—aided, perhaps, by advice—and occasional publications from this department,—but not otherwise continuing chargeable to the public purse.

45. In a scientific point of view, what has been accumulated here, since 1854, may be fully tabulated, discussed, and utilised—it is respectfully submitted, before overloading our shelves, and our minds, with materials increasing continually without advantage.

46. One of the greatest evils of meteorology hitherto has been the practice of incessantly making observations—without very definite objects in view—with the somewhat vague hope that eventually they might become of value; and the natural consequence has been, voluminous records exceeding the grasp of any genius and industry, however combined in individuals.

551.577.37(416)

Exceptional rainfall of 1 August 1980 over the North Antrim Plateau

By K. E. Woodley

(Meteorological Office, Bracknell)

Summary

An exceptionally severe and localized rainfall which occurred over the North Antrim Plateau on 1 August 1980 caused major damage to tarmacadam roads and swept a fisherman and his boat half a mile out to sea. Eyewitness accounts are given of this event, which has a return period of about 8000 years.

Mr John Young, the meteorological observer at Altnahinch Filters, witnessed and drew attention to an exceptional and very localized fall of rain and hail which occurred on the afternoon of 1 August 1980 in the North Antrim Plateau behind Cushendun in Northern Ireland. This led Mr S. J. G. Partington, Senior Meteorological Officer at the Climatological Services Meteorological Office in Belfast, to interview a number of other witnesses and later to visit the scene.

The downpour commenced at 1630 GMT and ended at 1715 GMT, during which 45 minute period 97·0 mm of precipitation fell at the Orra Beg rainfall station (located at Irish Grid reference iC 143277, altitude 335 m) and 47·0 mm fell at the Orra More, Ballybraddin rainfall station (located at IGR iC 125261, alt. 396 m). Daylight was reduced to virtually night-time conditions and hailstones the size of eggs were observed, with the mountainside white, so dense was the coverage. Some lightning was seen and thunder heard at Altnahinch, but the thundery aspect did not feature in the reports from other witnesses interviewed.

It was fortunate that the fall occurred on the 1st of the month, for the two rain-gauges are read only once a month and had been read and emptied that morning; otherwise the true amount of rainfall would not have been known.

A Mr McNeill, fisherman of Cushendun on the coast, was warned by telephone by some relations living up the valley of the River Dun, that a wall of water was forming, and this prompted him to rush to his boat moored in the estuary so that he might slacken his salmon nets. Whilst he was doing this, he saw this wall of water coming down the river, with an estimated height of between five and ten feet, and when it met the sea, he, in his boat, was swept out to sea about half a mile by the floodwater. This was some time between 1730 and 1800 GMT.

Some 60 metres' length of the Ballymone–Cushendall road was washed away, one end of the section being moved about 200 metres whilst the other end was washed about 400 metres (see Plates II and III). Two policemen in their patrol car were unable to stop before their car drove into the crater created by this landslip.

The area is a peat bog, laid on a solid rock base. The intense rain created fissures some 3 metres or so deep down to bedrock, and some craters appeared about 250 metres wide in which again all the thick peat was washed away, revealing the bedrock surface (see Plates IV and V).

The magnetic-tape rainfall recorder at Orra Beg, Ballybraddin was unserviceable at the time, and the next nearest rain-recorder (of the tilting-siphon pattern) at Altnahinch Filters recorded only a small amount of rainfall, it being on the extreme edge of this storm.

The fall of 97·0 mm in 45 minutes is a United Kingdom record fall for that period. If that information is fed into the return period statistical model developed after the United Kingdom Flood Studies Report, the 97 mm in 45 minutes has a return period for that part of Northern Ireland of around 8000 years.

Movements of peat and other debris from the bogs of Northern Ireland are not all that uncommon. The previous significant one known to the author was on 10 November 1963, again in the Glendun area. A list of bogflows was included in the paper 'Recent bogflows and debris slides in the North of Ireland' by Colhoun, Common and Cruickshank in the *Scientific Proceedings of the Royal Dublin Society*, Series A, Volume 2, No. 10 (1965). Another paper on the subject is 'Composite mudflows on the Antrim coast of North-east Ireland' by Prior, Common and Archer, in *Geografiska Annaler*, Vol. 50, Ser. A, 1968, 2.

We are grateful to Mr Young for his enthusiasm in returning promptly to the Orra More mountain rain-gauge sites to measure the rainfall of this storm: it is largely from such sources that the Meteorological Office and the former British Rainfall Organization have been able to collect reliable and detailed accounts of such localized events that go to make up the rainfall records of the country and are of such value to those who have to design and operate flood control systems.

Correspondence

A review of three long-term cloud-seeding experiments

We wish to comment on the above paper by Sir John Mason, published in the *Meteorological Magazine*, 109, 1980, pp. 335–344. We refer particularly to Mason's remarks concerning the experiment in Tasmania.

Analysis of the rainfall data of a cloud-seeding experiment of this type can only lead to valid statistical conclusions if the analysis is consistent with the design. Mason's 'reanalysis' of the Tasmanian data does not meet this requirement in several respects.

(a) Mason gives prominence to a comparison of the target area rainfalls in seeded periods with those in unseeded periods, making no use of the control area rainfalls. Because the Tasmanian experiment was conducted in an area of variable rainfall this method is insensitive: it would require an experiment conducted over several decades to give a statistically significant result. A rainfall change of reasonable magnitude could not be detected in this way over the four-year duration of the Tasmanian experiment, and it is even less appropriate to apply this method to the results of individual years (as in Mason's Table III).

The design of the experiment included control areas, chosen to have rainfall well correlated with that in the target area. Their use reduces the residual variance by 90% and so allows useful results to be obtained from a four-year experiment: for example they give a reasonable chance of detecting a 20% rainfall change at the 5% significance level.

(b) Mason compares target area rainfalls in seeded periods with those in years (1965, 1967, 1969) when there was no seeding and no randomization. This is not a valid statistical procedure. Moreover, the rain in these three years is known (Smith *et al.* 1977, p. 19) to have been about 27% less than that in the experimental years.

(c) Randomization was by period pairs, and the prespecified design includes stratification by season, pairs of periods being allocated to the season in which the mid-point of the period pair occurs. Mason transfers periods from one season to another in some of the columns of his Tables I and III.

(d) The design specified that results of the east and west halves of the target area should be analysed separately as well as together, because it was thought that results of seeding might differ in the halves, e.g. because of differences in orography. Our results in the halves did indeed differ, so when results for the halves are combined each dilutes the other and results for the whole target area are more difficult to detect than those in the halves. Mason considers only the combined results for the halves together.

We agree with Mason that a limitation of the Tasmanian experiment—designed in the early 1960s—is that there is not enough 'evidence of the structure, evolution and constitution of the clouds'. A body of supporting physical data could clearly answer many questions, including that posed by Mason—namely, to establish what was different about those clouds which appear to have responded to seeding. If a new experiment were planned for Tasmania extensive physical measurements would clearly be desirable; however, the data which could be obtained might well be limited by the hazardous flying conditions in the target area. Nevertheless, and in spite of the lack of physical measurement, the fact remains that the statistical evidence of the Tasmanian experiment clearly demonstrates an association between the seeding and increase in rainfall in the target area in certain seasons.

E. J. Smith

Division of Cloud Physics, CSIRO, Australia

L. G. Veitch
D. E. Shaw
A. J. Miller

Division of Mathematics and Statistics, CSIRO, Australia

Reference

Smith, E. J., Veitch, L. G., Shaw, D. E. and Miller, A. J. 1977 A cloud-seeding experiment in Tasmania—1964–1970. CSIRO Division of Cloud Physics Internal Report CP 183.

Reply by Sir John Mason

Smith *et al.* appear to misunderstand the point and purpose of my critique of the Tasmanian experiment. It was not my intention to criticize their statistical analysis and in particular their use of the double-ratio which may well be a more reliable and sensitive criterion than the single T_s/T_U ratio for the reasons which I acknowledge in my paper. I was concerned mainly with the overall credibility of the results of this and the other two experiments and to point out that one can arrive at quite different conclusions on the outcome of a cloud-seeding experiment depending on the statistical design and criteria adopted. For example, if Smith *et al.* had adopted the single ratio criterion used in the Florida experiment they would have concluded that seeding produced a decrease of rainfall in Tasmania. In the Israeli experiment, however, the single-ratio criterion indicates a distinctly positive seeding response which is confirmed by the double ratio. My real point is that when the magnitudes of both the seeding signal and the signal/noise ratio are low, as is usually the case, one can have little confidence in the statistical results unless there is strongly supporting physical evidence. This is surely the main lesson to be drawn from 30 years of largely fruitless effort.

Looking at the Tasmanian results overall one cannot overlook the fact that, although seeding took place only when the clouds were judged suitable and operational periods were arranged in pairs with one member of each pair being selected for seeding *at random* (the other being used as an unseeded control), the total rainfall in the target area during the 54 seeded periods of the 4-year trial was 8% *less* than in the unseeded periods. Moreover, only 19 of the 54 seeded periods produced more than the average target rainfall for the 108 operational periods and these occurred mainly in the spring rather than in the autumn.

The claim by Smith *et al.* that seeding produced a 25% increase in autumn rainfall therefore rests on the fact that the apparent 16% decrease in the target area rainfall ($T_S/T_U = 0{\cdot}84$) was more than offset by the corresponding ratio for the control areas C_S/C_U being as low as 0·66, i.e. by the rainfall being abnormally low everywhere, especially in the control areas, during the randomly selected seeded periods. This unfortunate bias, which apparently existed over the whole 4 year period, casts doubt on the efficacy of the experimental design and certainly merits investigation and explanation. In the absence of such an explanation, and of strongly supporting physical and dynamical evidence, I hold to my view that the overall evidence for a positive seeding effect, even in autumn, is not strong. The statistical evidence from the Israeli experiment is more convincing because both the single and double ratios were greater than unity (the target area rainfall was 16% higher during the seeded periods) but again supporting physical evidence is lacking.

Smith *et al.* imply that my conclusions are biased by the fact that in calculating double ratios I combined the two halves of the control area and that I would have obtained a different result had I used both halves separately. The following table shows that this is not the case.

Calculated double ratios using control areas

	C_1	C_2	$\frac{1}{2}(C_1+C_2)$
All 4 years	1·04	1·09	1·06
Autumn	1·24	1·27	1·25
Winter	1·02	1·12	1·07
Spring	0·98	1·01	0·99
Summer	0·94	0·91	0·93

B. J. Mason

Meteorological Office
Bracknell
27 *May* 1981

100 years ago*

THE HEAT IN JULY IN THE BRITISH ISLES, AND IN EUROPE GENERALLY.†

The occurrence of a temperature which at Greenwich has not been equalled for at least 40 years, and of a temperature at Brussels which has not been equalled for at least 48 years, naturally claims notice at our hands.

We have made a special effort to place the actual facts before our readers, and we desire in the first place to thank the Directors of nearly all the chief observatories of Europe for the promptitude with which they have supplied the information which we applied for.

We think that it will be convenient to separate the information relating to our own country from that furnished by our Continental friends, and we will therefore dismiss the records from our own little country first.

The British Isles

We might almost dismiss all parts of the British Isles except the South of England, for the exceptional temperatures were very local—a line from Barnstaple in Devonshire, to Peterborough in Northamptonshire would on its S.E. side have all the temperatures which could be regarded as exceptional. July 5th was a hot summer day, temperatures slightly exceeding 90° were recorded at several stations, and over the greater part of England it was the hottest day of the month, but we are not aware that any of the temperatures observed on that day were unprecedented. The remarkable feature of the month was the temperature reached on July 15th, in a belt of country extending from Wiltshire, through the north of Hampshire, north Surrey, west Kent, Middlesex, Essex, Suffolk and Norfolk.

The following tables contain the principal data upon which the foregoing remarks are based. These tables are mainly compiled from letters and returns sent by our own staff, but have been checked and completed by reference to those sent in to the Meteorological Society.

Space is so valuable that we have been obliged to condense much of the information furnished into a very small space; but we print two letters in extenso, one because it shows the evidence upon which we print the excessively high value of 101·0°; the other is inserted in support of the general statement as to the limitation of the phenomenal heat to the southern counties. As regards this, a curious illustration will be found in the Remarks, on page 132, where our correspondent at Portree, in the Isle of Sky, on the N.W. of Scotland, says July was "The coldest July on record." These letters will be found at the end of the article.

Symons's Monthly Meteorological Magazine*, **16, 1881.

†This spell of exceptionally hot weather is well known, and the temperatures recorded in the London area have seldom been exceeded. What makes the spell remarkable if not unique is that it occurred embedded in a summer which was otherwise distinctly on the cool side. Indeed, only two months in 1881 had mean temperatures above average at Kew—July and November; June and August had mean temperatures respectively 1·4 °F and 3·9 °F below average. Most spells of hot weather occur in summers that are as a whole warm, for example 1911, 1947, 1949, 1959 and 1976. The Revd T. A. Preston, in his 'Report on the Phenological Observations for the Year 1881' (*Quarterly Journal of the Meteorological Society*, Vol. VIII, p. 78) remarked that 'the weather of July was most extraordinary'.

MAXIMUM TEMPERATURES ON JULY 15TH, 1881.

Verified Thermometers in Stevenson's Stands.

(Large type indicates that the max. was the absolute max. of the month.)

95·0 Camden Square, Middlesex.
94·9 Eltham Green, Kent.
94·1 South Norwood, Surrey.
93·9 Strathfield Turgiss, Hants.
93·8 Walton-on-Thames, Surrey.
93·5 Regent's Park, Middlesex.
93·2 Beddington, Croydon, Surrey.
92·9 Isleworth, Middlesex.
92·4 Addiscombe, Croydon, Surrey.
92·0 Cranleigh, Surrey.
91·0 Watford, Herts.
90·9 Southend, Essex.
90·3 Tunbridge Wells, Kent.
90·2 Throcking, Buntingford, Herts.
89·4 Swarraton, Alresford, Hants.
89·3 Harestock, Winchester, Hants.
88·5 Somerleyton, Lowestoft, Nrflk.
87·7 Eastbourne, Sussex.
86·8 The Graig, Ross, Hereford.
86·0 Woodway, Teignmouth, Devon.
85·8 Portsmouth, Hants.
85·7 Burghill, Hereford.
85·5 Cullompton, Devon.
85·4 Hodsock Priory, Wrksop, Nots.
85·3 Kenilworth, Warwick.
85·0 Cheltenham, Gloucester.
84·9 Bitton, Teignmouth, Devon.
84·8 Mansfield, Notts.
84·6 Loughboro', Leicester.
84·4 Strelley Park, Nottingham.
83·7 Druid, Ashburton, Devon.
83·3 Ramsgate, Kent.
82·8 Babbacombe, Devon.
81·0 Brampford Speke, Devon.
80·8 Belper, Derby.
80·5 Guernsey.
80·3 Scarborough, York.
79·7 Oakamoor, Stafford.
79·7 Cardiff, Glamorgan.
78·5 Wakefield, Yorks.
78·4 Lowestoft.
78·2 Heath Ho., Cheadle, Stafford.
77·5 Macclesfield, Cheshire.
77·5 Sidmouth, Devon.
71·9 Llandudno, Carnarvon.
71·8 St. Michael's-on-Wyre, Lncsh.
65·9 S. Shore, Blackpool, Lncsh.

Records from Stands of other or unknown patterns.

(D.W.R.—Daily Weather Report of the Meteorological Council.)

101·0 Alton, Hants.
100·0 Alderbury, Salisbury.
97·1 Royal Obs., Greenwich, Kent.
96·7 Foxgrove, Beckenham, Kent.
95·6 Enfield, Middlesex.
95·0 D.W.R., London.
94·6 Camden Square, Middlesex.
94·2 Hornsey, Middlesex.
94·0 Hindringham, Norfolk.
93·8 Addiscombe, Croydon, Surrey.
93·3 Walton-on-Thames, Surrey.
92·0 Merton Villa, Cambridge.
92·0 Ipswich, Suffok.
92·0 Diss, Norfolk.
92·0 Cossey, Norwich, Norfolk.
91·0 Bromley Common, Kent.
91·0 D.W.R., Cambridge Obsvrty.
90·0 D.W.R., Nottingham.
89·0 Ellough, Beccles, Suffolk.
87·0 D.W.R., Oxford Observatory.
85·6 St. Leonards, Sussex.
85·0 Compton Basset, Calne, Wilts.
85·0 D.W.R., Jersey.
83·0 D.W.R., Spurn Head, Yorks.
83·0 Langton Herring, Weymouth.
82·5 Hythe, Kent.
81·0 D.W.R., Hurst Castle, Hants.
80·0 D.W.R., Dover.
80·0 Northampton.

CAMDEN SQUARE.—It was found that the temperature in different parts of the Stevenson stand varied more than a degree—a thermometer near the top recorded 95°·6, or one degree higher than on a Glaisher stand close by. The maximum on the Glaisher stand, 94°·6, is higher than has been recorded since observations commenced in 1858; the highest previously was that on July 21st, 1868, viz., 93°·3.—*G. J. Symons.*

ADDISCOMBE.—Observations have been made here with a Glaisher stand since 1872, hitherto the max. was 13th August, 1876 = 93°·6, but on the 15th July, 1881, it rose to 93°·8 on that stand, and to 92°·4 in the Stevenson.—*E. Mawley.*

GREENWICH.—The maximum temperature (97°·1) on July 15th is higher than any previously recorded in the period 1841-81. On July 22nd, 1868, the maximum temperature was 96°·6.—*G. B. Airy.*

FOXGROVE, BECKENHAM.—The following are all the readings of 90°·0 or upwards on a Glaisher stand since 1867:—1868, July 21st, 91°·9; 22nd, 93°·8; September 7th, 90°·0. 1870, June 22nd, 90°·8. 1871, August 12th, 90°·8; 13th, 90°·0. 1872, July 24th, 90°·0. 1873, July 22nd, 90°·6. 1874, July 9th, 92°·6; 19th, 91°·7. 1876, July 14th, 91°·3; 15th, 94°·1; 16th, 92°·1; 17th, 91°·3; August 13th, 93°·8; 14th, 90°·4; 15th, 90°·1. 1878, June 26th, 90°·1; 27th, 90°·1. 1881, July 5th, 92°·7; 15th, 96°·7.—*P. Bicknell.*

WALTON-ON-THAMES.—It is remarkable that the max. in the Stevenson stand is half-a-degree higher than on the Glaisher. The max. in the louvre screen on the tower, 50 ft. above ground, was only 91°·1, against 93°·8 at 4 ft. above ground.—*G. Dines.*

To the Editor of the Meteorological Magazine.

SIR,—As it was the hottest day I ever knew here yesterday, I thought you would like to be informed that my thermometer in the shade stood at 101°. The thermometers were made by Burrows, of Malvern, are about 4 feet from ground, on a stand made by them, painted white, facing North, with double back to the South; they were compared at Kew and found correct.—I am, yours truly,

FREDERICK CROWLEY.

Ashdell, Alton, Hants, July 16th, 1881.

To the Editor of the Meteorological Magazine.

SIR.—So much has been said and written about the almost tropical heat of July in the South, that it may interest you to contrast it with the cool moist weather we have experienced in the North-west of England during the same month.

The mean temperature of July at this station was 57°·7, which is 1°·8 below the average for the month during the previous nineteen years.

The maximum thermometer in the shade reached 70° on only one day during the month, viz., on the 5th, when the reading was 78°·2 (this was just before a thunderstorm). The next highest shade temperature was 68°·4, on the 13th.

Rain fell on 20 days during the month; the total amount being 4·633 inches, and the heaviest fall in 24 hours, 1·680 inches, on the 24th.—I am, Sir, yours truly,

H. DODGSON, M.D., F.R.A.S., &c.

Cockermouth, Cumberland, August 3rd, 1881.

Review

Application of remote sensing to agricultural production forecasting, edited by A. Berg. 250 mm × 170 mm, pp. vi + 266, *illus.* A. A. Balkema, Publishers, Rotterdam, The Netherlands, 1981. Price Hfl 120·00, £24.00, US $55·00.

This book describes itself as '18 lectures of a course held at the joint research centre of the Commission of the European Communities in the framework of the Ispra Courses in Ispra, Italy'. It has been printed from the typescript texts which were produced 'under the supervision of the individual authors'. This has had the advantage of providing a 'state of the art' survey of this important topic which is reasonably up to date (the course was held in October 1979) but the disadvantage that the book lacks the coherent structure that greater editorial control would have given. There are 19 authors in all.

As a consequence the reader is not presented with a logical development of the subject (even though no doubt the organizers tried to achieve this when they decided on the subject titles of each lecture and the order in which they were given). There is frequently a repetition of particular topics in different chapters (e.g. the surface radiation balance) but a complete lack of consistency in the use of symbols, subscripts etc. Only two chapters have a summary. There are several obvious errors in the text, most of which are fortunately irritating rather than misleading, and minor editing of the English of some of the authors would have improved their contributions considerably. The quality and comprehensiveness of the different chapters varies enormously.

An introductory chapter or preface describing the aims of the course at Ispra, and giving a short history of the development for agricultural purposes of remote sensing from aircraft and satellites (with a brief summary of the various satellite systems in use at the time and projected) would have been very useful to the non-specialist in the subject, and provided a rapid reference for the bemused reader when lost in some of the jargon of the later chapters.

A considerable part of the book is taken up with the problems and techniques of crop production forecasting from conventionally observed weather data. These chapters are generally interesting, readable and instructive, as would be expected with authors such as Thiede, Frère, Baier, Sakamoto and Nix. Various forms of simplified simulation models for estimating crop production (most of which involve calculation of a soil moisture budget) are described, as also are crop/weather regression models, whose limitations are well documented.

The three chapters on remote sensing techniques using different parts of the electromagnetic spectrum are numbers 5, 15 and 17 covering: (a) reflected radiation in the visible and reflectance infra-red; (b) thermal (emission) infra-red; (c) microwave. These give a general survey of the theory and practical limitations of each technique, and the need to obtain good temporal as well as spatial sampling in order to interpret the data is explained.

The discussion of the use of observations obtainable from remote sensing in crop production forecasting is the least satisfactory aspect of the book. To some extent this is due to the difficulty of the problem, but some of the chapters (excluding those of Berg and Rosema) are very superficial. The chapter by Heiss, Sand and Farley on 'Economic benefits of improved crop information on wheat and cereals for European countries' contains a very detailed mathematical exposition of the economic theory used, which the reviewer is not qualified to judge as to its applicability, and makes the assumption that the European Community is a net importer of cereals; however, Thiede in the first chapter has already made the point that he expects the Community to be self-sufficient in cereals in the near future with a clear surplus by 1985. The chapter by Heiss *et al.* is even more unsatisfactory since it does not give the results of the model, but says that they will be published in a future report.

The final chapter of the book by Walter gives a useful summary of the potential of the Landsat D satellite observations, but is over-optimistic with regard to the resolution which may become possible with geostationary satellites.

At a price of £24 the reader has the right to expect a more complete and accurate account of the present stage of development of this subject than is available in this book. However, there is a good deal of useful information if he is willing to search diligently.

Marjory G. Roy

Notes and news

551.507.362.1

Skua meteorological rocket program terminated

The Skua rocket launched from the Royal Artillery Range, South Uist, Outer Hebrides on 14 November 1980 marked the end of the Office's meteorological rocketsonde program. More than 500 Skua rocketsondes had been flown since 1963.

Small inexpensive rockets, which could carry a sonde aloft and deploy it and its parachute at a height of about 65 km, became available in the United States around 1960. These rockets made it possible to measure winds (by tracking the metallized parachute) and temperatures between 20 and 60 km on a regular basis. The Skua system was developed to obtain similar observations in Europe. The project was undertaken by the High Atmosphere branch and led by Dr R. Frith. Bristol Aerojet Ltd and the Rocket Propulsion Establishment, Westcott, developed the 5-inch diameter rocket system, whilst D. D. Clark (1965) and R. Almond (1969) were responsible for the development of the sonde. A coiled tungsten wire of fine gauge was adopted as the temperature-sensing element. By coincidence the first four Skua firings from South Uist (12–23 January 1964) spanned a stratospheric warming (Almond, Farmer and Frith, 1964).

The *Meteorological Magazine* has since carried a number of papers describing the project's progress and presenting some of the results. The Skua system came into regular use at South Uist in 1965 (Almond 1965). Substantial differences were revealed between mean winds and temperatures observed at South Uist in winter and those found at a similar latitude over North America (Farmer 1965). In the following years behaviour of the 20–60 km region in winter was studied by campaigns of firings from South Uist, during which two or three rockets were often fired each week from December to February. Large and rapid changes in temperature and wind were observed in association with stratospheric 'warmings' (Bridge 1971). The second half of December was often a very active period. Those involved were so enthusiastic that firings were maintained throughout the festive season (although no firings took place on Christmas Day). However, the extent to which atmospheric changes observed at South Uist represented advection or development was never clear, since the only other rocket observations, over North America, were too distant. During January 1970 Skua firings were made from both South Uist and ESRANGE (near Kiruna in Sweden), in collaboration with University College, London. This exercise was repeated in January–February 1971, with the addition of some firings from Aberporth. Unfortunately neither of these campaigns was graced by a major stratospheric disturbance over north-west Europe (Bridge 1973).

With the launch, in April 1970, of Oxford and Reading Universities' Selective Chopper Radiometer on board the Nimbus satellite, it was possible to produce global maps of stratospheric temperature. Whilst satellite observations of radiance have provided a much clearer picture of the behaviour of the stratosphere, there are problems in interpreting radiances coupled with slow drifts in instrument characteristics. Flights of rocketsondes at times at which the satellite is passing nearby are an important means for tackling these problems. During the past decade, most Skua firings at South Uist were made for this purpose, in conjunction with the series of Oxford University radiometers on Nimbus 4, 5 and 6 and, since 1978, with the Office's Stratospheric Sounding Units on Tiros N and NOAA 6. Although these firings formed only a small fraction of the total number of rocketsondes flown worldwide, we could control launch times at South Uist to coincide closely with satellite overpasses.

Rocketsondes provide much better vertical resolution than satellite sensors, making them specially suitable for certain investigations. About 70 Skuas were flown between 1969 and 1972 from the island of Gan, in the Indian Ocean, to study the diurnal variation of temperature and wind in the equatorial stratosphere (Shearman 1969, Hamilton and Shearman 1972). During the March 1970 campaign ten Skua rocketsondes were flown from Thumba, India, as a Commonwealth collaborative venture. Observations from two sites provided information on the spatial extent of features in the wind profiles.

Over the years considerable effort was devoted to reducing uncertainty in the corrections for dynamic heating and radiation which had to be applied to the temperatures indicated by the wire element (e.g. Mason and Acres 1972). The Skua system was flown alongside other rocketsonde systems during trials organized by the WMO Commission for Instruments and Methods of Observation (CIMO) at Kourou, French Guiana, in 1973. The performance of the Skua sonde was found to be in close agreement with that of the American sondes. The observations made at Kourou have been used to investigate diurnal variations in temperature and wind (Bridge 1979).

Temperature and wind profiles measured at South Uist have been distributed, as ROCOB messages, on the Global Telecommunication System (GTS) and archived at World Data Center A, Asheville, USA. Observations made up to 1972, including those from Kiruna and Aberporth, were used to produce a climatology of the stratosphere over north-west Europe (Hamilton, Mason and Bridge 1973). Some aspects of this climatology have been extended to include subsequent firings at South Uist (Carruthers and Francis 1981).

The Skua program benefited by co-operation and assistance of many people . Valuable contributions were made by the Commandants and staff of the Royal Artillery Range, Hebrides; Principal Meteorological Officers and staffs at Prestwick and Pitreavie; Senior Meteorological Officer and meteorological and Range staff at Aberporth; staff of the Equipment Provisioning Branch of the Meteorological Office and various contractors. Although the Skua program has ceased, the Office will continue to make a major contribution to the observational system for the stratosphere into the late 1980s, through provision of Stratospheric Sounding Units for the Tiros-N series of satellites. D. E. Miller

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The Society for Underwater Technology to sponsor Oceanology International '82

The Society for Underwater Technology has agreed to sponsor the Oceanology International Exhibition and Conference (Metropole, Brighton, 2–5 March 1982) and will be giving the event its full support. The Society will form a Conference Committee under the chairmanship of John A. Derrington, F. Eng., Director, Sir Robert McAlpine & Sons Ltd, Past President, Institution of Structural Engineers, Vice-President, Institution of Civil Engineers, and Chairman of the National Maritime Institute Board.

The Committee will include corresponding members from equivalent European Societies and organizations and the program will be international in character.

The Conference, which, like the Exhibition, will last for four days, will include sessions on the following subjects:

Geophysics/soil mechanics
Hydrography/sea bed surveys
Marine mining—deep ocean and near-shore
Navigation and position fixing
Dredging and coastal engineering
Underwater research and development
Oceanography/meteorology
Environment/ecology.

The Society has agreed to give the widest possible publicity to the Exhibition and Conference within and beyond its membership at home and abroad, commensurate with the traditional prestige and standing of Oceanology International.

More information about the composition of the Committee and the detailed program headings will be available during summer 1981. The program will consist of between 40 and 50 papers and the Society for Underwater Technology will hold a watching brief over the progress of the conference organization and ensure a high standard of paper presentation within a program having a strong international presence and appeal.

The rights to the title and goodwill of the Oceanology International series of exhibitions and conferences, which have been held in Brighton on five occasions since 1969, were acquired in February 1981 by Spearhead Exhibitions, organizers of the Offshore Europe series of exhibitions and conferences in Aberdeen, as well as the Latin American Oil Show, and the AODC's Underwater Engineering Symposium. Spearhead is also a partner in Offshore South East Asia in Singapore. Further information on Oceanology International '82 is available from Spearhead Exhibitions Ltd, Rowe House, 55–59 Fife Road, Kingston upon Thames, Surrey KT1 1TA. Telephone: 01-549 5831. Telex: 928042 SPEARS G.

Involvement of Meteorological Office with recent foot-and-mouth disease outbreak

The stand-by arrangements for the call-out of the staff of the Agricultural Meteorology section of the Office in connection with foot-and-mouth disease were activated late on Saturday 21 March 1981.

A watching brief and advice to MAFF veterinarians had been undertaken over the previous two weeks.

Computer programs which indicate the down-wind concentration of virus plumes were updated around midnight. A staff member travelled with the computer output to join the veterinary epidemiological team (which sets out to control the outbreak in the field). He was in the Isle of Wight early on Sunday, 22 March.

Several Branches contributed to the information channelled to MAFF through the section (both during the alert and in the development work leading up to the present advisory procedure). MAFF have expressed appreciation of the speed and quality of the advice given.

Last flight of Meteorological Research Flight Canberra

The last flight of Canberra WE 173 of the Meteorological Research Flight (MRF) took place on the afternoon of Tuesday 31 March 1981. The aircraft, the only PR3 still in service, was delivered to MRF in 1964, since when it has carried out a variety of meteorological research projects in the upper troposphere and lower stratosphere both in the United Kingdom and abroad. These included the measurement of stratospheric humidity—extending earlier MRF measurements in the Mosquito aircraft—of disturbed airflow at high levels using accurate winds derived from a combination of stable platform and wind vanes, of upward and downward radiation in a variety of wavelengths and spectral intervals using specially adapted multi-channel radiometers, and more recently of trace gases in the stratosphere above the aircraft using an advanced Michelson interferometer in the sub-millimetre wavelength region. The withdrawal of the Canberra marks the end of more than 30 years of research by the MRF on the atmosphere above the tropopause.

Correction

Meteorological Magazine, **110**, 1981, 139. Several numbers were misplaced in Table VI of 'The accuracy of London Weather Centre forecasts of surface wind and total wave heights and their comparison with computer products' by R. M. Morris. The corrected version is printed below.

Table VI. *Mean modulus errors (in knots) of wind speeds in the ranges* 0–20 *and* 30–39 *knots at* 61° N 2° E *with respect to period of forecast*

Method	Range of wind speeds (kn)	Forecast period T+12	T+24	T+36	T+48	T+72
Rectangle	0–20	4	5	5	—	—
	30–39	9	8	11	—	—
Octagon	0–20	—	—	5	5	6
	30–39	—	—	14	15	18
LWC forecaster	0–20	6	7	—	8	8
	30–39	6	6	—	7	9

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1.80 monthly
Dd. 716670 K15 8/81

Annual subscription £23.80 including postage
ISBN 0 11 726285 4
ISSN 0026-1149

THE METEOROLOGICAL MAGAZINE

September 1981

Met.O. 942 No. 1310 Vol. 110

HER MAJESTY'S STATIONERY OFFICE

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1310, September 1981, Vol. 110

551.501.9: 551.577.21(427 + 428)

A survey of rainfall recording in two regions of the northern Pennines

By P. D. Jones
(School of Environmental Sciences, University of East Anglia, Norwich)

Summary

Monthly rainfall records for three areas of the northern Pennines have been analysed for the years of available records. Composite records were produced for Allenheads (Northumberland), Kettlewell (Yorkshire) and Malham Tarn (Yorkshire) back to 1854, 1853 and 1870 respectively. The records are compared with each other and suggestions are made for extending them back further in time.

Introduction

The Pennine Chain, which forms the backbone of England, marks the divide between two distinct precipitation régimes, north-west and north-east England. The former region has enhanced orographic precipitation while the latter is in the rain shadow. All the rivers of northern England have their headwaters in the Pennines, so rainfall variability directly determines the return periods of dry flow sequences and flood flows in both north-western and north-eastern England.

Rainfall recording in the northern Pennines began later than in most other mountainous parts of the British Isles. The lack of rain-gauges at altitudes over 1000 ft (305 m) prior to 1880 is particularly pronounced (see, for example, Symons's (1866) report to the British Association). Two areas where recording began early were the Alston region in the South Tyne valley (Fig. 1(a)) and Kettlewell in Upper Wharfedale (Fig. 1(b)). Both sites possess a sufficient number of rainfall records to enable a composite record to be produced since 1854 at Allenheads (Alston) and since 1853 at Kettlewell. At the headwaters of the River Aire, the valley south of Wharfedale, lies Malham Tarn from where a number of rainfall records are available (Fig. 1(b)). These are combined into a third composite Pennine record.

Rainfall recording in the Alston region of Cumbria

Table I lists the rain-gauges that have operated within 15 miles of Alston that were considered important for the construction of a composite record to represent the region. The list is almost certainly complete up until about 1900. After this, and particularly during the last 20 years, only a selection is given. Table I lists only the principal observer or observers and the main height above mean sea level at which the gauge was operated. At a number of sites the observer and gauge height change frequently, especially from one 10 year sheet to the next. Only changes which have affected the gauge catch are noted in the text. Fig. 1(a) shows the relative positions of the gauges. The construction of the composite

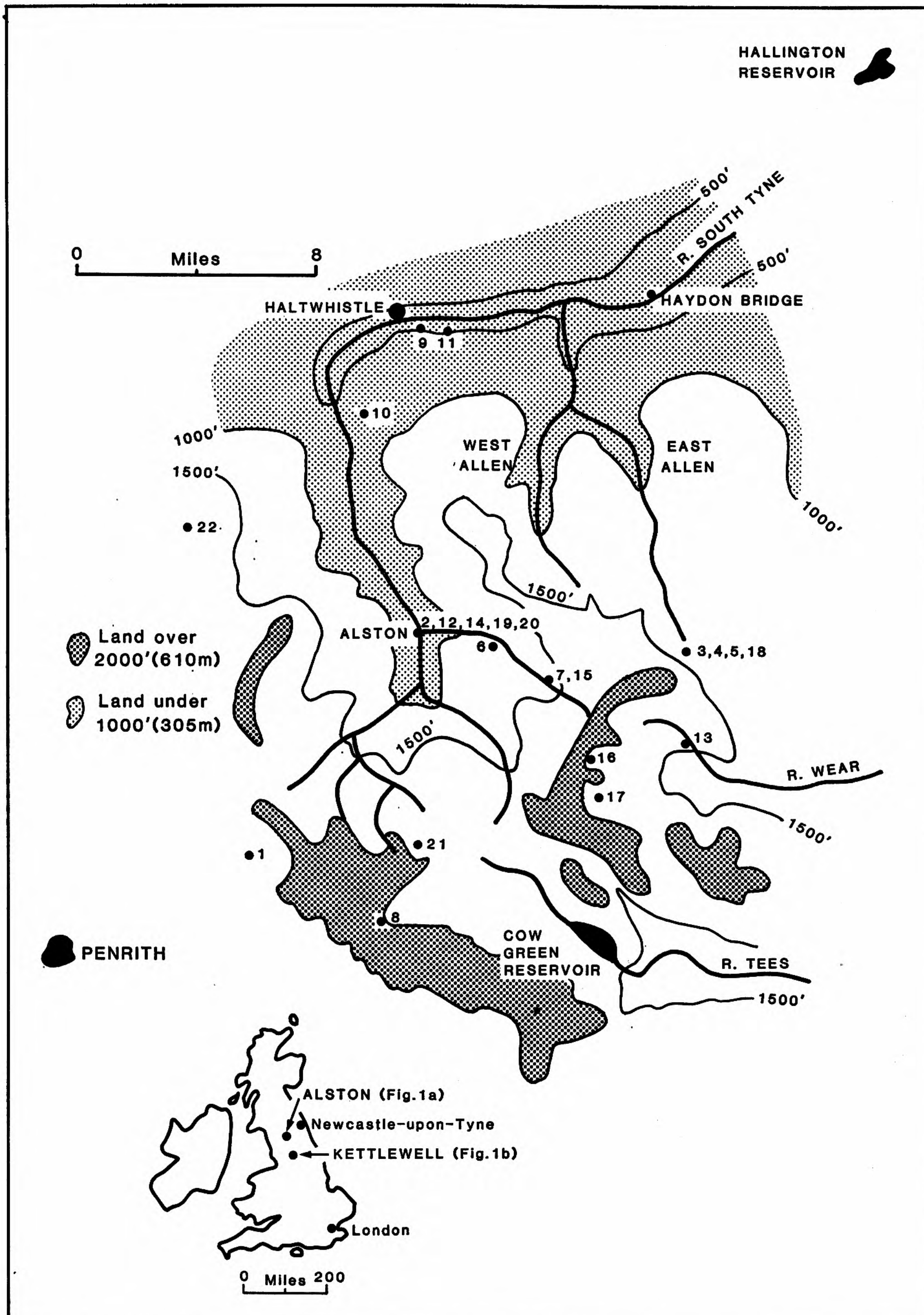

Figure 1(a). Rain-gauges in the Alston–Allenheads region of the northern Pennines.

Table I. *Rain-gauges in the Alston region of Cumbria*

Gauge No.	Gauge name	First year	Last year	Missing years	Height *metres*	Observer(s)
1	Crewgarth (nr Ousby)	1835	1852		?	Mr J. P. Spedding
2	Alston	1851	1852		?	?
3	Allenheads 5 in above ground	1854	1885		412	M. Varty, Esq.
4	Allenheads 6 ft 9 in above ground	1852	1872	1867–69, 1871	417	M. Varty, Esq.
5	Allenheads	1837	1846	1844	427	Rev. W. Walton
6	Alston Love Lady Shield	1863	1894	1870–74, 1886–91	351	J. Dickinson
7	Nenthead	1866	1869		432	W. Dalton
8	Hurth Syke	1876	1879		610	Mr J. Todd
9	Haltwhistle Unthank Hall	1869	1900		116	Rev. D. Dixon Brown
10	Haltwhistle Shaft Hall	1879	1893		191	R. Hetherington
11	Haltwhistle Bellister Castle	1906	1918		116	J. M. Clark, Esq.
12	Alston (nr Church)	1889	1891		265	?
13	Wearhead	1899	1909		377	Mr R. Rust
14	Alston Lowby Manor House	1907	1910		280	J. R. Walton
15	Nenthead	1901	1919		446	Caldwell Harpur
16	Wellheads Hush	1901	1964	1902–22 } Annual	515	N.W.A.
17	Grassmeres	1901	1977	1902–22 } totals only	564	N.W.A.
18	Allenheads	1910	1977	1919, 1937, 1971–72	411	various
19	Alston Vicarage	1931	1952		287	Rev. N. A. Walton
20	Alston King Samuel School	1970	1974		290	?
21	Moor House	1953	1977		556	Nature Conservancy Council
22	Geltsdale	1898	1977		229	City of Carlisle then N.W.W.A.

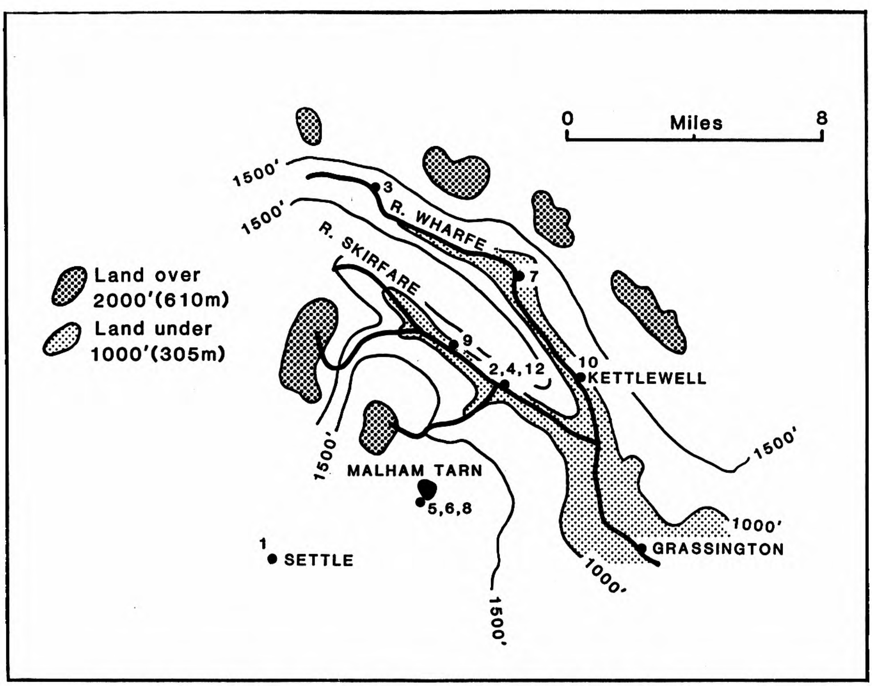

Figure 1(b). Rain-gauges in Upper Wharfedale.

record follows the pattern of previous work by Craddock (1977) and Jones (1980) in that conversion factors are produced from comparisons of the time series of the ratio of annual catches. The ratio should vary about a straight line, any change being due to a change in the gauge, its location or its environment.

Selection of key site

The choice of a key site for this region is between the four sites (Nos 17, 18, 21 and 22) where recordings have been made for at least 25 years. The site at Geltsdale (No. 22) was moved during 1962 without an overlap period. The site at Allenheads (No. 18) ceased operation during 1971 when the record was not kept for some months. However, a new site (also No. 18, and treated as the same site as the gauge kept from 1910–70) was introduced in 1972 by the Northumbrian Water Authority. As well as a daily rain-gauge, a Fisher and Porter punched tape autographic recorder was installed. The site at Moor House (No. 21) at an altitude of 556 m is in a rather exposed position. A detailed description of this site is given by Manley (1980). The Grassmeres gauge (No. 17) situated in the catchment area of Burnhope reservoir in Weardale is only read at monthly intervals and is thus prone to errors that can occur with this type of record, e.g. undetected leakage or damage. Between 1902 and 1922 only annual totals are available for the Grassmeres gauge. Thus, none of the sites is ideal as a key site for a variety of reasons. As early records are available at Allenheads (Nos 3, 4 and 5), the first lasting from 1854 to 1885, Allenheads (No. 18) was chosen as the key site. Furthermore, as far as can be gained from the Meteorological Office Archives, site No. 3 was very near to the key site (No. 18) record. This site has the added advantage of having two gauges operating, the normal daily gauge and the autographic one.

Construction of composite record

The earliest rainfall record in the region was kept at Crewgarth near Ousby in Cumbria (No. 1) on the western side of the Pennine Ridge from 1835 to 1852 by Mr J. P. Spedding. The first record in Alston (No. 2) was kept for two years from 1851 to 1852 by an unknown observer. It is, therefore, difficult to assess the Crewgarth readings, but a record was located in Penrith (see Fig. 1(a)) and the Crewgarth gauge caught about 72% of the Penrith gauge catch during the overlap period 1836–39 and 1851–52.

A record from Allenheads (No. 5) from 1837 to 1846 was kept by the Rev. W. Walton (referred to below as Allenheads 'W'). Annual values only are available, however, for the years 1840, 1843, 1845 and 1846, with no values at all for 1844. Little is known about this record and the source is given in the 10 year sheets held at the Meteorological Office as 'Manuscript, held by the Meteorological Society' on one decade sheet and on the other as 'Atkinson's Maps'. Many sheets during this period in northern England often refer to the source 'Atkinson's Maps'. Symons (1866) refers to Mr Joseph Atkinson of Harraby, near Carlisle, who published rainfall maps for the British Isles for 1841 and 1842 at least. Symons was unable to obtain a copy of this in 1866, but from the number of references to Atkinson's Maps in the 10 year sheets it can be assumed that he did so at some later date. For the years available between 1837 and 1846, the Allenheads 'W' gauge caught almost twice as much as the Crewgarth gauge during their nine years of overlap.

Later records at Allenheads cover the period from 1853 to 1885 and in the 10 year sheets are referred to as 'not compatible with the Allenheads record from 1910 to 1977'. However, on examination of the record it becomes obvious that the first observer, Thomas J. Bewick, was operating two gauges: a 12 inch diameter gauge, 6 feet 9 inches above the ground (site No. 4, the Allenheads 'post' record), and an

8 inch gauge, 5 inches above the ground (site No. 3, the Allenheads '8 inch' record). The former operated from 1854 to 1866 and again from 1870 to 1872 while the latter ran from 1853 to 1885. A change of observer during the late 1860s, when Matthew Varty continued the record may explain the termination of the 'post' record shortly afterwards. Fig. 2 shows the comparison of the annual catches of the two gauges for the years between 1854 and 1872, revealing that the larger 'post' gauge caught approximately 9% more than the smaller, conventionally sited gauge.

The location of both gauges during the 1860s and 1870s is almost certainly the same, and distances from nearby churches, gauge heights and wall positions of these gauges suggest that the site is very similar to that of the later records at Allenheads from 1910 (site No. 18). This impression is gained on two counts from the 10 year sheets at the Meteorological Office. Firstly, the gauges are at *exactly* the same surveyed heights. Secondly, gauge position for the records from 1854–85 and from 1910 onwards indicate that both are in the walled garden of a house two miles south of St Peter's Church, Allendale.

Figure 2. Ratio of annual catches, Allenheads (8 in, 5 in above ground): Allenheads (12 in, 6 ft 9 in above ground.) $\bar{x} = 0{\cdot}915$.

During the 1860s a number of records started in the South Tyne Valley: at Love Lady Shield (No. 6) (four miles south-east of Alston in the Nent Valley, by Mr Dickinson) for various periods from 1863 to 1894; at Nenthead (No. 7) from 1866 to 1869; and at Unthank Hall (No. 9), Haltwhistle, from 1869 to 1900—a record kept by the Rev. D. Dixon Brown. Fig. 3 shows the comparison of the longer Allenheads (1854–85) record (No. 3, 8 inch diameter, 5 inches above ground level) with the Unthank Hall (No. 9) record. The Allenheads record (No. 3) used in Fig. 2 has been shown to be in good agreement with the 'post' record (No. 4) until 1872. The Allenheads annual rainfall totals are less than those at Love Lady Shield (No. 6) only for the years between 1880–85, except 1881, thus these records must be considered unreliable and can only be used until 1879. Fig. 3 suggests that the Unthank Hall and Allenheads records are in good agreement during the 1880s, thus indicating the need to perform all possible comparisons. If the Unthank Hall (No. 9) is compared with that about 25 miles north-east at Hallington Reservoir (unnumbered, see Fig. 1(a)) then the totals for the period 1869–78 are low. This discrepancy in the Unthank Hall records can be partially confirmed with Love Lady Shield records although the number of overlap years is small.

In 1879 a record started at Shaft Hall (No. 10) near Lambley about six miles north of Alston. It would be preferable to use this record in preference to Unthank Hall to cover the unreliable part of

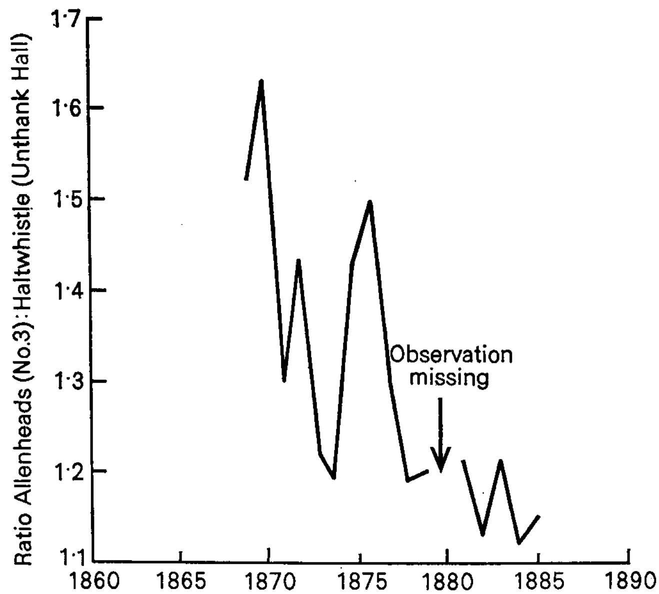

Figure 3. Ratio of annual catches, Allenheads (No. 3): Haltwhistle (Unthank Hall). $\bar{x}$ (1869–79) = 1·352, S.D. = 0·16. $\bar{x}$ (1869–85) = 1·277, S.D. = 0·16.

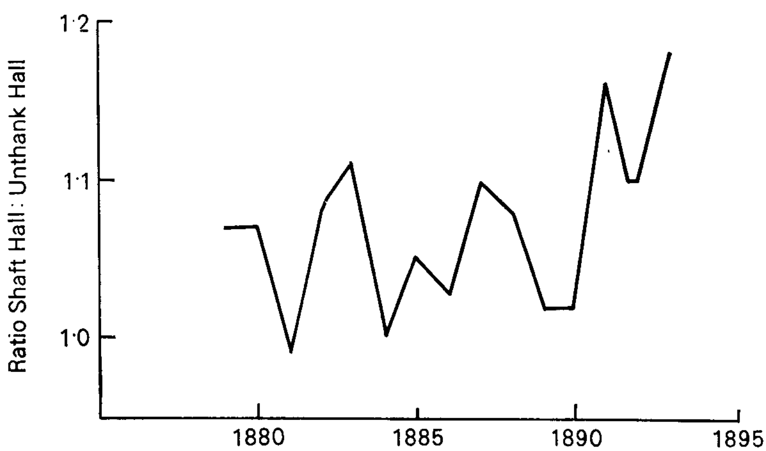

Figure 4. Ratio of annual catches, Shaft Hall: Unthank Hall. $\bar{x}$ = 1·070, S.D. = 0·055.

the Allenheads record as it is significantly nearer Allenheads. Fig. 4 shows that the record is in good agreement with Unthank Hall and that it can be used for the composite record, from 1880, the date from which the Allenheads record is suspect, until 1893. It is preferable to use only a small number of records when building up a composite record. For this reason the Love Lady Shield record, which is rather fragmentary and which may have occupied different sites during its period of operation, is only used for comparison purposes. Between 1895 and 1898 the only gauge operating in the region is that at Unthank Hall, so this record must be used. The composite series up to 1898 is made up of Allenheads (No. 3) for 1854–79, Shaft Hall (No. 10) for 1880–93 and Unthank Hall (No. 9) from 1894 to 1898.

In 1898 the Geltsdale (No. 22) record begins, and in 1899 so does a record from Wearhead (No. 13) across the catchment divide, five miles to the south of Allenheads. In 1901 another record begins at Nenthead (No. 15), a village five miles south-east of Alston. For the period from 1910 to 1919 this gauging overlaps with the key site at Allenheads. An interesting feature regarding the Nenthead (No. 15) record kept by Caldwell Harpur is that all the measurements were made in millimetres and the height of the gauge surveyed in metres. All these records were converted to inches and feet by the British Rainfall Organization. Fig. 5 compares Nenthead and Wearhead. Further comparison with Grassmeres (No. 17) indicates that the records for Nenthead are too low for the first four years (1901–04). The composite record therefore uses the Nenthead record from 1905, and the Wearhead record from 1899 to 1904. Using these two gauges between 1899 and 1909 is preferable to using the Geltsdale (No. 22) record since the latter is much farther from the key site at Allenheads. As was stated earlier, only annual values are available at Grassmeres for the years 1902–22.

After 1910, the Allenheads record is available and this forms the basis of the composite series. Internal consistencies can be checked by comparisons with Alston Vicarage (No. 19) (Fig. 6), Grassmeres (No. 17) and Moor House (No. 21). The comparisons indicate that the catch at Allenheads was about 10% lower before 1940 compared with the period thereafter. No move is mentioned in the 10 year sheets but a change from an eight inch to a five inch diameter gauge is noted. In the 10 year sheets stored at the Meteorological Office it is pointed out that, for the years before 1940, the annual totals are consistently low. The composite record will therefore need to increase the record for the period from 1910 to 1940 and the years when the record is incomplete, 1919, 1937 and 1971–72 must be filled by Nenthead (No. 15), Alston Vicarage (No. 19) and Alston King Samuel School (No. 20) respectively.

The conversion factors for the appropriate gauges in the composite record are given here and further details may be found in Appendix 1. Annual rainfall totals for the composite series, smoothed by a nine year binomial filter, are plotted in Fig. 7.

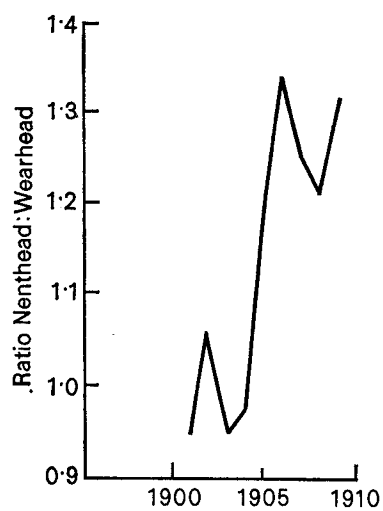

Figure 5. Ratio of annual catches, Nenthead:Wearhead. $\bar{x}$ (1905–09) = 1·274, S.D. = 0·074.

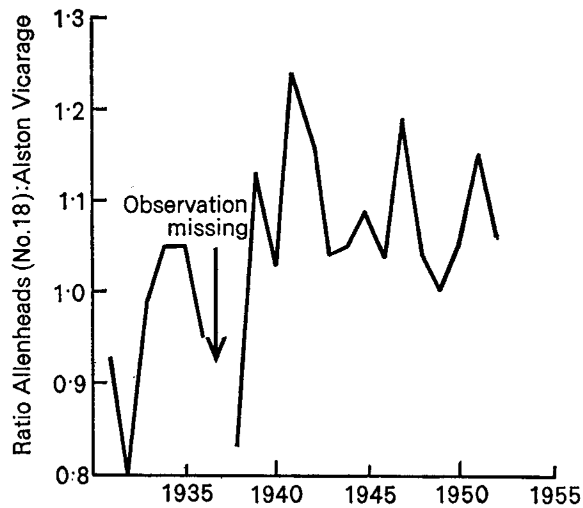

Figure 6. Ratio of annual catches, Allenheads (No. 18): Alston Vicarage. $\bar{x}$ (1931–40) = 0·977, S.D. = 0·110. $\bar{x}$ (1941–52) = 1·090, S.D. = 0·074.

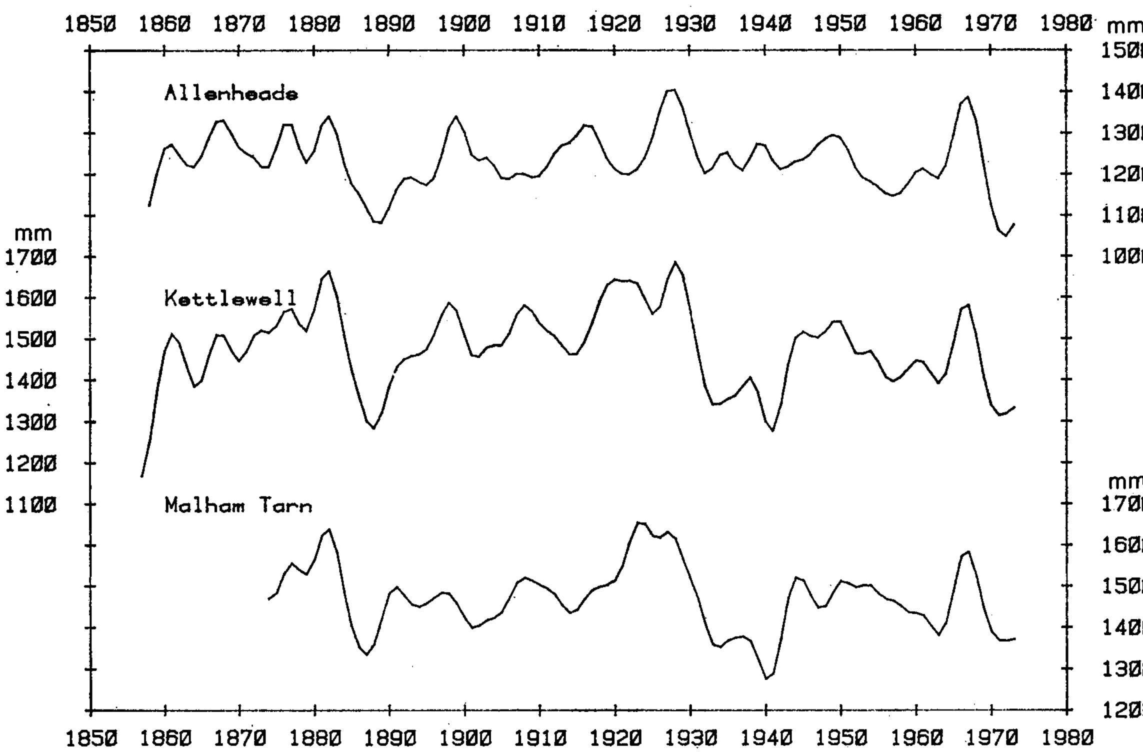

Figure 7. Annual rainfall totals for the three composite records smoothed by a nine weight binomial filter.

Allenheads (Summary)

Period	Station	Factor
1854–79	Allenheads (No. 3)	1·000
1880–93	Haltwhistle Shaft Hall (No. 10)	1·264
1894–98	Haltwhistle Unthank Hall (No. 9)	1·352
1899–1904	Wearhead (No. 13)	0·972
1905–09	Nenthead (No. 15)	0·763
1910–18	Allenheads (No. 18)	1·115
1919	Nenthead (No. 15)	0·763
1920–36	Allenheads (No. 18)	1·115
1937	Alston Vicarage (No. 19)	0·977
1938–40	Allenheads (No. 18)	1·115
1941–70	Allenheads (No. 18)	1·000
1971–72	Alston King Samuel School (No. 20)	1·000
1973–77	Allenheads (No. 18)	1·000

Rainfall recording in Upper Wharfedale and at Malham Tarn

Table II lists all the rain-gauges that have been or are currently operating in the extreme headwaters of Wharfedale and Littondale in the vicinity of Kettlewell and Arncliffe. Also included in the Table are gauges at Malham and Settle in Airedale and Ribblesdale which enable comparisons to be made throughout the period from 1853 to 1977. The location of these gauges can be seen from Fig. 1(b).

Table II. *Rain-gauges in or near Upper Wharfedale*

Gauge No.	Gauge name	First year	Last year	Missing years	Height *metres*	Observer(s)
1	Settle	1837	1870		152	J. Talham
2	Arncliffe	1853	1917		229	Rev. W. Boyd
3	Oughtershaw	1863	1957	1876–84	358	C. H. L. Wood; Miss G. J. Wood
4	Arncliffe Anerdale	1890	1909		226	J. Hammond
5	Malham (5 in gauge)	1870	1928		226	various
6	Malham (8 in gauge)	1890	1925		395	various
7	Buckden	1919	1936		244	G. E. Clayton
8	Malham (High Mask)	1929	1950		503	D.I.W.B.*
9	Litton Manor Cottage	1956	1977		250	various
10	Kettlewell	1957	1977		212	Y.W.A.†
11	Malham Tarn	1949	1977		395	C.P.F.S.‡
12	Arncliffe	1971	1976		227	Y.W.A.

* = Docks and Inland Waterways Board, † = Yorkshire Water Authority, ‡ = Council for the Promotion of Field Studies.

Selection of key site

The choice of key site for Upper Wharfedale rests between the rainfall recordings made at Kettlewell (No. 10) and Litton Manor Cottage (No. 9). The latter site was moved in 1972 and was terminated during 1978. Thus the Kettlewell site is the only one available. For Malham Tarn the gauge (No. 18) currently operating will be used as a basis for this composite series.

Construction of the composite record

The earliest record in Upper Wharfedale is that from the village of Arncliffe (No. 2) in Littondale kept by the Rev. William Boyd from 1853 to the early years of the twentieth century and continued until 1917 by the Rev. Canon W. A. Shuffrey. The gauge was sited 50 yards from Arncliffe Church at an unusual height of two feet six inches. The comparison between the Arncliffe record with J. Talham's gauge (No. 1) at Settle in Ribblesdale for the period from 1853 to 1870 reveals two distinct periods in the Arncliffe record which can be corroborated by the record from Kendal in Westmorland (about 20 miles north-west of Arncliffe). The earlier part of the record will therefore need to be increased relative to the latter.

In 1863 Charles H. L. Wood began recording at Oughtershaw Hall (No. 3) in the extreme headwaters of Wharfedale on the Langstrothdale Chase. Mr Wood was the local schoolmaster and he continued recording until 1899 when Miss G. J. Wood, presumably his daughter, continued until the 1940s after which the record was kept by Mr T. White until 1957. Apart from the latter part of the 1870s and the early 1880s the record is complete from 1863 until 1957. For the period from 1896 to 1957 daily rainfall values are available for all the years except parts of 1916. During the 1860s and 1870s it is clear from the 10 year sheets held at the Meteorological Office that Mr Wood also maintained gauges at Oughtershaw School and at Swarthghyll (the source of the River Wharfe). The records from both these sites are, however, fragmentary and not capable of filling in the missing years at the Oughtershaw Hall site. Figs 8, 9 and 10 show comparisons of this gauge record with the Arncliffe (No. 2) record, a gauge at Malham Tarn (No. 5) from 1870 to 1928, and a record from Buckden (No. 7) for the years 1919 to 1936. Further comparison is possible with another record from near Malham Tarn called High Mask (No. 8) for the years 1929 to 1950. All these graphs confirm the validity of the Oughtershaw record throughout the period, except for the later years in the 1880s which are low. The composite record uses the entire Arncliffe record until 1917 after which the Oughtershaw record (No. 3) will be used. The current rainfall site at Kettlewell (No. 10) commenced in 1957 and will be used for the composite record for the period from 1957 to 1977. Fig. 11 shows comparisons between Kettlewell and Litton Manor Cottage (No. 9) for the period 1957 to 1977 confirming both records. The gauge at Litton Manor Cottage was moved in 1972, which explains the peak in that year when some monthly values were estimated.

A comparison between Oughtershaw and the current Malham Tarn record shows good agreement and it was noted that the ratios between Oughtershaw and the Malham Tarn records (No. 5 and No. 8) from 1870 to 1928 and for 1949–57 are remarkably consistent, indicating that the records at Malham Tarn may be homogeneous. Shaw (1956) states that when the rain-gauge was installed by the Council for the Promotion of Field Studies in 1949 the Meteorological Office attempted to position the gauge at very nearly the earlier site. The Oughtershaw : High Mask ratios for 1929–50 indicate a change in that site after 1942. A correction factor for the latter period was calculated. It is therefore possible

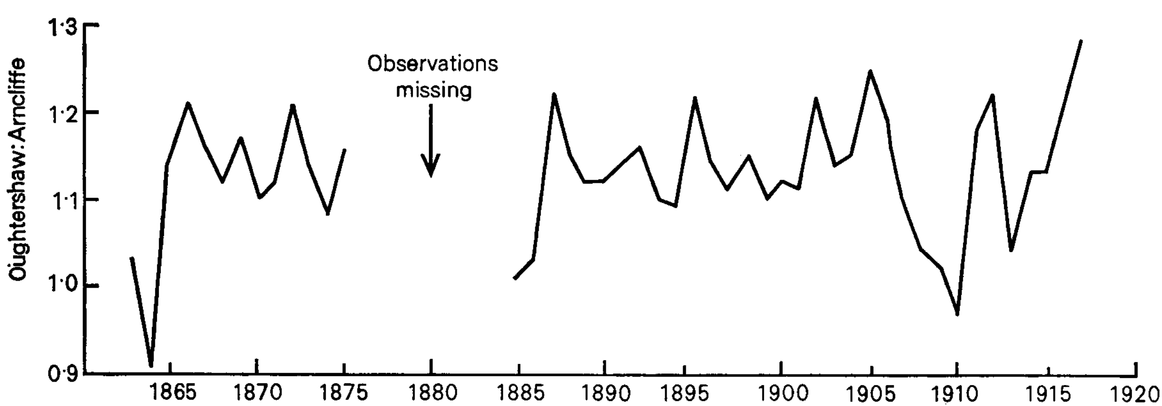

Figure 8. Ratio of annual catches, Oughtershaw : Arncliffe.

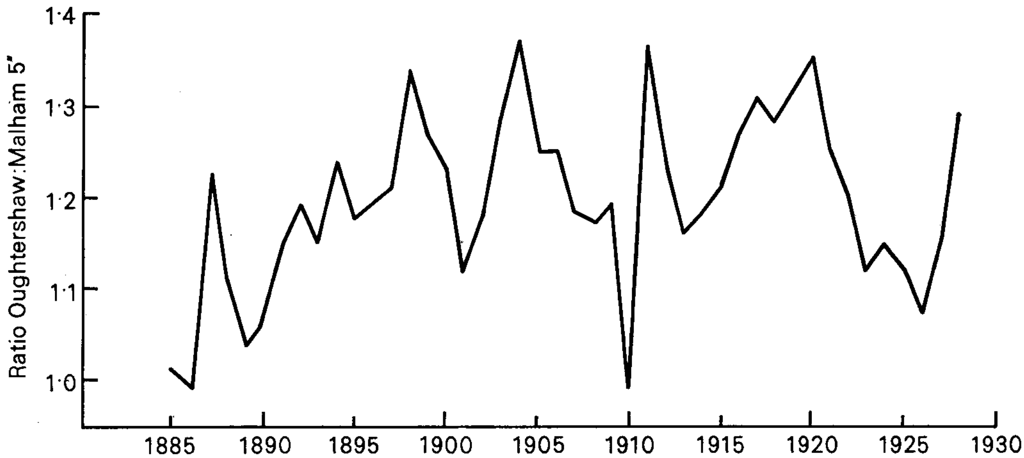

Figure 9. Ratio of annual catches, Oughtershaw: Malham 5 in. $\bar{x}$ (1885–1928) = 1·170, S.D. = 0·077.

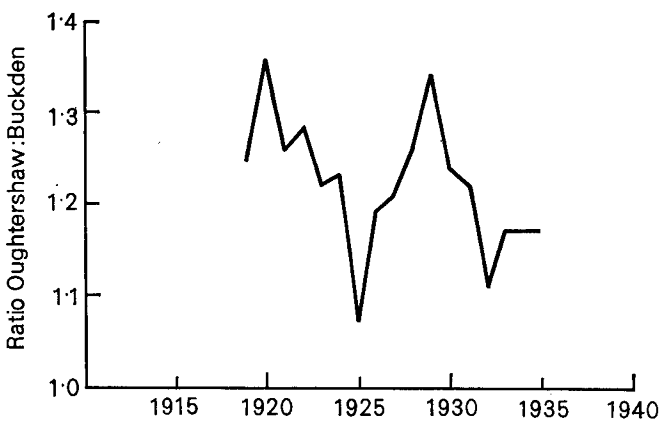

Figure 10. Ratio of annual catches, Oughtershaw: Buckden.

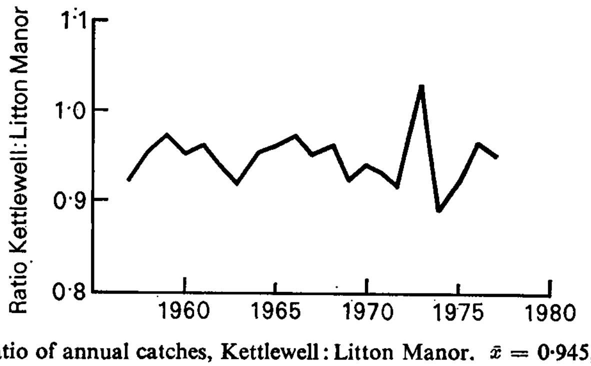

Figure 11. Ratio of annual catches, Kettlewell: Litton Manor. $\bar{x}$ = 0·945, S.D. = 0·029.

to produce a homogeneous record for the years from 1870 to 1977 for Malham Tarn from the three records (Nos 5, 8 and 11) by simply increasing the High Mask record for 1942–48 and treating the rest of the High Mask record and both Malham Tarn records as being for the same site.

The conversion factors for the appropriate gauges in the two composite records (Upper Wharfedale and Malham Tarn) are given here and further details are in Appendix 2 and Appendix 3. Both annual rainfall series, again smoothed by a nine weight binomial filter, are plotted in Fig. 7.

Kettlewell (summary)

Period	Station	Factor
1853–60	Arncliffe (No. 2)	1·127
1861–1917	Arncliffe (No. 2)	0·960
1918–56	Oughtershaw (No. 3)	0·850
1957–	Kettlewell (No. 10)	1·000

Malham Tarn (summary)

Period	Station	Factor
1870–1928	Malham 5 in (No. 5)	1·000
1929–41	High Mask (No. 8)	1·000
1942–48	High Mask (No. 8)	1·170
1949–	Malham Tarn (No. 11)	1·000

Concluding remarks

Annual and monthly rainfall totals have been presented for Allenheads, Kettlewell and Malham Tarn. Monthly values for each series are of course available but would involve pages of tables. Copies of the monthly values for any of the series are available from the author. Copies have also been lodged with the Meteorological Office. Variations in air temperature over the past 40 years have been discussed recently by Manley (1980) with reference to the Nature Conservancy Council's site at Moor House (a site 10 miles south-west of Allenheads and 145 metres higher in the lee of Crossfell, the highest peak in the Pennines).

Further extension of the Allenheads record is possible using the Crewgarth (No. 1) (Table I), Alston (No. 2) (1851–52) and the Allenheads (No. 5) (1837–46) records; however, the lack of sufficient overlap makes this extension difficult. Knowledge of the complete record kept by the Rev. W. Walton at Allenheads from 1837 to 1846 at least, would undoubtedly make this possible. Manley (1980) comments on a record of air temperature kept at Allenheads by Thomas Sopwith from 1857 until 1876. Data for 1836 to 1856 were thought by Manley to exist but he was unable to locate them. It would be interesting to know if a rain-gauge had also been kept at the site.

Further extension of the Kettlewell and Malham series is possible back to 1837 using the Settle (No. 1, Table II) record of J. Talham, a record kept from a gauge at a height of 35 ft above ground, presumably on a roof. Serious discrepancies are apparent during the early part of the Settle record compared with that for Kendal, making the record unreliable. Earlier records in the region are available for Garsdale Head, 15 miles to the north of Oughtershaw, for the period from 1777 to 1779, but these are too short for any practical use.

Acknowledgements

The author wishes to thank the staff of the Agriculture and Hydrometeorology Branch (Met O 8) and the Archives (Met O 18e) of the Meteorological Office, and Dr T. M. L. Wigley. The author also acknowledges the support of the Department of the Environment Research Contract No. 116/2/2.

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Appendix 1. Details of the composite rainfall record for the Alston–Allenheads region of Northumberland.

1941–77 *Allenheads.* Conversion factor 1·0 (except 1971–72).

The Allenheads gauge record was terminated in 1971 and recommenced during 1972 at a site 100 yards to the west. The years 1971 and 1972 therefore need to be filled by Alston King Samuel School.

1971–72 *Alston King Samuel School.* Factor 1·0.

The record is only complete for the years 1970–74 and the ratios between this and the Allenheads records for 1970 and 1974 are approximately unity.

1910–40 *Allenheads.* Factor 1·115 (except 1919 and 1937).

Ratio Allenheads: Alston Vicarage (1931–40) = 0·977 (neglecting 1937).

Ratio Allenheads: Alston Vicarage (1941–52) = 1·090.

The factor required to convert to the Allenheads record for 1941 onwards is therefore 1·090/0·977 = 1·115.

1937 *Alston Vicarage.* Factor 0·977.

1919 *Nenthead.* Factor 0·763.

1905–09 *Nenthead.* Factor 0·763.

Ratio Allenheads: Nenthead = 0·684,

therefore to convert to Allenheads for 1941 onwards the required factor is 0·684 × 1·115 = 0·763.

1899–1904 *Wearhead.* Factor 0·972.

Ratio Nenthead: Wearhead = 1·274,

therefore to convert to Allenheads for 1941 onwards the required factor is 1·274 × 0·763 = 0·972.

1894-98 *Haltwhistle Unthank Hall.* Factor 1·352.

Ratio Allenheads: Unthank Hall (1869–79) = 1·352.

1880–93 *Haltwhistle Shaft Hall.* Factor 1·264.

Ratio Shaft: Unthank (1879–93) = 1·070,

therefore to convert to Allenheads for 1941 onwards the required factor is 1·352/1·070 = 1·264.

1854–79 *Allenheads (earlier records).* Factor 1·00.

Ratio Hallington: Allenheads (1910–77 neglecting 1937, 1971–72 and correcting the earlier period (1910–40)) = 0·59.

Ratio Hallington: Allenheads (earlier 1862–79) = 0·594,

therefore Allenheads records are compatible.

The Hallington reservoir site is a continuous record kept from 1862 approximately 20 mile north-east of Allenheads and is the nearest record that covers all the years of both records.

Appendix 2. Details of the composite rainfall record for Upper Wharfedale

1957–77 *Kettlewell* × 1·0.
1918–56 *Oughtershaw*. Conversion factor 0·850.
Ratio Oughtershaw: Malham Tarn (1949–57) = 1·157.
Ratio Malham Tarn: Kettlewell (1957–77) = 1·017,
therefore ratio Kettlewell: Oughtershaw = 1/(1·017 × 1·157) = 0·850.
1861–1917 *Arncliffe*. Factor 0·960.
Ratio Oughtershaw: Arncliffe (1885–1917) = 1·129, S.D. = 0·076,
therefore to convert to Kettlewell multiply by 1·129 × 0·850 = 0·960.
1853–60 *Arncliffe*. Factor 1·127.
Ratio Settle: Arncliffe (1861–69) = 0·689.
Ratio Settle: Arncliffe (1854–60) = 0·809,
therefore to convert early Arncliffe records multiply by 0·809/0·689 = 1·174,
therefore to convert to Kettlewell multiply by 0·960 × 1·174 = 1·127.

Appendix 3. Details of the composite rainfall record for Malham Tarn

1949–77 *Malham Tarn* × 1·0.
Ratio Oughtershaw: Malham Tarn (1949–57) = 1·157, S.D. = 0·079.
1942–48 *High Mask*. Conversion factor 1·170.
Ratio Oughtershaw: High Mask (1942–50) = 1·385, S.D. = 0·077,
therefore to convert to Malham Tarn multiply by 1·385/1·157 = 1·170.
1929–41 *High Mask*. Factor 1·0.
Ratio Oughtershaw: High Mask (1929–41) = 1·184, S.D. = 0·085.
Factor of unity used owing to the similarity of the ratios of the Malham gauges with Oughtershaw.
1870–1928 *Malham 5 in*. Factor 1·0.
Ratio Oughtershaw: Malham 5 in (1885–1928) = 1·170, S.D. = 0·077,
Factor of unity used owing to the similarity of the ratios of the Malham gauges with Oughtershaw.

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Routine calibration of solar radiation instruments

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(Meteorological Office, Bracknell)

Summary

The article describes the solar radiation work within the Test Laboratory section of the Operational Instrumentation Branch of the Meteorological Office and its relationship to the Meteorological Office National Radiation Centre. The equipment and methods used for the calibration of pyranometers and net pyrradiometers, and a system for the determination of the cosine response of pyranometers to varying angles of incident radiation in the laboratory are described.

1. Introduction

Collingbourne (1969) described the early history and the current practice of the solar radiation measurement and calibration organization within the United Kingdom. He referred mainly to the National Radiation Centre which at that time was based in the Meteorological Office Observatory at Kew.

In January 1974 the responsibility for (a) the calibration and development of operational instrumentation, and (b) the maintenance of radiation standards and the operation of the United Kingdom network of observing stations, was transferred from Kew to the Meteorological Office experimental site at Beaufort Park, Easthampstead. At the same time the functions of (a) and (b) were devolved to two branches, Operational Instrumentation (Met O 16) and Observational Requirements and Practices (Met O 1) respectively. Although these functions are, of necessity, related, this article is concerned mainly with (a) which is undertaken by the Test Laboratory section of the Operational Instrumentation Branch.

2. Standards and traceability

The National Radiation Centre (NRC), now based at Beaufort Park, maintains the UK national standards for solar radiation and houses the reference instruments. These are Ångström pyrheliometers (see Plate I). Two transfer standard instruments, held in the Test Laboratory for use in routine calibrations, are compared twice a year with these standard instruments. The transfer standards used are a Linke–Feussner pyrheliometer* (see Plate II) and a Kipp and Zonen pyranometer*. May (1980) describes previous and current practice in the maintenance of radiation standards by the Meteorological Office.

3. Measurement systems

During the calibration of radiation sensors voltages between about 0·2 and 10 mV are usually encountered. It is also necessary to monitor continuously three or more pyranometers simultaneously to determine their mean output voltages over a specific period.

When the calibration laboratory was set up at Beaufort Park in 1974 the opportunity was taken to improve the measurement facilities previously used at Kew. A console was constructed housing all the power supply units and a Leeds and Northrup 12-channel chart recorder. Arrangements were made to suit the different instruments being calibrated.

* Pyranometers are a class of instrument used to measure global and diffuse solar radiation. The Kipp and Zonen instruments are commonly referred to by the manufacturer's name 'Solarimeter', which has no accepted definition. Similarly the Linke–Feussner pyrheliometer is commonly referred to as an actinometer.

This system was modified and augmented a number of times, and in 1978 a full investigation of the accuracies of voltage measurement was carried out. The results showed that uncertainties varied between ±0·25% for voltages up to 1 mV and ±3·0% for voltages above 1 mV. Further errors were being introduced into the calibrations owing to visual estimations of the chart trace by the operator, and also owing to small variations in the accuracy of the calibration of the transfer standard instruments compared with the standards held in the NRC.

To reduce these uncertainties a new system for voltage measurement was acquired and put into service in mid-1979. The system acquired, illustrated in Plate III, consists of a digital voltmeter (DVM) (1) and multi-channel scanner (2), a printer (3), and a Commodore PET microcomputer (4). The DVM has an uncertainty of ±1 μV over the range of voltages encountered in radiation calibration. Programs were supplied with the system to cover both pyranometer and net pyrradiometer calibrations.

The equipment is based on the interface 'bus' system originally published by the Institute of Electrical and Electronic Engineers (1975) but with subsequent modifications (1978). This interface bus system is now becoming accepted, under various guises, as the standard for automatic test equipment (ATE). Under this system up to 15 suitably interfaced devices can be connected together to produce ATE capable of meeting most individual needs. At the heart of each ATE is the controller, a programmable microcomputer, which will direct, via the program, the various measuring and display devices, store and use the data produced, and display any results.

4. Calibration of pyranometers

In 1966 a spherical integrating chamber was installed in the laboratory at Kew. This enabled pyranometers to be calibrated more quickly and conveniently indoors. The chamber was based on a design suggested by Latimer (1964). Principally because of its physical size and the need for air to be drawn into the chamber from outside, it was decided against moving it to Beaufort Park where, instead, a new chamber was designed and built within the Operational Instrumentation Branch.

The current layout of this new chamber which differs in a number of ways from the Kew model is illustrated in Fig. 1. Instead of consisting of two large hemispherical mouldings the new chamber was made up from six sections (1), which can be easily dismantled and moved elsewhere. Because the original site at Beaufort Park was in a laboratory with no external walls, no direct inflow of cool outside air was possible. Vents (2) were therefore placed near the base of the chamber to admit air from an air-conditioned laboratory, the air then being removed through the top of the chamber (3) by an extractor fan. Light from six 600 W tungsten–halogen lamps (4), similar to those used in the Kew chamber, is reflected off the white interior surface of the chamber providing an even, steady source of radiation. The irradiances within the chambers at Kew and Beaufort Park have been shown to be very similar. However, it was found that the temperatures of the sensors and of the interior of the new chamber would vary from about 30 °C up to about 50 °C, especially during long calibration sessions. Eventually, during a reorganization of laboratories within Beaufort Park in mid-1979, an air-conditioner unit (5) and an electrical heater (6) were fitted into the side of the chamber. A portion (7) of the incoming cold air is directed over the heater and up the central column to the underside of the sensors, while the remainder (8) enters the main body of the chamber. With the air-conditioner running continuously and the heater thermostatically controlled, the temperature of the test sensors is held at 22 °C±0·2 °C while the chamber temperature, being more dependent on the external laboratory condition, will rise after an hour to about 26 °C. The sensors (9), one transfer standard and two under test, are mounted below a shade plate (10) which allows only the glass hemispheres and thermopile surfaces to be exposed. The mounting plate is linked to the shaft of a motor (11) and can be rotated

Plate I. Ångström pyrheliometer.

Plate II. Linke–Feussner pyrheliometer.

Plate III. Radiation calibration measurement system.

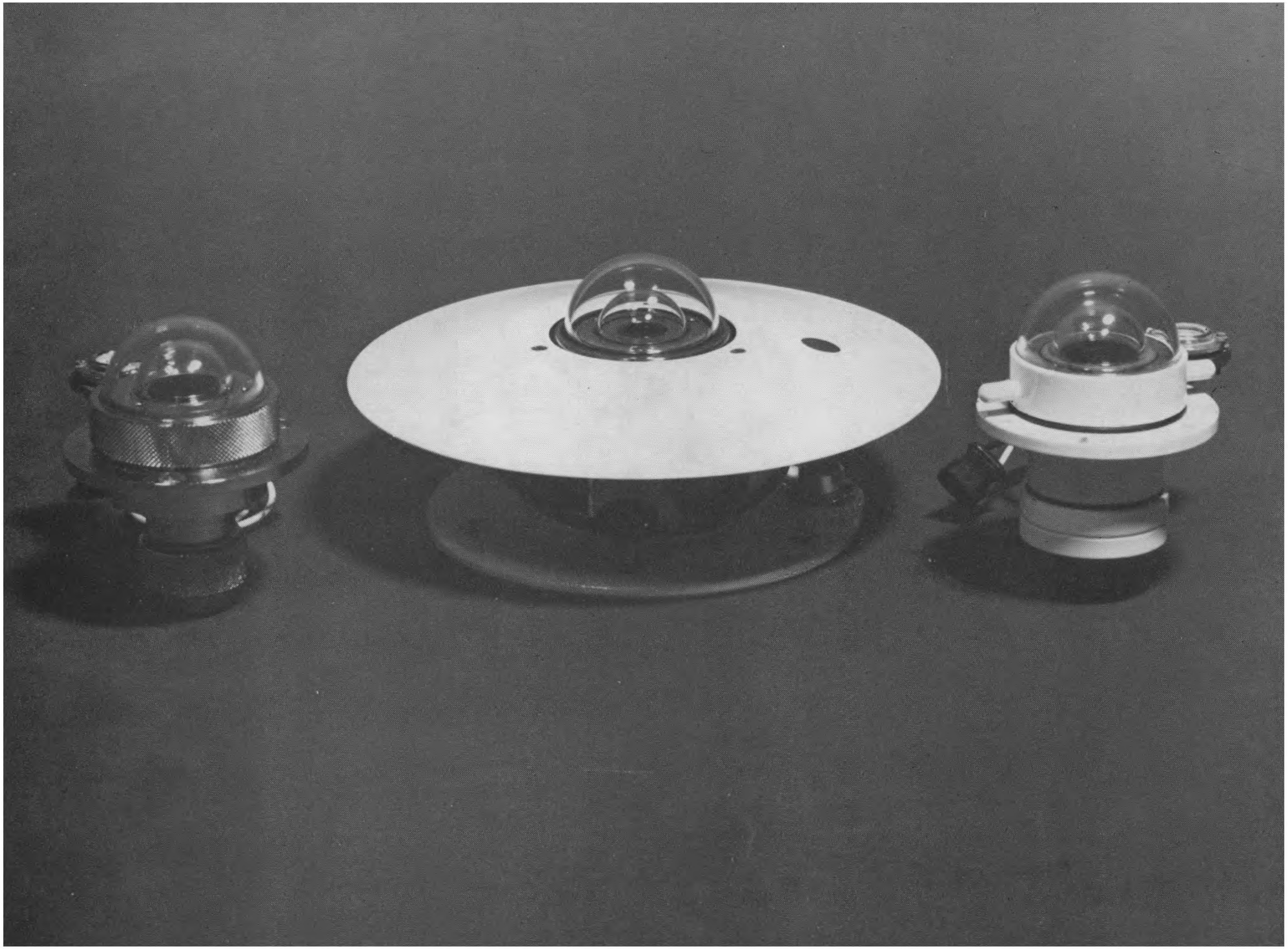

Plate IV. Pyranometers. Left to right: Kipp and Zonen CM5, Eppley precision spectral pyranometer, Kipp and Zonen CM2.

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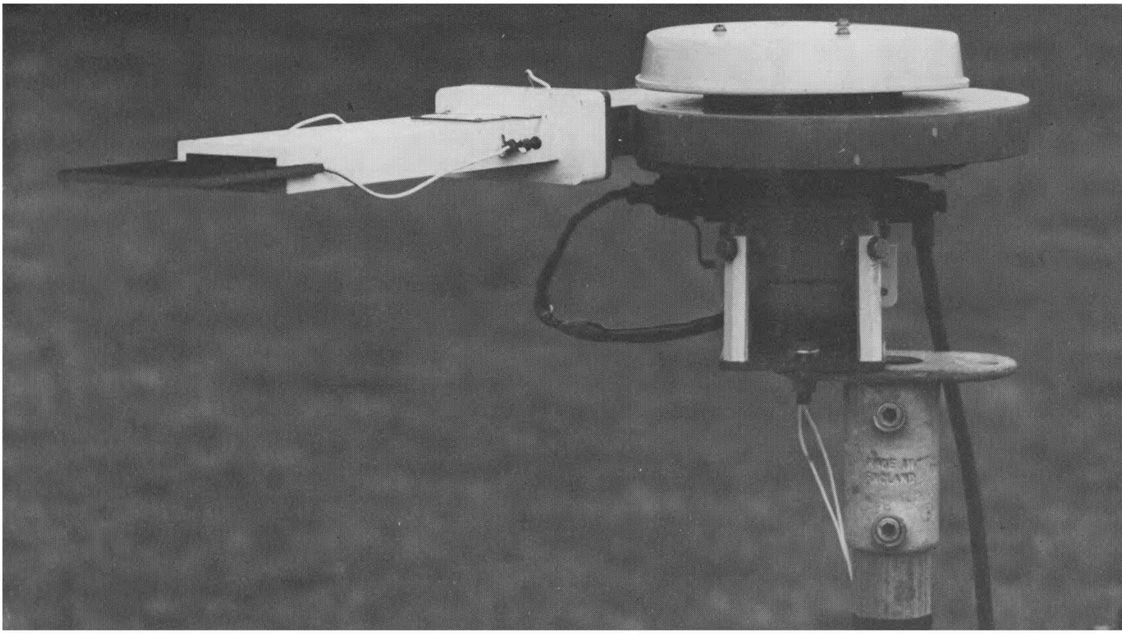

Plate V. Meteorological Office pattern net pyrradiometer.

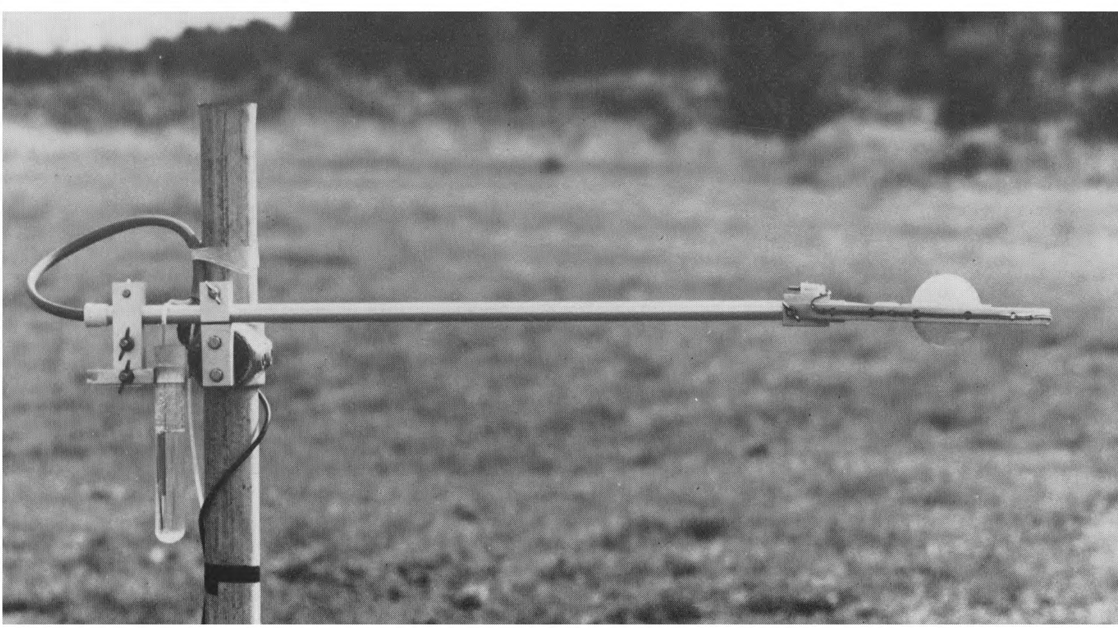

Plate VI. Funk-pattern net pyrradiometer.

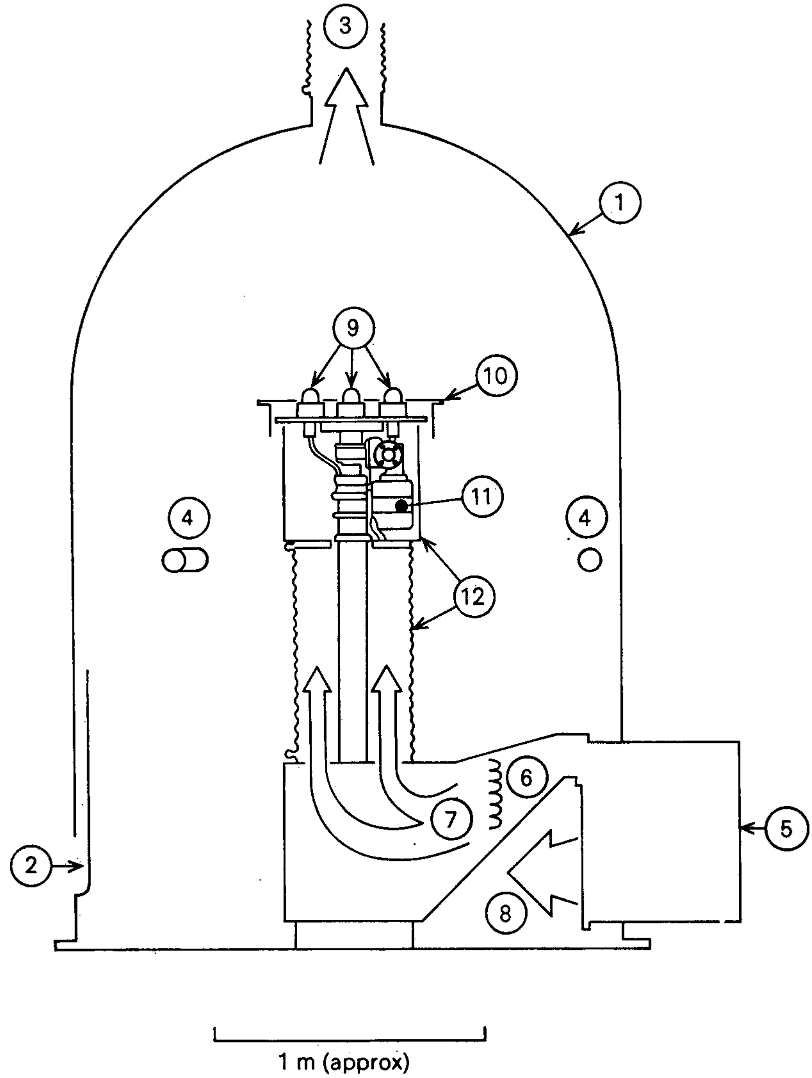

Figure 1. Pyranometer calibration chamber. A table carrying a transfer standard pyranometer and two pyranometers under test, rotating in a field of uniform irradiance.

through 360° in either a clockwise or an anticlockwise direction; one revolution in either direction takes 10 minutes. The whole mechanism is enclosed within a shield (12) to prevent the bases of the sensors and motor becoming heated.

A normal calibration is carried out by comparison of the output of the transfer standard with the two pyranometers under test. The instruments are revolved once in each direction in the chamber to take account of any slight inhomogeneity of the radiation source. During the test period of about 20 minutes the PET microcomputer directs the DVM to take readings of the outputs of each sensor at intervals decided by the operator, usually every 10 seconds for Kipp and Zonen pyranometers. All the readings are stored and, at the end of the run, mean voltages are calculated and then, from the known sensitivity of the transfer standard instrument, the sensitivities of the test instruments are computed. A certificate of calibration for each of these instruments is automatically produced on a printer.

Although, at present, pyranometers can only be calibrated in the chamber, it will be possible to calibrate them outdoors, if necessary, when suitable mounts and connecting cables have been installed. This facility should be available at Beaufort Park in a year or so.

The types of pyranometer which can be calibrated using this system are:

(a) Kipp and Zonen pyranometers, models CM2 and CM5, these being the main instruments used by the Meteorological Office and many outside authorities, and

(b) Eppley precision spectral pyranometers, used by the Meteorological Office for specialized purposes requiring more accurate measurements.

Examples of these instruments are shown in Plate IV.

5. Calibration of net pyrradiometers

The calibration of net pyrradiometers both in the laboratory and field at Kew was described in detail by MacDowall (1955). At that time the method of short-wave calibration consisted of shining a tungsten 2000 W lamp upon the sensor plate, held between two large plates of glass in an attempt to reduce the excess long-wave radiation emanating from the lamp housing. It was later thought, however, that these glass plates became heated by radiation from the lamp, and then re-radiated long-wave radiation to the sensor. The Kew system also had the lamp and net pyrradiometer mounted in a horizontal plane and this was believed to have an effect on the sensitivities of the instruments, especially the enclosed sensor types, owing to differences in the internal convection currents.

In view of these shortcomings in the Kew laboratory calibration system a new one was designed and built within the Operational Instrumentation Branch at Beaufort Park in 1974. A frame mounted on a bench in a darkroom holds a 600 W tungsten–halogen lamp shining vertically down on the sensor plate 1·5 metres below. As the radiant flux of the lamp is rather low, some attempt has been made to amplify the beam by incorporating two silvered prisms in the lamp housing. Even so, the irradiance is still only about 5 mW cm^{-2} at the sensor position. An extractor fan in the lamp housing removes excess heat to the outside. At regular intervals a shade plate is automatically interposed midway between the lamp and the sensor. In this way the sensor is alternately exposed to and shielded from the short-wave radiation from the lamp, for periods of five minutes in each state. As the long-wave radiation reaching the sensor is essentially the same for both positions of the shade plate, the difference between the two readings of the sensor represents the radiant flux of the lamp.

Before any calibration of a net pyrradiometer takes place the output of the lamp is accurately determined by placing the Linke–Feussner pyrheliometer transfer standard in the position to be occupied by the test sensor.

The net pyrradiometer under test is next mounted and levelled in a precise position beneath the lamp. A calibrated marker enables the instrument to be positioned at the correct distance from the two adjacent walls and from the floor. The actual test consists of monitoring the output of the sensor with the microcomputer programmed to distinguish between the 'unshaded' and 'shaded' modes and then to compute the mean value of the readings taken during four 'unshaded' and three 'shaded' periods. Quality control routines in the program ensure that the spurious readings encountered during the changeover from 'unshaded' to 'shaded', and vice versa, are eliminated from any calculations. The difference between the 'unshaded' and 'shaded' readings is determined and the sensitivity of one side of the sensor plate is calculated, using the lamp output factor previously measured. The sensor plate is then inverted and repositioned and the whole calibration sequence repeated. At the end of this sequence the final sensitivity is computed as the mean of the sensitivities of both sides of the sensor plate. A certificate of calibration is then produced automatically on the printer.

Net pyrradiometers must have symmetrical plates, i.e. the sensitivites of both sides of the plates must agree within 2%. To take acount of any deterioration of the sensor during exposure in the field the instrument is calibrated before any necessary refurbishing takes place prior to a final calibration and re-issue.

For many years the black paint used for coating the sensor plates was Parsons Optical Black whose properties had been investigated by the National Physical Laboratory and described in more detail by MacDowall (1955). Supplies of this paint became increasingly difficult to obtain. Also the surfaces produced with it were not very durable. At each return from an outstation the plates needed to be cleaned and repainted. The application of this paint was a difficult task when the requirement was to produce a coating which had to have equal absorption of radiation on both sides of the sensor. The process often resulted in asymmetric sensitivities and had to be repeated.

After extensive comparison trials at Beaufort Park in 1978 a new paint was introduced for use on net pyrradiometer plates. This was 'Nextel' Velvet Coating 101-C10 produced by 3M. The manufacturer's claimed performance for this paint indicates that the reflectance for radiation of wavelengths between 0·7 and 1·1 μm is 1·5% and between 2 and 35 μm is 1·0%. In field trials at Beaufort Park no appreciable difference in sensitivity was noted between Parsons paint and 3M's Nextel. However, the 3M's paint was found to be much more durable and easier to apply. It is now no longer necessary to repaint plates every time an instrument is returned for routine calibration. The plates are carefully washed and the sensitivities are found to have altered little from the original calibration, provided no other damage to the surface has occurred.

The main instruments calibrated under this system are the standard Meteorological Office pattern net pyrradiometer with the open ventilated sensor plate, (see Plate V) and enclosed sensor types based on the pattern designed and described by Funk (1959) (see Plate VI). These are mainly being used by universities and some other government departments.

6. Determination of cosine response

The output of a pyranometer varies theoretically as the cosine of the zenith angle of the incident light. Ideally pyranometers should obey this cosine law with no deviation but unfortunately they do not.

In the 1960s an apparatus was built at Kew to determine such deviations of response for any particular pyranometer and this was described briefly by Collingbourne (1969). Although this apparatus was brought to Beaufort Park, certain drawbacks were encountered, particularly in the uniformity of the light beam. Also the sequence of operations necessary to determine the cosine response of a single pyranometer was both long and labour-intensive. With these shortcomings in mind the Operational Instrumentation Branch began to develop an improved, automated version of the Kew apparatus.

Although it is not yet fully developed, a new apparatus has been built and it is hoped it will be operating in the near future. The basic layout of the new machine (Fig. 2) follows that of the Kew model in that a fixed light source (1) is directed via mirrors (2) and (3) mounted on a movable arm on to a rotatable table (4) holding the test sensor (5). For clarity, the arm is not shown on the diagram. Thus, by moving the arm and rotating the table, light can be made to fall upon the sensor from any angle of azimuth and elevation. The arm and the table are driven by servo systems (6) and (7) incorporating photoelectric sensors and sector discs. By this means it is possible to set the arm at certain

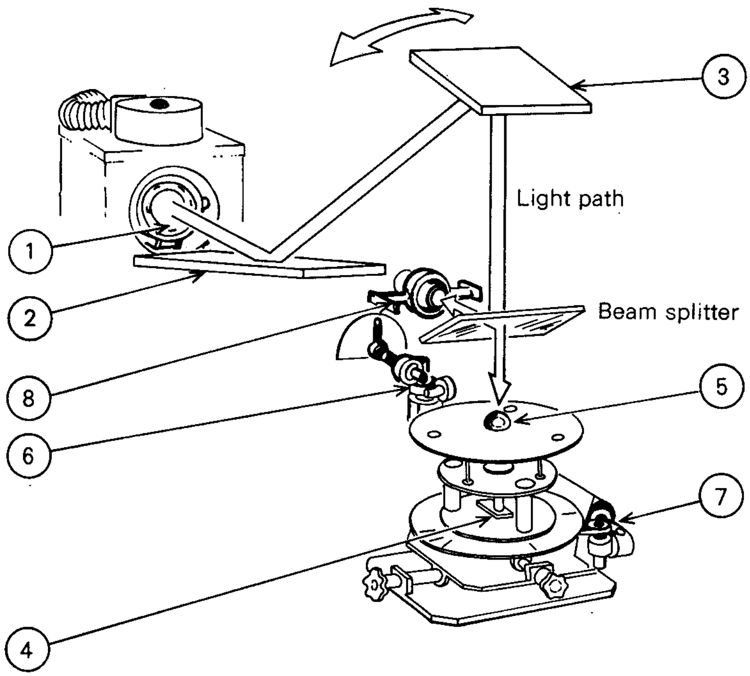

Figure 2. Pyranometer 'cosine response' apparatus. Apparatus for directing a stable, uniform beam of light on to a pyranometer from precise angles of incidence and azimuth.

standard angles of elevation to within 3 minutes of arc, and the table to within 2 degrees, the latter being sufficient for our needs. Control circuitry has been designed for the servo motors, so that the whole sequence of cosine response testing can be operated by the automatic measurement system.

When the system is used operationally, pyranometers will have routine tests carried out which will determine the deviation of response from the ideal at every 30° of azimuth at zenith angles of 30°, 45°, 60°, 70°, 75° and 80°. Standard pyranometers will have tests carried out at the same zenith angles but at 10° azimuth intervals. The complete automatic calibration sequence will take about 9 hours for a routine test and 11 hours for a standard pyranometer test. At the end of tests, again, a certificate will be printed out.

Although the electrical and mechanical systems work well, problems have arisen concerning the stability of output of the lamp. The intensity of the light output of the lamp is controlled by varying the applied voltage in response to variations in intensity detected at (8). A 1000 W compact-source iodide discharge lamp was obtained, which has a spectral distribution similar to that of the sun. A series of tests was carried out with the machine positioned so that the beam of light was directed vertically down on to the pyranometer, that is in the zenith position. A linear interpolation between two readings from the pyranometer taken at the zenith, one hour apart, showed that the intermediate reading gave errors which rarely exceeded 0·3%. However, a further series of readings taken with the lamp beam at 80° from the zenith (i.e. 10° above the horizontal) gave an average output which varied by as much as 7%. The greatest errors were experienced when the lamp was switched off and then on again.

It is suspected that these errors are caused by shifting of the lamp arc. As it is to be expected that all discharge lamps will give rise to similar errors, it has been decided to obtain a tungsten–halogen lamp. It is hoped that this, although not having the correct colour temperature (3200 K as opposed to 5400 K), will be inherently more stable than the compact-source iodide lamp.

7. Future developments

The systems at present in use are under constant review with particular emphasis on the need for suitable transfer standard instruments. Also under active consideration is equipment to determine operationally the temperature coefficient and linearity of response of pyranometers.

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Weather forecasting for construction sites

By M. J. Prior and E. G. E. King
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Summary

Many types of forecast benefit from the forecaster having some awareness of the use to which his advice is put and this is particularly so in respect of forecasting for building and civil engineering sites. The purpose of this paper is to assist forecasters who provide such services; parts of it should also prove helpful in enquiry bureaux when providing climatological data to the building industry.

Weather forecasts and site management

Bad weather during the early stages of a building contract can cause delays for which no amount of good weather later on can compensate; at later stages there is more concern with inside work which is much less prone to interruption by the weather. On the other hand, most civil engineering projects are open to the elements at all times, so that the adverse effects of bad weather can remain much the same throughout. The contractor can fairly claim for the contract period to be extended when bad weather has caused long delays but this is in the hope of reducing his losses rather than recouping them entirely; bad weather means a financial handicap for the contractor as well as for his client.

In recent years building operations have been made less weather-sensitive by means of protection while work proceeds (e.g. enclosure within plastic sheeting), use of additives (e.g. antifreeze in concrete and mortar) and the protection of completed work that is liable to damage. However, shrinking profit margins have meant that every item that costs money has had to be re-examined on a cost–benefit basis and as protective measures can be expensive firms do not want to take them unnecessarily. A report commissioned by the Construction Industry Research and Information Association (Smith and Rawlings 1974) showed that forecasts prepared specifically for building operations, combined with regular discussions between site manager and forecaster, were a useful tool for technical management. While the results of this informed dialogue were seldom spectacular, the operational advantages which accrued over a period of several months were carefully quantified and showed that the scheme was nearly always cost-effective, a benefit: cost ratio as high as 10:1 being noted in some cases. The report concluded that the main uses of weather forecast information are in (a) the prevention of damage, (b) aiding work relocation decisions and (c) day-to-day operational planning.

Many firms already use the free public weather forecast service as a tool in the control of work but, up to now, relatively few firms have paid for forecasts and warnings tailored specifically to the operating limits of individual projects. The potential exists for a much greater demand for the benefits of construction-weather forecasts.

Because of the development of improved techniques construction processes have become more complex and, in consequence, there are now many firms which specialize in a limited range of work. In many cases this narrows their individual weather interests to such an extent that a forecaster concentrating upon specific weather elements can provide valuable assistance in the short-term planning of operations. For the main contractor, however, the important criteria at any particular time are the practical operating limits for the work in hand, so the emphasis will change as the work progresses, sometimes even from one day to the next, and a routine forecast in standard form may well be inappropriate. If the site manager has regular contact with a particular team of forecasters then both sides can achieve some understanding of the relationship of the current pattern of work to the weather prospects. As is so often the case when seeking meteorological advice it is sometimes more difficult to get the question right than to get the forecast right. Optimum results are most likely to be achieved through the flexible approach offered by a consultancy-type service.

Operating limits

A RILEM report (1965) and Lacy (1977) described the effects of weather on construction processes and explained how more than one weather element can hold up a particular activity. The weather can hinder work either because it will lead to an unsatisfactory end-product or because it is affecting the efficiency or safety of the people involved. Table I lists 'stop work' criteria for various operations; some of these values are based on subjective estimates and are therefore uncertain but, wherever possible, the criterion quoted has been obtained by reference to a code of practice or construction industry publication (the suffixes shown in Table I relate to these references). For some of the operations, additional considerations pertain which could not be included in Table I conveniently and these are set out below.

Excavation and earth moving. These are essentially spring, summer and autumn activities which can be adversely affected by wet weather. During and after rainfall, although the contractor may take some form of remedial action, the effect on work largely depends on how quickly the additional moisture can be either absorbed by the soil or removed by evaporation; these processes, in turn, depend on the surface conditions and soil properties (e.g. soil moisture deficit), as well as the weather.

Concreting. Drying winds can lead to the cracking of large areas of unprotected concrete and this is thought to be due to drying shrinkage of the surface layer. Wind conditions therefore need to be considered in conjunction with air temperatures when contractors are assessing the need for protective measures. However, the minimum temperatures quoted in Table I will not apply if heated concrete or antifreeze admixtures are used.

Roads: asphalting. During rolling, asphalt needs to remain above a temperature within the range 80–120 °C, according to type, so strong, cold winds can present problems because they can cause premature cooling and thus inhibit compaction.

Roads: surface dressing. Apart from the low temperature thresholds given in Table I, high temperatures can also be a problem because the bitumen can be too liquid for the stone chippings to adhere properly; the limiting weather conditions are those likely to lead to a road surface temperature of 35 °C or more.

External painting and joint sealing. These processes cannot be done on surfaces which are moist, and materials such as steel and masonry may become moistened by condensation when the air becomes markedly warmer and more humid. A forecast of such a change could help a contractor to decide to defer operations or take precautions.

The imprecise nature not only of the weather but also of the various construction processes will, of course, lead to some differences from the values quoted in Table I. Moreover, the working method being used may modify the 'stop work' point.

Some operations are not themselves directly affected by bad weather; rather it is the discomfort of the people involved that decides the weather limits. For example, some outdoor jobs may be stopped when it is raining merely because it is too unpleasant to continue working. The point at which work will stop may well also depend on temperature or wind speed, or a combination of the two.

Forecast content

(a) *Working day*

Apart from the demands of human safety, the contractor's principal concern with the weather is the extent to which work may be delayed with resulting disruption to the program for the completion

Table I. *Weather inimical to construction operations*

	Rainfall intensity	Snow	Wind gusts exceeding *knots**	Air temperature *degrees Celsius*	Other factors
Surveying and setting out	Slight or more[1] (but not 'very slight')	Falling[1]	35[1]	—	Hard frozen ground (for peg driving). Fog
Excavation and earth moving†	Prolonged moderate/heavy[1]	Falling/lying[1]	—	Severe frost	Hard frozen ground. Drying conditions. Dense fog[1]
Concreting†	'Slight to moderate' or more[2]	Falling/lying[2]	—	<+2 when falling[3] <+1 when rising[3]	Sub-surface frozen or flooded—roads. Frost on reinforcement or shuttering—casting
Roads: asphalting†	Slight or more (but not 'very slight')[4]	Falling/lying[4]	—	<0 when falling, <−1 when rising } recipe mixes[4] <8 designed mixes[5]	Sub-surface wet or frozen[4] <2 °C surface temperature—recipe mixes[5] <5 °C surface temperature—designed mixes[5]
Roads: surface dressing†	Slight or more (but not 'very slight')[6]	Falling/lying[6]	—	<15 stone chippings[6] <8 using hot binder <5 using emulsion	Sub-surface wet or frozen[6]
Sheet steel piling	Moderate or more[1]	—	35[1]	—	—
Steel frame erection	Any intensity	Falling/lying[1]	20[1]	—	Frost or ice on frame members. Dense fog[1]
Welding	Slight or more (but not 'very slight')	Falling/lying	30	—	Very cold members, especially when large
Scaffolding	Slight or more (but not 'very slight')	Falling/lying	30	—	Frost or ice on members
Cradles	Heavy	Heavy snow falling	25	—	Task may dictate criteria
Tower cranes	—	Heavy snow falling	40 at jib height[7]	—	Dense fog on ground or at jib height

Table I.—*continued*

Craning lightweight panels	—	Heavy snow falling	25 at load height[8]	—	Dense fog on ground or at load height
Bricklaying	Slight or more (but not 'very slight')	Falling/lying	30[1]	<2 when falling[3] <1 when rising[3]	Frost on building surfaces
Roofs: slating and tiling	'Slight to moderate' or more	Falling/lying	30	—	—
Roofs: asphalting	Slight or more (but not 'very slight')	Falling/lying	25	<7[1]	Sub-surface wet, frosty or icy[9]
Roofs: built-up felt	Any intensity	Falling/lying	25	<1	Sub-surface wet, frosty or icy
Roofs: sheeting (e.g. corrugated asbestos)	Slight or more (but not 'very slight')	Falling/lying	25	—	—
Rendering	Slight or more (but not 'very slight')	Lying	35	<3 when falling <2 when rising	—
External painting† and joint sealing	Any intensity[10]	Falling[10]	25 (painting only)	<4 or >32	Moisture on surfaces[10] Relative humidity >90%
Glazing	Any intensity[1]	Falling[1]	25[1]	—	Surfaces wet or frozen
Materials: storage or access to	Moderate/heavy	Lying	—	Severe frost	Frost following >5 mm rain (bricks)
Partially completed structures: damage risk	Prolonged moderate/heavy	Substantial snow depth	40	Moderate/severe frost	Large hail. Sudden temperature changes

Notes. † Special considerations for these processes are described in the text.
* Some users would be more familiar with speeds expressed in miles per hour, metres per second or Beaufort force.
The superscripts shown relate to the references, given at the end of this paper, which were used to obtain the criteria quoted. 1. Russo 1971, 2. Pink 1978, 3. Smith and Rawlings 1974, 4. British Standards Institution (BSI) 1973a, 5. Department of Transport 1979, 6. Department of the Environment 1972, 7. BSI 1977, 8. Lacy 1977, 9. BSI 1973b, 10. BSI 1966.

of the various stages of the contract. Timing is an essential element in weather forecasting for contractors who need to know the likely starting time and duration of weather that is prohibitive for particular processes or for work in general. The most useful prohibitive values are probably:

Rain

(1) Any rain

(2) 'Slight to moderate' rain or slight showers (about 0·5 mm h^{-1}), or more

(3) Moderate rain or 'slight to moderate' showers (about 2·0 mm h^{-1}), or more

(4) A fall of 10 mm or more in 24 hours (ground very wet or flooded).

Temperature. Less than 2 °C.

Wind

(1) Gusts over 20 knots

(2) Gusts over 30 knots.

Snow. Falling or lying.

Even using descriptive terms for precipitation the forecast can be worded to give a clear indication of the likely loss of time on outdoor work. For example, a forecast of 'frequent showers developing by the afternoon' may mean that only the morning will be suitable for work, whereas 'occasional mainly light showers' gives hope for a full day's output. The description of rainfall intensity uses words in their ordinary sense so as to avoid misunderstanding, and yet has to be related to what different jobs can tolerate. Terms such as 'very slight' or 'moderate, sometimes heavy' may be useful. If it is raining when work should start then a contractor will often wait until he is sure that a clearance has arrived before committing his resources. Light drizzle in a warm sector may prevent work from starting merely because it looks like a threat of worse to come. A clearance as late as mid-afternoon usually means that little can be done in the rest of the day; wet surfaces may have to dry off first, and work may be hindered if the ground is wet or muddy.

The actual working day is usually limited to daylight hours so there is often some restriction in winter and especially if there is thick cloud cover. If particularly poor light is expected some mention of this could be made in a forecast.

(b) *Overnight and beyond*

The prevention of damage to many types of newly completed work may require action by the contractor before the end of the working day. Particularly important are the prevention of frost damage to concrete and mortar, the protection of partially completed walls from wind damage and the avoidance of damage due to flooding. The most useful warnings will usually be:

Temperature. Moderate or severe frost.

Wind. Gusts over 40 knots.

Rain. Prolonged periods of heavy rain.

To allow time to arrange any necessary protection a forecast for the following night is required by 1600 local time at the latest. Before a weekend the forecast will need to be extended.

(c) *Forward planning*

Some contractors may wish to be advised of the weather prospects for several days ahead, especially where phased operations are involved. With this in mind, the 'Three days dry?' consultancy service has recently been made available to contractors.

Local environment

For a satisfactory forecast an adequate mental picture of the site and its surroundings is often necessary. In built-up areas, for example, increased surface roughness reduces the wind flow and the 'heat island' can affect temperatures. As a new structure rises above the surrounding buildings the effects of wind are felt increasingly so it is essential for the forecaster to know the height above the ground at which work is being performed. The gust is the important wind speed and at a height h the gust speed G_h is approximately given by the power law $G_h/G_{10} = (h/10)^{0 \cdot 085}$, where G_{10} is the gust speed at 10 m above ground level (a.g.l.). Thus at 50 m a.g.l. a 40 knot gust may, on average, be expected when a gust of only 35 knots is forecast at 10 m a.g.l. Table II shows this variation for other heights and gust speeds. In urban areas the effective 10 m height can be taken as 10 m above the general roof level.

Table II. *Variation of gust speed with height above ground*

Height above ground level *metres*					
10	20	30	40	50	60
Gust speed *knots*					
15	16	16	17	17	17
20	21	22	23	23	23
25	27	27	28	29	29
30	32	33	34	34	35
35	37	38	39	40	41
40	42	44	45	46	47

Topographical effects will often be present in some degree on construction sites and may be difficult to quantify. Over exposed hill tops, for example, gusts may be from 10% to 50% greater than gust speeds over level country—perhaps 50% greater for exceptionally prominent hills and for coastal cliff tops.

While much construction work takes place in urban areas, the civil engineering sector of the industry is frequently concerned with building roads, bridges and television masts in upland regions and these structures present some difficult problems in forecasting. For example, a site may be clear of fog all day owing to a local lifting of the cloud base in the lee of a high ridge. In the winter half-year a sharp contrast may exist between snow on the hill and rain in the valley. In moist warm sectors giving only occasional drizzle over low ground upland areas can sometimes have continuous moderate rain. In situations such as these the lack of representative observations makes forecasting more than usually difficult and the meteorologist should ensure that the uncertainties are appreciated by the contractor. Close liaison with the customer can soon lead to the forecaster learning the local peculiarities—even at a distance—and the standard of meteorological advice will improve.

Conclusion

There are few 'stop work' weather criteria which will always govern a particular outdoor activity on construction sites. Nevertheless, some understanding of the weather parameters that could halt or hinder operations can help the forecaster to concentrate his attention appropriately. Thus, with a little effort on the part of the meteorologist, a forecast can be given substantial relevance to construction work and so have a direct beneficial influence on the conduct of operations, thereby making a positive contribution to the whole project. A check-list of what the forecaster may need to find out is given in Table III.

Table III. *Check-list for forecasters*

(a) *Obtain information on:*
(1) exact location, altitude and extent of site, topographical details if possible,
(2) duration and character of project; materials, equipment and operations involved; dates between which particular operations are expected to take place,
(3) height of work above ground at various stages of the project,
(4) hours of work and whether 5, 6 or 7 day working weeks are planned, and
(5) method of transmission to be used for the forecast; address, telephone and telex numbers.

(b) *Agree with the customer:*
(1) threshold values for interference with work,
(2) threshold values for possible damage to newly completed work,
(3) optimum time(s) of day for the issue of forecasts,
(4) whether meteorological measurements will be made by the customer and whether these could usefully be communicated to the forecaster, and
(5) units in which wind speeds should be given.

Acknowledgement

The authors are grateful to Mr E. J. Keeble of the Building Research Station, Garston, for his valuable assistance in preparing Table I and its associated text.

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Notes and news

Retirement of Mr R. J. Ogden

Mr R. J. Ogden, B.Sc., Assistant Director (Public Services) retired from the Meteorological Office on 28 July 1981 after a career of 42 years.

Dick Ogden was educated at Whitgift School, Croydon, where he specialized in Mathematics and Physics and represented the school with distinction at Rugby Football. He joined the Office in September 1939 as an Assistant III experiencing through the war years the quick succession of postings through various Royal Air Force stations that was the lot of most of his colleagues at the time. Early in 1943 he was promoted to Assistant II and soon after was mobilized into the Royal Air Force, Meteorological Branch, serving as a dependent forecaster in the United Kingdom and south-east Asia until January 1946 when he was promoted to Flight Lieutenant, RAFVR, and qualified for duties as an independent forecaster. In the post-war reconstruction he was assimilated as an Assistant Experimental Officer and, while on posting as instructor at the Meteorological Office Training School, then in Alexandra House, Kingsway, he was able to resume his studies part-time, obtaining London University external degrees in Mathematics and Physics that enabled him to enter with success the Civil Service Competition for the grade of Scientific Officer.

In 1950, with a posting to London (Heathrow) Airport there began a particular association with civil aviation work that lasted until his retirement. He was promoted as an aviation forecaster to Senior Scientific Officer in 1953 and his growing interest and expertise in the international aspects of the work led to his selection as a member of United Kingdom delegations to meetings of the International Civil Aviation Organization and the WMO Commission for Aeronautical Meteorology where he quickly gained a reputation for the soundness of his arguments and judgements in technical matters. He was responsible for the United Kingdom contribution to the WMO Technical Note on high-level analysis and forecasting techniques. After a decade in this field Mr Ogden moved in 1960 to take up a post as a Senior Forecaster in the Central Forecasting Office, then at Dunstable, but soon transferred to the new Meteorological Office Headquarters at Bracknell. He was recognized as an outstanding senior forecaster, only that his characteristic thoroughness and attention to detail led sometimes to difficulty with tight schedules.

Following his early spell as a junior instructor at the Meteorological Office Training School, Dick Ogden continued to develop his talents as a lecturer both within the Office as a guest speaker on Senior Meteorologists' courses, for example, and extramurally to a wide variety of audiences, some with professional interests and some without. He was therefore well prepared for his next appointment in 1965 as head of the Training School, by then at Stanmore. Here he was involved in the early planning stages for the residential college at Shinfield Park that was to supersede the Training School, the general shape and scope of the new building and conversions owing much to his work at that time. Before he could see the project through to its conclusion, however, he was called in 1969 to take charge of the London Weather Centre which was then developing in its role as a key facility in the provision of services to national television and radio, the Press, the public and commerce and industry, especially the new offshore industry created by the discovery of the reserves of gas and oil in the North Sea. Before long he was a familiar figure in the corridors of Broadcasting House and the BBC Television Centre at White City and in the halls of British Gas, the Central Electricity Generating Board, British Rail, the departments and committees of the petroleum industry and the rest as he bent his energies to the reorganization of the Centre's work for them all. He revealed talents at this time as a radio and television broadcaster and, to the benefit of the Office, as a skilful interviewee. He continued to find time to give talks and lectures and was in demand as a member of selection boards of the Overseas Development Administration, the Crown Agents and the Civil Service Commission.

In 1975 Mr Ogden was rewarded with promotion to Senior Principal Scientific Officer and took up the post of Assistant Director in charge of Climatological Services, moving to become Assistant Director in charge of Public Services in 1978, thus returning towards the close of his career to the fields of public service and civil aviation in which he had already contributed so much. His final contribution to international civil aviation may turn out to be the most important since, in 1980, he took a leading role with other members of the ICAO Area Forecast Panel in laying the foundation for a new streamlined and more effective Area Forecast System. In public services he will want to be remembered for the efforts he has made to bring into being, after a gap of many years, two new Weather Centres, one newly opened in Bristol and the second, due to open later this year, in Cardiff. Typically, in his final year, he undertook a complete revision of the *Public Services Handbook*, enshrining in it much of the background and experience that he had gathered during the past ten years.

Dick brought to his career the personal qualities for which he was noted even as a young man: energy, strength of character and seriousness of purpose. As an administrator he wrote at length and in fine detail. He was not easily diverted from a course once his mind was made up. What he didn't get through at the Office he took home, working sometimes late into the night. He was responsible for a number of useful investigations usually closely related to his work at the time and had articles published in *Weather*, the *Meteorological Magazine* and elsewhere. For a time in the 1950s he was a member of the Council of the Meteorological Office Branch of the Institution of Professional Civil Servants, as Overseas Secretary and as Vice-Chairman. Some of his extramural interests overlapped with those of his vocation. He helped the Boy Scout movement in the development of the Weatherman and Meteorologist Badges, writing booklets and organizing courses for them at Scout Headquarters.

In 1953 while at Heathrow Dick married another meteorologist, Sylvia Kirby. He has shared with her since an interest in the heritage of Britain both natural and cultural that has led to countless expeditions into the country and to life membership of the National Trust. In his retirement Dick proposes, after spending a year or so in his present home in Camberley, to move out into the countryside and to find time for some serious carpentry. Sylvia and Dick will never be at a loss for things to do and we hope that they will long enjoy good health and contentment in their retirement.

Reviews

Atmospheric planetary boundary layer physics, edited by A. Longhetto. 245 mm × 170 mm, pp. x + 424, *illus*. Elsevier Scientific Publishing Company, Amsterdam, 1980. US $70·75, Dfl 140·00.

If you live in an attractive part of the world where the sun shines, the sea is blue and remains of history abound, you are indeed fortunate. You are even more fortunate if you have ambitions to improve the know-how of your local scientific community. Hold a lecture course. Invite top-level scientists from colder wetter climes as speakers, choosing a time in winter when they've almost forgotten what the sun looks like! You cannot fail; lecturers and students alike will enjoy every minute of it. And why not? Why not indeed! So, well done Sicily and well done the International School of Atmospheric Physics. You held your fourth course at Erice on the western tip of that sun-blessed isle in February 1978. I only hope the sun did shine for you (unfortunately I wasn't there to tell). And if perchance it didn't, better luck next time—at least you had some good lectures to listen to.

The course was devoted to 'Atmospheric planetary boundary layer physics' and attracted first-rate lecturers from Europe, the USA and Australia. The intention was to examine the current state of the art: the fundamental physical and mathematical modelling of the boundary layer itself and of the dispersion and transport of airborne pollution.

Not a snack for the beginner it's true, but a hearty meal for experienced scientists who wanted to learn from the experts. Being too good to let it slip by without putting it down in print, Professor Longhetto has brought all the lectures together into this book as a lasting repository. The chapters vary considerably in length and, I suppose, in interest to any one reader. I most enjoyed Svante Bodin's Chapter 1 on 'Applied numerical modelling of the atmospheric boundary layer', Bob Lamb's Chapter 6 on 'Mathematical principles of turbulent diffusion modelling' and the interesting juxtaposition of two chapters on plume rise by David Moore and by Pietro Bacci and Arnaldo Longhetto. Other readers would no doubt find their own favourite parts.

Much as there is to be gained and enjoyed from reading the book, I cannot help being reminded of a row of young lettuces after an attack by hungry slugs—however succulent the remaining morsels may seem, the gaps seem all too many and obvious. For example, the chapters on plume rise are excellent but who cares about plume rise unless it tells us something about likely ground-level concentrations? Not I, for one. (All right, I do really but only for rather subtle reasons!) And yet not a word about such things here, which only emphasizes what is obvious: the subject is now a very big one and there is no way that a course like this could contain it all.

Other parts by now seem a little dated. For example, results from the Minnesota experiment which for the first time investigated the structure of the whole depth of the boundary layer over land in various stability conditions are not included and are sorely missed. Nevertheless, don't be put off by this. The book is worth reading if you are a boundary layer meteorologist or have an active interest in pollution. It is well produced and does have a lasting value.

F. B. Smith

Ocean wave climate, edited by M. D. Earle and A. Malahoff. 250 mm × 160 mm, pp. xi + 368, *illus.* Plenum Press, New York and London, 1979. US $36·00 (+20% outside USA).

This volume contains the proceedings of the Ocean Wave Climate Symposium held at Herndon, Virginia, in 1977. It is concerned with the present state of knowledge of wave climate and with requirements for improving that knowledge. It is mainly concerned with coastal waters of the United States although the techniques described have quite general applications. The book is split into three sections. The first deals with wave models and with applications of wave data, the second deals with wave measurements and the third consists of recommendations from the symposium working groups. The second section will be of limited interest to most meteorologists since it deals mainly with the technical aspects of wave measurement. It concentrates on remote measurement by radar and several different methods are described. The first section is of more direct interest. Chapter 1 describes the National Meteorological Center (NMC) and Fleet Numerical Weather Central methods for analysing and forecasting sea surface winds. Many of the comments made about the NMC models are applicable to those used in the United Kingdom. The remaining chapters describe wave simulation methods used in the United States, ranging from very crude systems to the most advanced ones available and very thoroughly covering the field. There are also chapters on methods of determining the influences of waves on ships.

B. Golding

Obituary

We regret to record the death on 1 April 1981 of Mr M. A. Walsh, Scientific Officer, who was on the staff at Glasgow Airport. Mr Walsh joined the Office in July 1946 at Aberdeen as a Meteorological Assistant, and was promoted to Senior Scientific Assistant in January 1969. Most of his career was spent at Renfrew and Glasgow Airport, but he served overseas for a couple of years at Sharjah. For a number of years he acted as local representative for the IPCS and also the Civil Service Benevolent Fund.

We regret to record the death on 6 May 1981 of Mr C. E. ('Jim') Collins, Higher Scientific Officer, who was on the staff of London (Gatwick) Airport. Mr Collins joined the Office as a Meteorological Assistant in March 1941 and served at a number of outstations in the United Kingdom with most of his time being spent at Mildenhall. He was promoted to Senior Scientific Assistant in April 1956 and to Experimental Officer in October 1961. From 1970 to 1974 he served at Wildenrath in Germany and on his return was, after a spell at Thorney Island, posted to Gatwick in 1976. Mr Collins was fluent in French, German and Italian, and could also speak some Russian. He was an amateur radio enthusiast.

THE METEOROLOGICAL MAGAZINE

No. 1310 September 1981 Vol. 110

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1.80 monthly **Annual subscription £23.80 including postage**

Dd. 716670 K15 9/81

ISBN 0 11 726286 2
ISSN 0026-1149

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

October 1981

Met.O. 942 No. 1311 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1311, October 1981, Vol. 110

551.509.52:551.515.13:797.1

The Fastnet storm—a forecaster's viewpoint

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(Meteorological Office, Bracknell)

Summary

The 1979 Fastnet Race is remembered for the exceptional weather conditions which were experienced to the south of Ireland and caused havoc among the competitors. The origin and development of the storm are reviewed on the basis of the data available at the time to the forecasters in the Central Forecasting Office at Bracknell. In particular, the guidance from the various numerical models is discussed, together with its interpretation by the forecasters.

1. Introduction

At 1230 GMT on Saturday 11 August 1979, 303 yachts sailed from Cowes, Isle of Wight at the start of the biennial Fastnet Race. This race, which is organized by the Royal Ocean Racing Club (RORC), forms part of the series of international yacht races counting towards the Admiral's Cup trophy. The course takes the competitors to the Fastnet Rock and then back to Plymouth via Bishop Rock (Fig. 1). On the same day a small depression (identified as low LY) was centred just south of Nova Scotia and it was the arrival of this low over southern Ireland on the night of 13/14 August that was to have such dramatic and tragic consequences. During that night the competitors, who were mostly located between Fastnet Rock and the Isles of Scilly, caught the full force of the storm. Of the 303 starters only 85 finished the race, 24 yachts were abandoned and 15 crew members were lost.

Besides describing the development of the storm, this paper also discusses the basic observational data available at the time, the guidance from the numerical models and the forecast material which was actually issued.

2. Saturday 11 August

(a) *Synoptic situation*

Fig. 2 shows the surface and 300 mb analyses for 12 GMT on Saturday 11 August, close to the time of the start of the Fastnet Race. A broad upper ridge was moving slowly eastwards over the British Isles and was associated at the surface with a good deal of warm and very moist air originating from near the Azores, behind the warm front WX. Ironically, the main problems worrying competitors at the start of the race were possible lack of wind and increasing likelihood of sea fog. A major surface low LX and its associated upper vortex were drifting north-eastwards to the south of Greenland whilst another vortex was almost stationary over Hudson Bay. On the southern flank of these two upper vortices a strong westerly flow was propagating forwards over the central North Atlantic with maximum wind speeds of

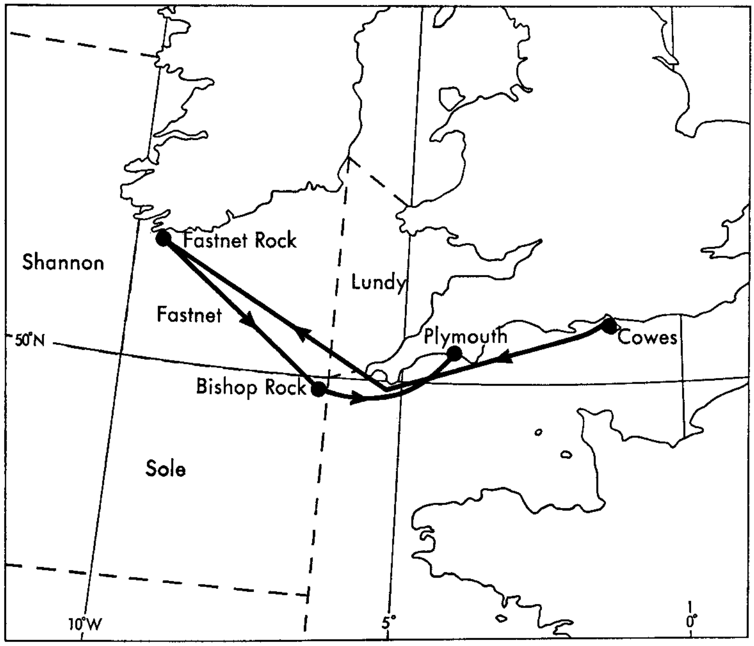

Figure 1. The course of the Fastnet Race.

the order of 120–130 kn. Low LY, which had broken away three days earlier from a shallow area of low pressure over the north-western United States, was well documented at this stage. The centre was located 150–200 n. mile south of the jet axis and, with the vorticity advection term obviously small, its eastward movement at about 30 kn was mainly controlled by the thermal steering with little change in the central pressure. In fact some slight filling of the centre from 1002 to 1005 mb was apparent during the second half of Saturday.

(b) *Forecast guidance*

Numerical forecasts from the coarse-mesh (octagon) version of the Meteorological Office 10-level model gave consistent advice during these early stages in the life of low LY. Even the guidance produced on Friday 10 August for four and five days ahead suggested that the depression would deepen later in the period as it approached the British Isles.

On Saturday 11 August the 48- and 72-hour numerical forecasts reinforced this advice and were subsequently supported by the 500 mb products from the United States. The models showed the upper ridge over the British Isles declining and moving away as the strong westerly jet over the Atlantic extended eastwards. Numerical forecast charts for midday on the 14th indicated substantial development and sharpening of the upper trough associated with LY as it approached 20°W, helped by a veering of the flow over the western Atlantic as the upstream ridge amplified near Labrador. This is well illustrated in Fig. 3(a) which shows the 72-hour forecast at 500 mb from the 10-level model, based on data for 12 GMT on 11 August. The corresponding forecasts of surface pressure showed LY running rather quickly eastwards at about 30–35 kn during the first 48 hours with no development—quite the reverse,

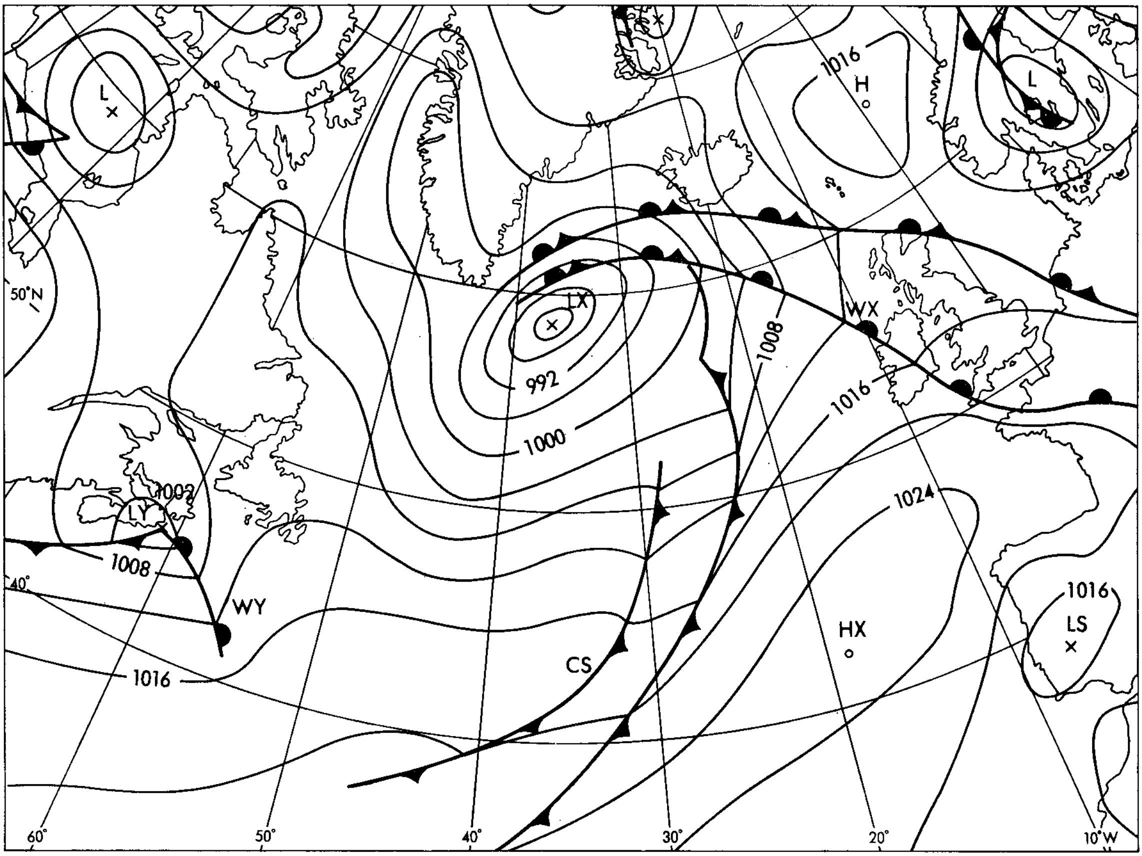

Figure 2(a). Central Forecasting Office (CFO) surface analysis for 12 GMT, 11 August 1979.

in fact, with the 48-hour forecast for 12 GMT on 13 August giving no discrete centre associated with the low, merely a trough implying a wave of about 1012 mb near 48°N 30°W. However, after 72 hours a significant change had taken place in the forecast field as the low moved into the well-marked diffluent area ahead of the sharpening upper trough. On the forecast chart for 12 GMT on 14 August (Fig. 3(b)) a separate low centre had been developed to the west of Ireland with a closed circulation and a central pressure of 1003 mb.

The medium-range guidance issued on 11 August followed the general developments predicted by the model—not surprising in view of the plausibility and consistency of the solutions produced by the computer. The forecasters were particularly impressed by the massive upper trough generated behind LY on the 72-hour prognoses and the highly developmental nature of the pattern. Experience has shown that in this type of situation the model frequently underestimates the deepening of the associated surface low. Consequently, on the subjective prognoses the forecasters considerably accentuated the depth of the low as it moved over the eastern Atlantic, encouraged also by the rapid deepening suggested by the model in the latter stages of the forecast period. The 72-hour forecasts based on data for 00 and 12 GMT on 11 August produced by the medium-range forecaster are shown in Figs 3(c) and 3(d)

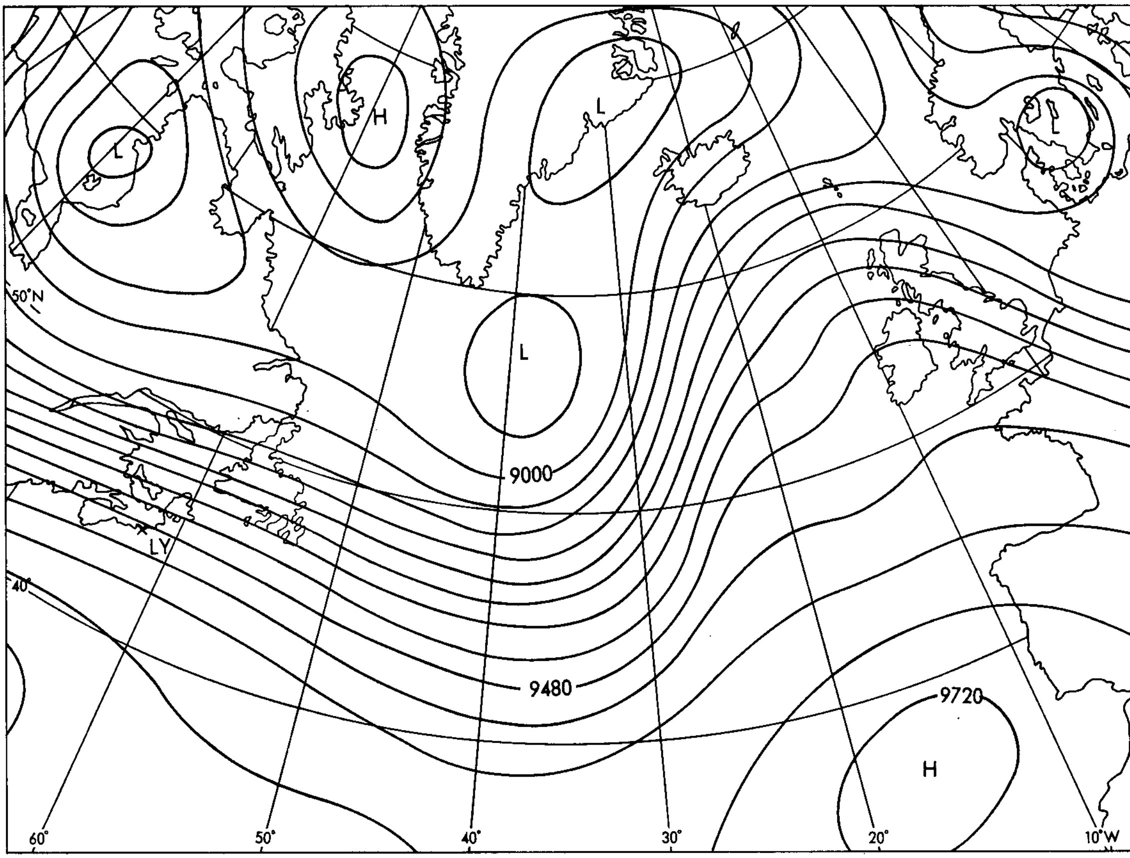

Figure 2(b). CFO 300 mb analysis for 12 GMT, 11 August 1979. Values in geopotential metres.

respectively. Although these charts were originally drawn at intervals of 8 mb, intermediate isobars at 4 mb have been interpolated so that the subjective prognosis in Fig. 3(d) may be directly compared with the original numerical forecast (Fig. 3(b)). It is noteworthy that the central pressure of LY in Fig. 3(d) is about 17 mb deeper with a resultant marked increase in the pressure gradients.

Both sets of medium-range forecasts issued on 11 August proved to be slow as far as the eastward movement of LY was concerned. Even so there is no doubt that they provided useful guidance and correctly conveyed the idea of a vigorous low with pressure gradients strong enough to produce gales or severe gales approaching western Ireland by early on 14 August (although the track was expected to be further to the north-west than actually occurred).

Southampton Weather Centre had been asked by the RORC for an extended forecast to be prepared about seven hours before the start of the race. The advice included an outlook until 23 GMT on 13 August (about the time when the first severe effects of the storm were to be felt) and was written after consultation with the medium-range forecaster in the Central Forecasting Office (CFO). When the situation was discussed the 72-hour forecast chart shown in Fig. 3(c) was still being prepared and, since it was thought that the main wind strength in Fastnet would develop after the end of this particular

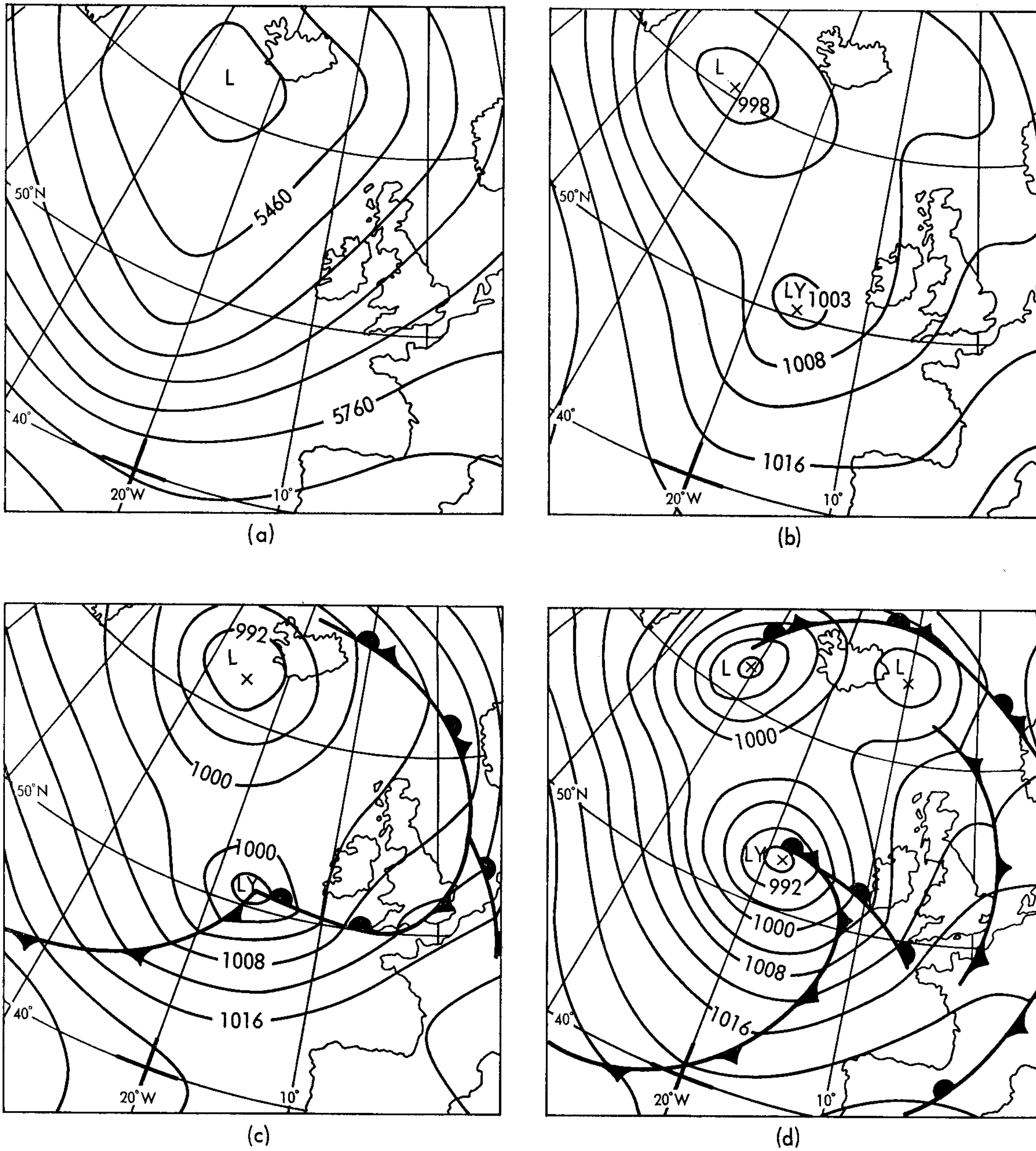

Figure 3. (a) Octagon 72-hour 500 mb forecast for 12 GMT, 14 August 1979. Values in geopotential metres.
(b) Octagon 72-hour surface forecast for 12 GMT, 14 August 1979.
(c) Medium-range 72-hour surface forecast for 00 GMT, 14 August 1979.
(d) Medium-range 72-hour surface forecast for 12 GMT, 14 August 1979.

forecast period, the advice issued by Southampton did not reflect the potential vigour of LY. The RORC made no arrangements to receive updated forecasts during the race because they had no means of transmitting the information to the competitors once they had sailed. The British national team were also briefed by a member of the Meteorological Office acting on a private basis. At the final briefing which took place shortly before the start of the race (again after consultation with CFO) the possibility was indicated of winds reaching gale force (Beaufort force 8) at times from Tuesday 14 August onwards.

3. Sunday 12 August

(a) *Synoptic situation*

During Sunday 12 August developments proceeded along the lines expected earlier. Low LY continued on a general easterly track with ship observations giving a reasonable fix on the position and depth, at least until midday when the centre was approximately 300 n. mile east of Newfoundland (Fig. 4). Continuity charts (Fig. 5) indicated that the system was accelerating at this stage as its track slowly became closer to the jet axis, the mean speed between midnight and midday being about 40 kn. There was still no discernible deepening and the upper trough associated with the low remained as a minor perturbation in the strong zonal flow.

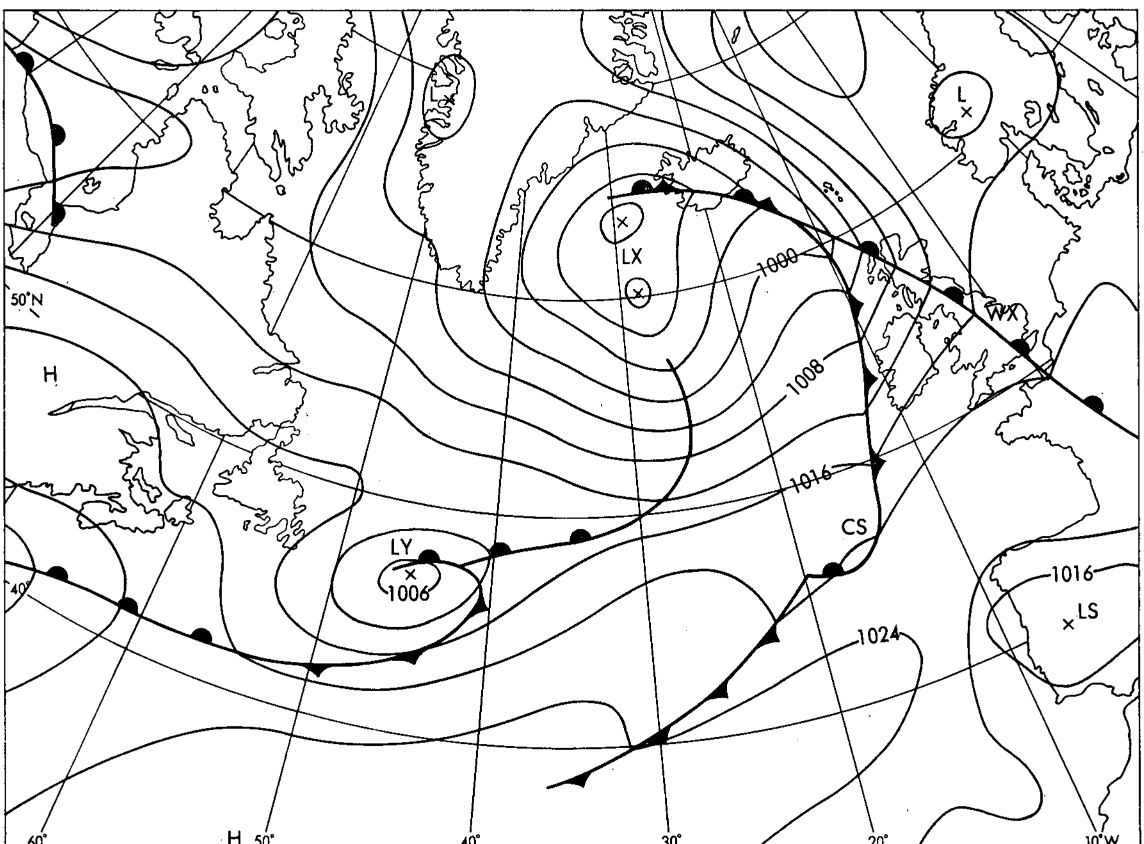

Figure 4. CFO surface analysis for 12 GMT, 12 August 1979.

(b) *Forecast guidance*

The run of the numerical model based on data for 00 GMT on 12 August maintained the same general evolution as previous runs and the medium-range forecaster again accentuated the depth of LY on his 48- and 72-hour forecast charts, developing a low of 986 mb off western Ireland (12 mb deeper than the model).

During the day the senior forecaster became increasingly unhappy with the detail of the numerical guidance as far as the 24-hour prognoses were concerned. By now low LY was just appearing on the forecast charts produced from the fine-mesh (rectangle) version of the model (these charts extend only as far as 35°W over the North Atlantic). The two versions of the model gave similar solutions, suggesting that LY would be near 50°N 30°W at midday on the 13th with central pressure around 1010 mb. This represented a slight *filling* of the low and an average speed of only 25 kn. Such movement appeared much too slow considering the strength of the upper flow, the recent observed acceleration of the system and the evidence from satellite pictures (which showed the associated cloud mass extending very quickly eastwards across the Atlantic). Moreover, it was expected that some deepening would be initiated as the low became located in an increasingly diffluent pattern on the cold side of the jet. The models had clearly not made the low deep enough, since even in the 12-hour forecast for 12 GMT that same day the central pressure was 7 mb higher than the analysed value, despite a satisfactory numerical analysis.

In his subjective prognosis for 12 GMT on 13 August (Fig. 6(a)), the senior forecaster therefore deepened the low to 998 mb (12 mb deeper than the model) and moved the centre quickly east-north-east to near 50°N 20°W. This turned out to be close to the position suggested by the later rectangle run based on 06 GMT data. The main intention behind this prognosis was to portray the start of vigorous cyclonic development with geostrophic winds up to 50 kn round the low. In the accompanying Synoptic

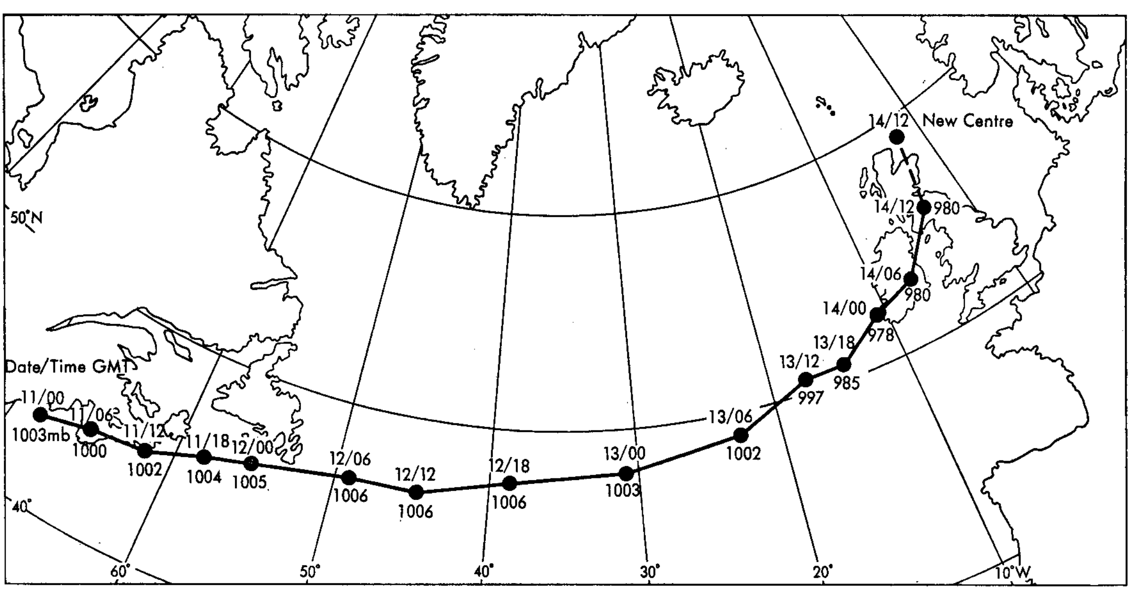

Figure 5. Track and depth of Low LY from 00 GMT, 11 August to 12 GMT, 14 August 1979.

Review the comment was made: 'Low LY is expected to start deepening substantially tomorrow as it engages the very cold air now extending south over mid-Atlantic'. The reference to 'very cold air' was especially pertinent since the analysed 1000–500 mb thickness values near 55°N 35°W were close to the 25-year (1951–75) extreme minimum of 534 decageopotential metres. This had produced very strong baroclinicity over the central North Atlantic near 50°N and AIREPs (aircraft reports) indicated that the associated jet was slowly strengthening, maximum wind speeds of around 150 kn being reported by early on Monday 13 August. The flow pattern was in many ways appropriate to a winter situation and the potential was obviously there for major cyclonic development.

Numerical guidance based on midday data received later on 12 August presented few surprises. After showing no development in the first 24 hours the 36-hour rectangle forecast for 00 GMT on 14 August (Fig. 6(b)) at last showed the low starting to deepen more noticeably. However, both the rate of deepening and the eastward movement of the centre were about 12 hours slower than the senior forecaster's prognosis which had just been issued (Fig. 6(a)).

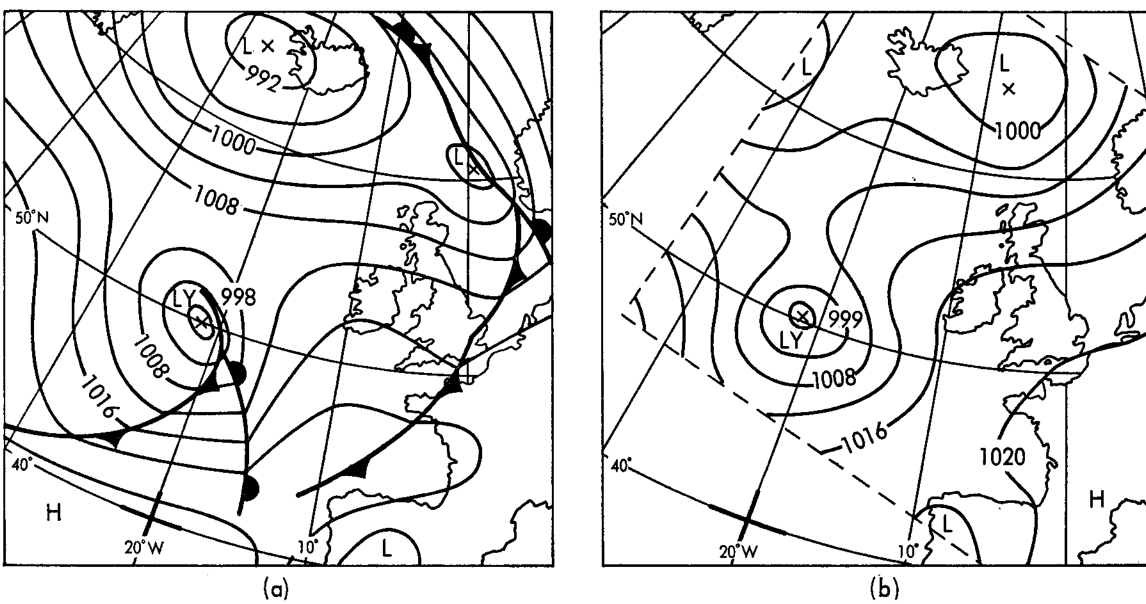

Figure 6. (a) Subjective 24-hour surface forecast for 12 GMT, 13 August 1979.
(b) Rectangle 36-hour surface forecast for 00 GMT, 14 August 1979.

Thus, throughout Sunday 12 August the general feeling continued that LY would be a notably vigorous system as it approached Ireland, probably much more so than indicated by the models. A forecast prepared by Southampton Weather Centre for Offshore Instruments Ltd in connection with the Fastnet Race included the possibility of severe gales (force 9) on the 14th, in line with the medium-range guidance and outlooks issued from CFO. However, the shipping forecasts which were the main source of weather information for the yachtsmen contained no such information, since the major intensification of LY was expected to take place after the 24-hour period covered by the forecast.

4. Monday 13 August

(a) *00–12 GMT*

When the senior forecaster came to draw the midnight surface analysis in the early hours of Monday 13 August he was faced with a complete dearth of information in the area of the North Atlantic where low LY was located. No observations were available within about 350 n. mile of the estimated position of the centre, the nearest being from Ocean Weather Ship 'C' (52·7°N 35·5°W) which was outside the circulation of the low and gave little clue to its depth. The analysis therefore had to rely heavily on continuity with the centre of the low estimated at 1006 mb near 48°N 32°W. In contrast, the flow pattern at 300 mb (Fig. 7) was well defined by AIREPs with a maximum wind speed of 150 kn at 33 000 feet just north-east of the estimated position of the low centre, decreasing rapidly to 40–60 kn in a classic left-exit region near the British Isles.

Despite the uncertainty over the depth and exact position of LY, it was clear from satellite pictures that the very strong upper flow was bringing the low eastwards much faster than indicated by the model, as had been anticipated on the previous day. Moreover, it was considered that with the jet also propagating forwards quickly, the major development of the low would occur later and further east than expected previously. In his draft 24-hour prognosis for 00 GMT on 14 August, the senior forecaster ran

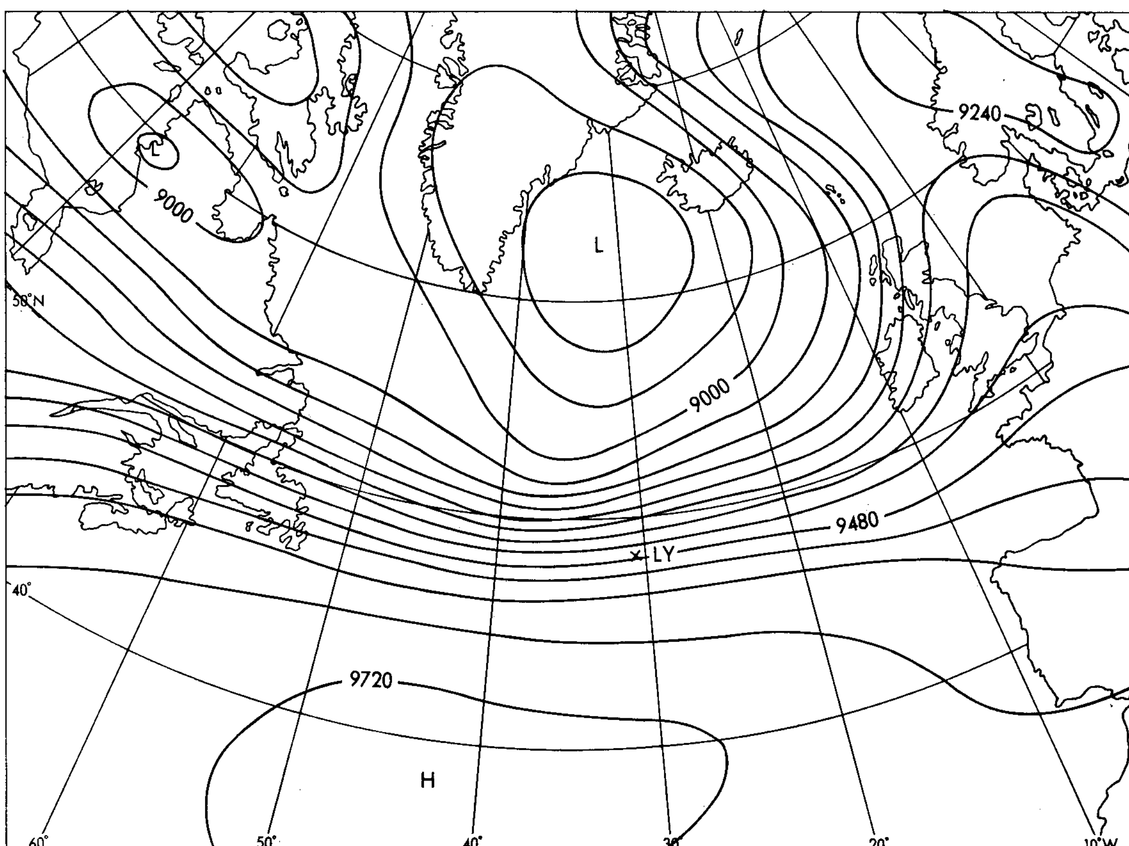

Figure 7. CFO 300 mb analysis for 00 GMT, 13 August 1979. Values in geopotential metres.

LY quickly towards the north-west of Ireland with only slight deepening. As it happened, when the new numerical guidance based on midnight data was received, it supported these ideas and the forecast chart shown in Fig. 8 was issued with LY kept more as an open wave than hitherto. It is true, of course, that the numerical analysis also suffered from the lack of data over mid-Atlantic and this aspect has been investigated by Day (1981). However, although the initial analysis was very poor for the rectangle run, rectification of this for the octagon forecast did not result in any greater development.

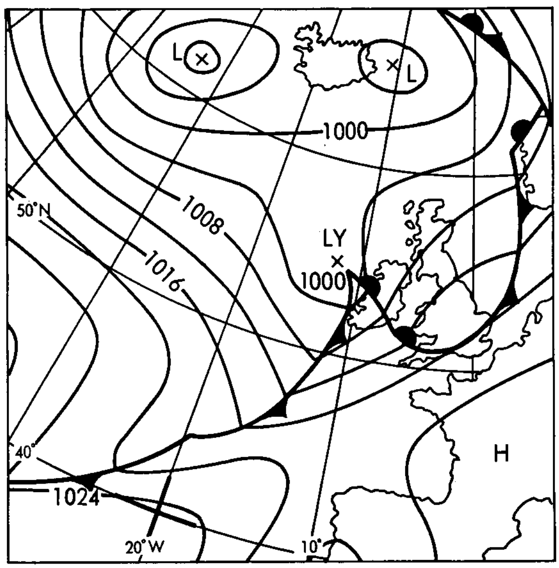

Figure 8. Subjective 24-hour surface forecast for 00 GMT, 14 August 1979.

A complex situation existed near the British Isles with the weather during the coming day expected to be controlled by frontal waves on the cold front CS. One particular wave which had been identified at 46°N 20°W at 12 GMT on the 12th (Fig. 4) was moving towards south-west England and was destined to complicate the picture throughout the day. By the end of the night it appeared that the upper pattern was pushing so far eastwards that this small wave was going to be the deepener rather than low LY (pressure falls in the south-west approaches were then significantly larger than at Ocean Weather Ship 'R' ahead of LY).

Doubts about the surface analysis persisted through the morning, the only ship observation on the chart for 06 GMT closer than 400 n. mile to the low centre being that from Ocean Weather Ship 'R' (47·0°N 16·9°W). This report just ahead of the associated warm front seemed fairly innocuous with a surface pressure of 1013·4 mb, a falling pressure tendency of 2·2 mb in three hours and a wind of 210°, 16 kn. Satellite pictures helped to estimate the centre of the low near 49°N 25°W and, with no evidence for any significant deepening, the story followed the general lines adopted overnight.

In the late morning the surface analysis was reviewed when some delayed ship observations for 06 GMT were received. Amongst these (see Fig. 9) was an observation from the Panamanian-registered *Carmelita* (call-sign 3EJE) giving the first report of a gale and suggesting some deepening of the low. For clarity only the coded pressure and wind have been plotted in Fig. 9. However, just 40 n. mile to the north-west of this ship was another observation from the British vessel *Resolution Bay* (call-sign GXEV) with a wind of only 18 kn and a slightly higher pressure. *Resolution Bay* is a ship noted for the excellent quality of its observations and the 06 GMT analysis was subsequently revised accepting its observation rather than that from the Panamanian vessel. Thus, only very slight deepening of LY was diagnosed although it was clear that further acceleration of the system had occurred overnight, the mean speed of movement of the low in the 12 hours up to 06 GMT being about 50 kn!

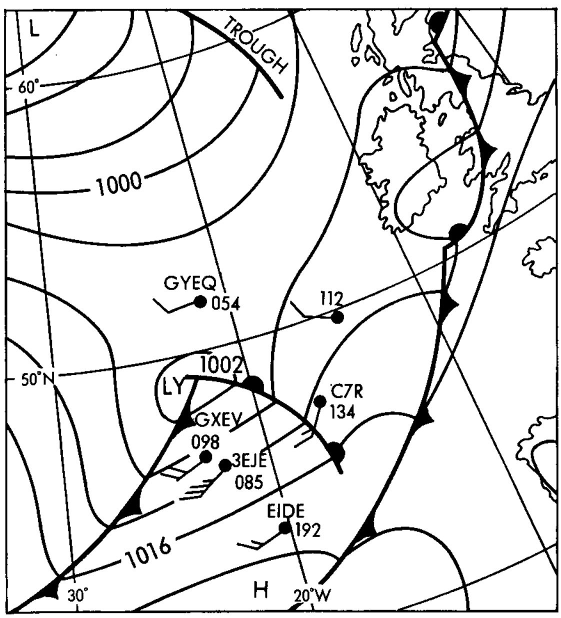

Figure 9. Finalized CFO surface analysis for 06 GMT, 13 August 1979.

(b) *12–18 GMT*

Around midday, the pressure falls at Ocean Weather Ship 'R' which had averaged a modest 2 mb in three hours for most of the morning suddenly accelerated to 5 mb in three hours with an equally abrupt increase in surface wind from around 20 to 31 kn between 11 and 12 GMT. In addition, the rectangle forecast received in the early afternoon, based on 06 GMT data, indicated rather more development of LY than the run based on midnight data with the 30-hour forecast (Fig. 10(a)) showing a low of 996 mb near eastern Scotland. Comparison of the 6-hour forecast with the current midday analysis revealed that the model already had the low much too shallow. The apparent discrepancy was around 10 mb, arising partly from errors in the analysis (3 mb) but mainly from spurious filling of the low in the early stages of the forecast. Again there was some uncertainty over the exact position and depth of the low on the midday analysis, with no ship reports closer than about 180 n. mile to the estimated position of the centre. However, the evidence that the model had probably underestimated the development of LY, combined with the increasing wind and pressure falls at Ocean Weather Ship 'R', encouraged the senior forecaster to make the low a much more vigorous feature on his 24-hour forecast for 12 GMT on 14 August (Fig. 10(b)). This was the first prognosis produced on Monday 13 August which correctly developed very strong pressure gradients around LY as well as keeping it on a track over southern Ireland.

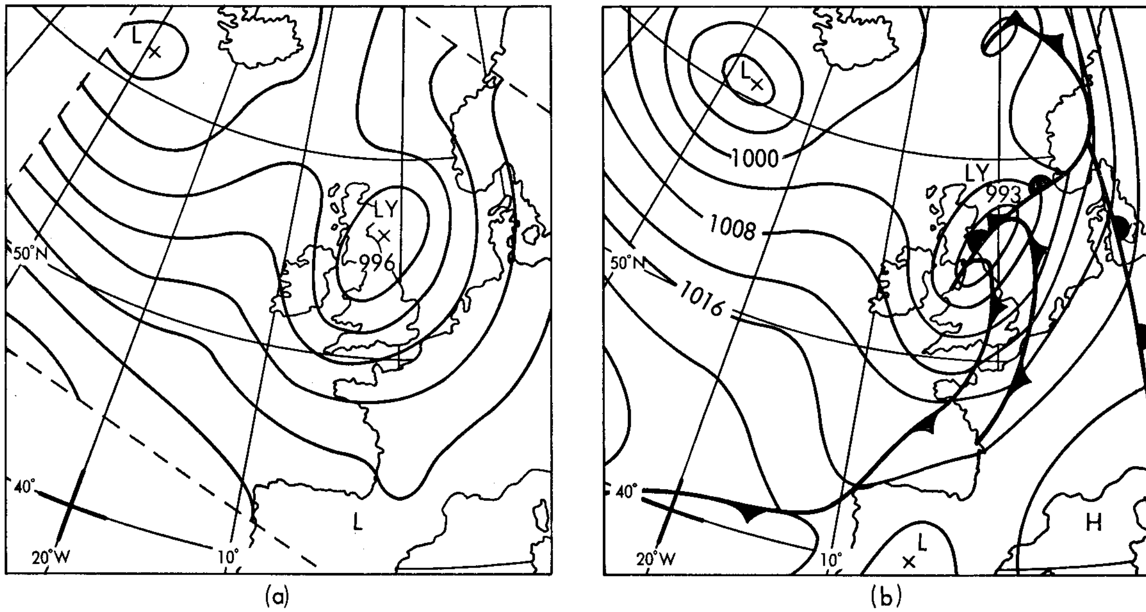

Figure 10. (a) Rectangle 30-hour surface forecast for 12 GMT, 14 August 1979.
(b) Subjective 24-hour surface forecast for 12 GMT, 14 August 1979.

With the wind at Ocean Weather Ship 'R' continuing to increase to 40 kn, it was now clear that the low was starting to slow down and deepen. The Synoptic Review issued at 1525 GMT added the further qualification: 'With LY now engaging the cold trough at 30°W considerable deepening is now expected. . . . Winds are now expected to be even stronger than indicated on the 1200 prognosis'. The TIROS N satellite picture received in the late afternoon (Plate I) gave further evidence that LY was deepening. The cloud was developing a marked 'comma' shape indicating increased circulation, with signs of a significant trough already forming in the cold air.

The finalized CFO surface analysis for 12 GMT on 13 August (Fig. 11) differed little from the preliminary drawing, none of the late ship reports being in a position to help define the centre of the low better. However, inspection of the tracking in Fig. 5 suggests that the centre may well have been slightly further to the south-west as it entered the deepening stage and slowed down. The wind, coded pressure value and tendency are plotted in Fig. 11 for a selection of key observations. In retrospect, the outstanding impression is how ordinary the low looked at that time with only one report of a gale and generally light or moderate winds in Fastnet and to the south-west of Ireland. Pressure tendencies were by no means exceptional; indeed by 15 GMT pressure falls over the southern Irish Sea ahead of the developing wave on cold front CS were larger than those in south-west Ireland (3·3 mb in three hours at Valentia). So even after the event it is difficult to isolate any features on the surface charts which should have given firm warning of such explosive development as actually occurred. Lack of ship reports near the low centre at the crucial time meant that the only real clue lay in a qualitative assessment of the upper pattern (which, as stated before, was exceptionally favourable for cyclonic development). Further guidance from the numerical model was not available during the afternoon, owing to the breakdown of both the IBM 360/195 and 370/158 computers, which also disrupted the supply of plotted charts to CFO.

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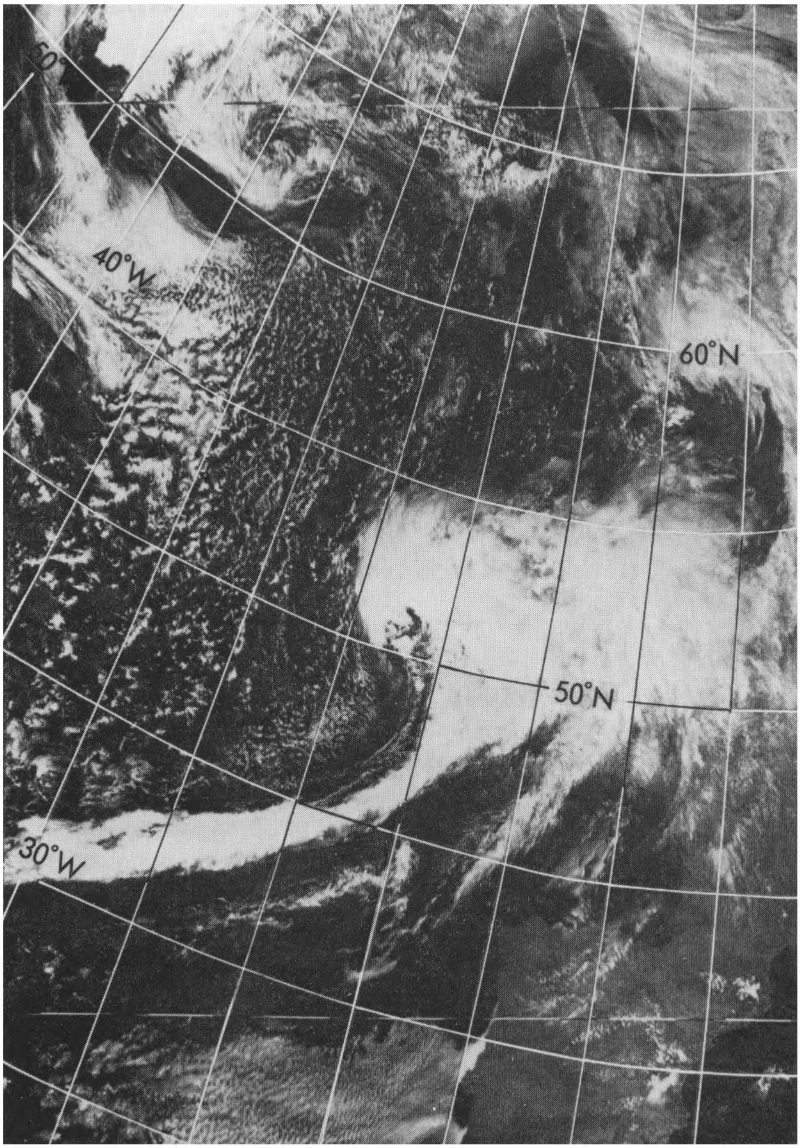

Plate I. TIROS N visible satellite picture received on the afternoon of 13 August 1979.

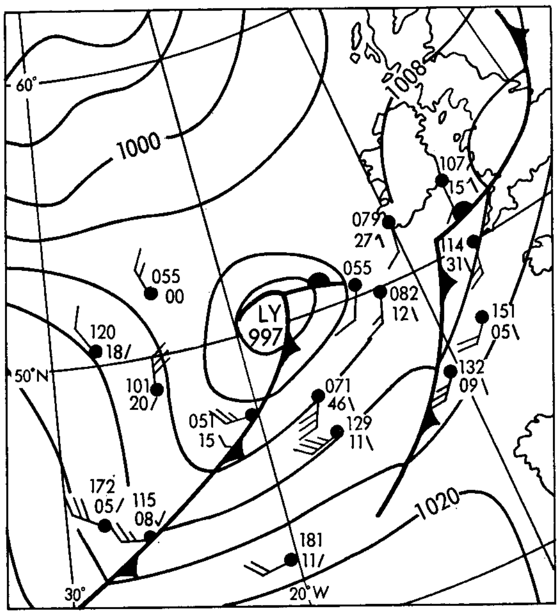

Figure 11. Finalized CFO surface analysis for 12 GMT, 13 August 1979.

(c) *18–24 GMT*

During the early evening of 13 August, steadily accelerating pressure falls over south-west Ireland confirmed the vigorous nature of the low, although similarly increasing falls were also evident ahead of the developing wave on the cold front CS as it moved northwards over the Irish Sea. This wave was still occupying some attention from the senior forecaster, since by now it was associated with a broad area of moderate or heavy rain and the need for FLASH messages was being actively considered.

With the computer complex now back in service, new guidance from the fine-mesh model was received around 20 GMT confirming what was already apparent, namely that LY was going to deepen substantially. However, even at 2015 GMT when the senior forecaster came to draw the 18 GMT surface chart, the analysis was still in doubt. Fig. 12 shows that the three ship reports closest to the low centre (call-signs KGCW, D5MI and UITO) had pressure values which almost certainly were wrong or incorrectly coded. Without knowing this, it was possible to draw the low as a much shallower feature but then no satisfactory explanation could be given for the very strong winds reported from ship KGCW (55 kn) and Ocean Weather Ship 'R' (40 kn). The most likely solution appeared to be that the pressure reports from ships KGCW and D5MI had been erroneously coded in whole millibars. The resultant analysis produced in CFO that evening was very similar to Fig. 12 which was constructed by Painting (personal communication) after the event using all available data. The low had deepened, therefore, by around 12–13 mb between midday and 18 GMT, an exceptional rate of development for August, whilst its speed of movement had halved to about 25 kn. In the Synoptic Review issued at 2235 GMT, considerable stress was placed on the strength of wind to be expected in the unstable westerlies on the southern side of the low (particularly in gusts); in addition, a warning was sent to Ministry of Defence Headquarters of severe weather conditions (heavy rain and severe gales) which might call for military aid to the civil community.

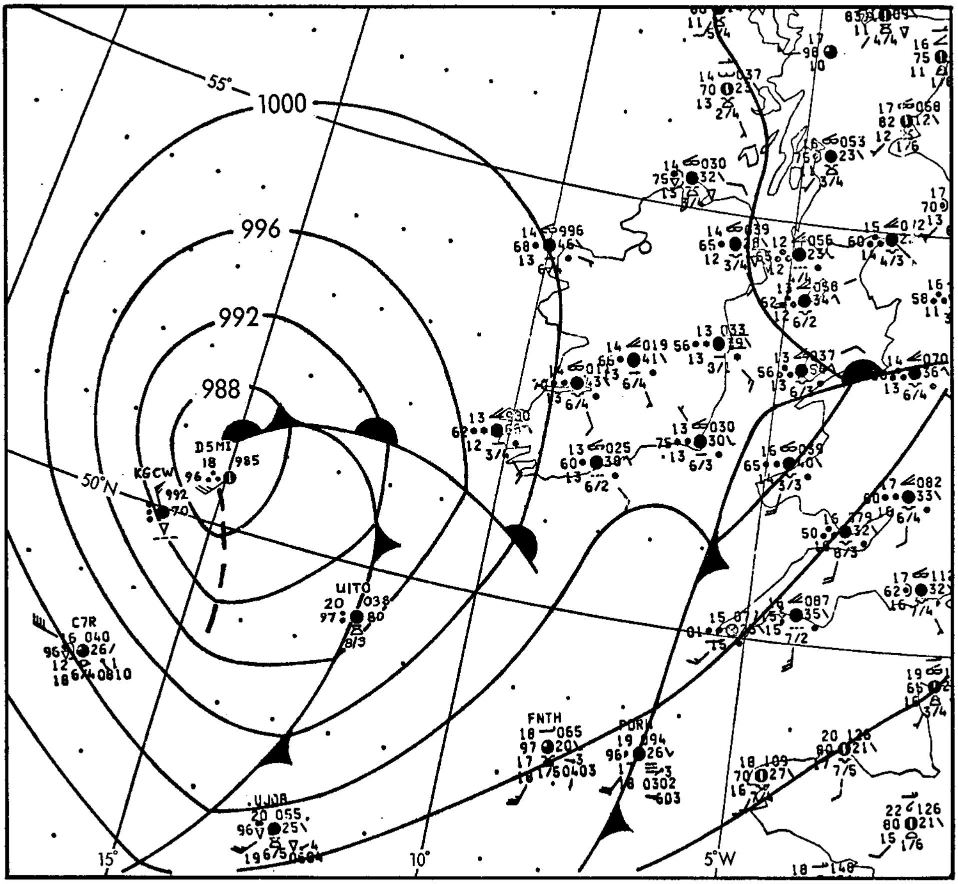

Figure 12. Retrospective surface analysis for 18 GMT, 13 August 1979.

5. The storm

Figs 13 and 14 show the retrospective surface analyses constructed by Painting for 00 and 06 GMT on 14 August, spanning the period when the majority of the race competitors thought the weather was at its worst. It is outside the scope of this paper to attempt any detailed analysis of the climatological aspects of the storm. However, a few points are worth noting to put the occasion in perspective.

As shown in Fig. 13 the strongest winds were undoubtedly located in the unstable westerly flow behind the trough extending southwards near 9°W. Painting's investigation concluded that storm-force winds with very high seas reached Fastnet Rock just before 23 GMT on 13 August and spread rapidly eastwards across the race area during the next three hours. He estimated mean wind speeds reaching 50–55 kn with gusts up to 68 kn (the upper reaches of force 10) and waves as high as 15 metres at times. Another important point to come out of Painting's work was the sudden veer and abrupt increase of wind which occurred with the passage of the trough, accompanied by enhanced gustiness and very high seas. This may well explain why the majority of race competitors estimated the wind speed as force 11 or more. The report prepared for the Royal Yachting Association and the RORC (1979) pointed out that

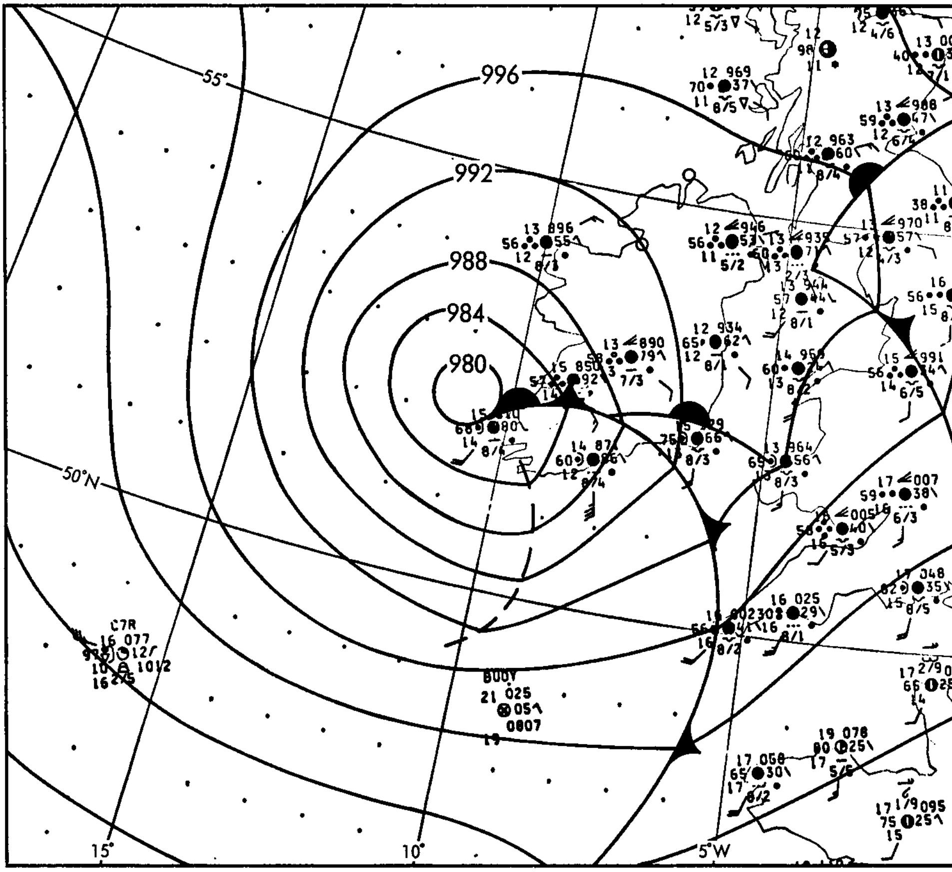

Figure 13. Retrospective surface analysis for 00 GMT, 14 August 1979.

the rapid wind veer would result in wind and waves coming from different directions, making conditions particularly difficult during the hours of darkness. Apparently many experienced competitors stated that the wind strength was not unusual but the sea conditions were the most dangerous they had ever experienced.

The storm went on to cause considerable damage over land during the day, especially in Wales and the west Midlands where many roads were blocked by fallen trees and camping sites were devastated. The highest steady wind speed reported at a land station was 50 kn from Mumbles in South Wales at six consecutive hours from 06 to 11 GMT. Many stations inland over England and Wales had gusts of 50 kn or more, several places recording their highest gust speed for any August. The maximum gusts reported were 65 kn at Milford Haven and 74 kn at Hartland Point, although the latter must be treated with some reserve because of its peculiar exposure. However, the belt of exceptionally strong winds was of very limited lateral extent since, as pointed out by Littlejohns (personal communication), many stations in south-west England and southern Ireland did not even report a mean wind of as much as gale force (although gusts between 43 and 50 kn occurred widely).

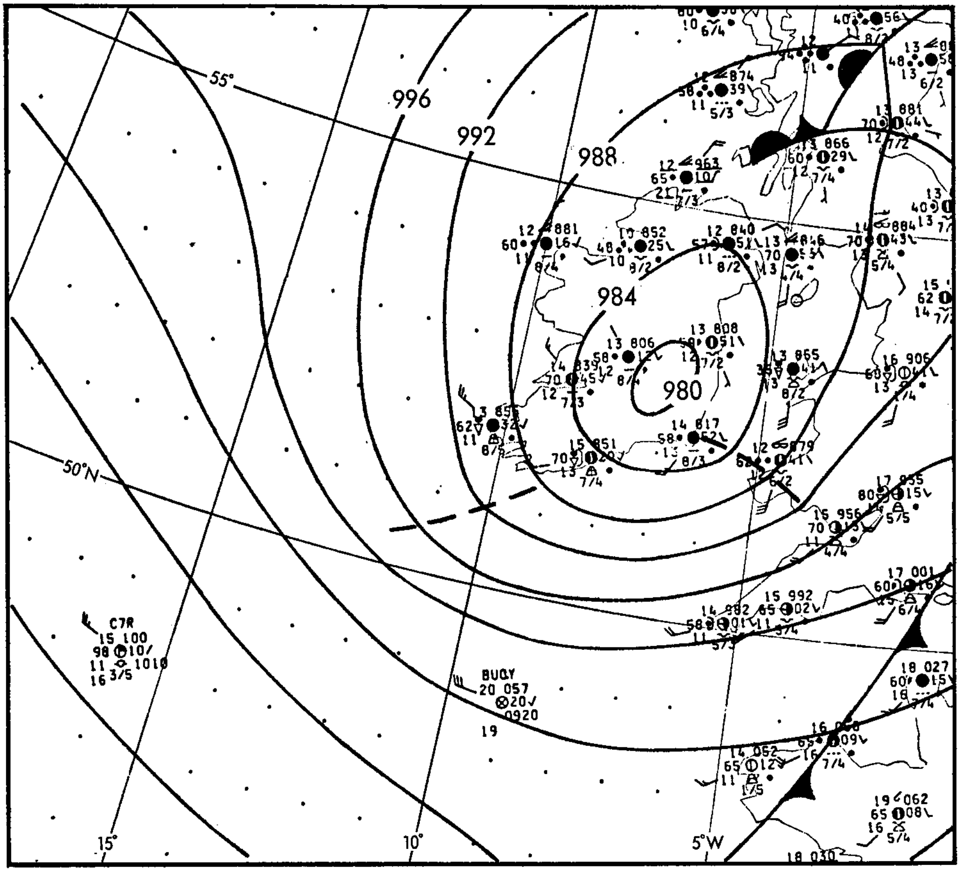

Figure 14. Retrospective surface analysis for 06 GMT, 14 August 1979.

During Tuesday morning the low turned on a more northerly track and became complex with a second centre developing off eastern Scotland. This was another surprising feature of the storm, viz. despite the massive deepening which occurred there was no major deviation of the track to the left until after 06 GMT on 14 August (presumably because of the resistance of the very strong upper flow to buckling). Although the storm was unusually severe for August it was not without precedent. Painting (personal communication) has noted a depression of amazing similarity which also moved across southern Ireland, on the night of 15/16 August 1970, and gave severe gales in many parts of the British Isles.

6. Conclusions

(a) Guidance for 48 and 72 hours ahead from the 10-level model gave firm indications that low LY was likely to deepen as it approached western Ireland, although the surface pressure forecasts seriously underestimated the amount of deepening by 20–25 mb.

(b) The medium-range forecasters made substantial improvements to the numerical guidance, deepening the low by an extra 12–17 mb, thereby indicating a distinct possibility of gales or severe gales in the Fastnet area. This was an outstanding example of the contribution that the forecaster can still make to the so-called 'man–machine mix'.

(c) Retrospective analysis of the storm indicates that the belt of exceptionally strong winds (force 9 or more) was of very limited lateral extent, probably of the order of 100 miles wide. Bearing in mind the grid length of the model and the enormous distance travelled by the low, it would appear unrealistic at present to expect reliable medium-range forecasts of the development and location of such features.

(d) Fine-mesh forecasts for 24 and 36 hours ahead failed to give advance warning of the sudden deepening and exceptional vigour of the low. Forecasts of the depth of LY at the peak of the storm were generally in error by 20 mb or so (even if we exclude the run from 00 GMT on 13 August which was affected by a very poor analysis).

(e) Twenty-four hour subjective forecasts for the period when the storm was at its height showed some improvement over the corresponding fine-mesh product. Nevertheless, forecast winds in the race area were underestimated at this stage.

(f) Although it was recognized that conditions were generally very favourable for cyclonic development, the short-term assessment of the timing and magnitude of the deepening proved much more difficult. Apart from the complications introduced by the forward wave in the South-west Approaches, the lack of and discrepancies between observations near the low centre undoubtedly delayed recognition of the start and the rapidity of the major deepening. This case-study clearly demonstrates the vital importance of reliable and correctly coded ship observations, even in this era of computers and satellite data.

7. Acknowledgements

I am indebted to my colleagues in CFO for their recollections of the situation at different stages in the development of the storm. I am also grateful to Mr W. B. Painting for various information and data which have been used in the preparation of this paper.

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Comparison of wind speeds recorded by pressure-tube and Meteorological Office electrical cup generator anemographs

By S. G. Smith

(Meteorological Office, Bracknell)

Summary

The electrical cup generator anemograph has replaced the pressure-tube anemograph as the most commonly used instrument for recording winds for climatological purposes in the United Kingdom. The Climatological Services Branch of the Meteorological Office has been concerned that records might not be homogeneous from stations where a change of anemograph has taken place. This paper discusses some of the characteristics of the anemographs and the problems of wind speed estimation. Values of 10-minute and hourly mean speeds at five United Kingdom stations are used to compare observations from the two instruments. A procedure for adjusting wind speed data is also given to improve the homogeneity of speeds measured by the different anemographs.

1. Introduction

Before 1955, climatological tabulations of wind speed observations in the United Kingdom (UK) were made using the pressure-tube anemograph (PTA). Since then this instrument has gradually been superseded by the electrical cup generator anemograph (CGA) which is easier to install and maintain as well as being more suited to requirements for remote and multiple displays. Any discrepancies between the anemograph observations may be unimportant for synoptic work since wind speed can vary considerably over short distances and on small time-scales. However, for climatological applications small but systematic differences of only 1–2 kn may be significant.

Before the acceptance of the CGA for climatological purposes, Hartley (1955) stated that for daily averages of hourly mean speeds recorded by a PTA and Mk Ib CGA at South Farnborough the two sets of readings showed 'close agreement'. In contrast, work by Rijkoort (1955) revealed systematic differences between hourly means recorded by a PTA and a cup anemometer. Since then it has been the opinion of the Climatological Services Branch that the CGA gives higher mean speeds than the PTA. Despite many discussions between the climatologists and instrument specialists, the question of homogeneity has never been conclusively resolved. This is partly because, apart from the comparison at South Farnborough (which involved a different version of the CGA from that in general use since 1955), no other record exists of observations made in the UK by a co-located PTA and CGA. The analysis described later, therefore, uses data from five stations where a CGA replaced a PTA but without a change of site. Ten-minute and hourly mean speeds are considered.

2. Measurement of wind speed

2.1 *The anemographs*

2.1.1 *Pressure-tube anemograph.* The pressure-tube anemograph (PTA) is basically an adaptation of the pitot-static tube with a chart recorder attached to a sensitive float manometer. It is described in the *Handbook of meteorological instruments*, part I (Meteorological Office 1956), and by Giblett (1932), who also gives details of wind trial experiments carried out with PTAs at Cardington.

The starting speed of the instrument is about 1·5 kn and its chart has a linear scale throughout the range of recorded speeds. At low speeds its response time is significantly less than that for cup anemometers. Nevertheless, Wieringa (1980a) states that, owing to the response lag, the PTA tends to overestimate the mean speed in fluctuating speeds by about 5%. This feature is not mentioned in the references given above.

2.1.2 *Electrical cup generator anemograph*

(a) *General.* The electrical cup generator anemograph (CGA) uses the rotation of its cups to generate an electrical current. Wind tunnel calibration enables wind speeds to be derived from measurements of the current. The anemometer, as distinct from the anemograph (which is taken to mean the anemometer and associated chart recorder), is also described in part I of the *Handbook of meteorological instruments.* Three versions of the CGA have been used for obtaining climatological tabulations in the UK—the Mk 2, Mk 4 and Mk 5. Hartley (1955) describes the Mk Ib and Else (1974) describes the Mk 5. Pearce (Meteorological Office, private communication) has investigated the response characteristics of the Mk 4 and Mk 5.

This paper will present results for a comparison of the PTA with the Mk 2 and Mk 4 CGA. Both these CGA versions have charts whose scale is markedly non-linear for low wind speeds and the instruments have starting speeds between 5 and 6 kn, i.e. a speed of this magnitude is required to start the cups rotating from rest. The cups of the Mk 2 have greater inertia than those of the Mk 4 and there is a number of less important differences between the instruments. However, those who have had substantial working experience of the anemographs believe that observations from them are compatible. The Mk 5 CGA has now been installed at several stations in the UK. This has a starting speed about 2 kn less than the earlier versions, its chart is linear for all ranges of speed and its mode of operation is slightly different from that of its predecessors. Further work may therefore be required in the future to determine whether Mk 5 observations are consistent with those from the Mk 2 and Mk 4.

(b) *Overestimation error.* Cup anemometers, and hence CGAs, would be expected to give an overestimate of the wind speed in variable winds because the cups accelerate more quickly than they decelerate. This is due to the variation in drag characteristics between the convex and concave faces of the cups, leading to a non-linear relationship between wind speed and turning moment of the cup system.

A number of workers have derived values for the magnitude of the overestimation error. For example, Izumi and Barad (1970) deduced the error to be about 10%, based on observations from a lattice-type tower in Kansas, although Wieringa (1980b), in a re-evaluation of the results, suggests this figure should be nearer 6%. Other researchers, using theoretical as well as empirical approaches, have obtained estimates which vary considerably. In this context, Kaganov and Yaglom (1976) give a useful review of the literature.

2.2 *Practical difficulties*

Wind speed can vary considerably in space and time. The site and height of the anemometer and response time of the anemometer and recorder are therefore important factors in the estimation of a representative wind speed. Other factors include the data-averaging procedure employed and the sensitivity of the instrument to relative wind direction; these points are discussed by MacCready (1966). Instrument faults can often be hard to detect and it is possible that systematic variations exist in recorded speeds by anemometers of the same type and version (Bond, private communication).

The mean speed has to be visually estimated from a dial or chart. This can be difficult, especially in gusty conditions or when the background mean speed is changing. Mean speeds in light winds are particularly difficult to measure because:

(a) Anemometers, in general, are not designed to record very low speeds accurately. For example, the starting speed may be substantially above zero and for a cup generator system magnetic drag effects are significant at low speeds.

(b) For the anemographs, if the zero setting of the charts is incorrect, the resultant error at low speeds is large in percentage terms.

(c) The majority of CGAs employed so far in the UK (namely the Mk 2 and Mk 4) have a chart which is highly non-linear in the 0–10 kn range. Fig. 1 shows a wind speed trace from a Mk 4 CGA.

The above points should be borne in mind for the comparison study of wind speeds which will now be described.

3. Stations and data

3.1 *Stations*

Most stations that have replaced a PTA with a CGA also changed their anemometer site at the same time. Data from these stations were considered unsuitable for study. Five stations, referred to as changeover stations, were selected at which there was no more than 1 m change in anemometer height and no change of site. These are listed in Table I. All are located at airfields in reasonably flat and open country. The heights above ground of the anemometer cups range between 9 m and 21 m. For each changeover station a control station was chosen, situated as near as possible to the changeover station and whose data were considered to be homogeneous around the time of the changeover. These are also listed in Table I. For long-period comparisons of the wind speeds two other control stations were used—Kew and South Shields. Both these stations have had PTAs since records began and no reported site changes after 1950. The locations of the changeover and control stations are shown in Fig. 2.

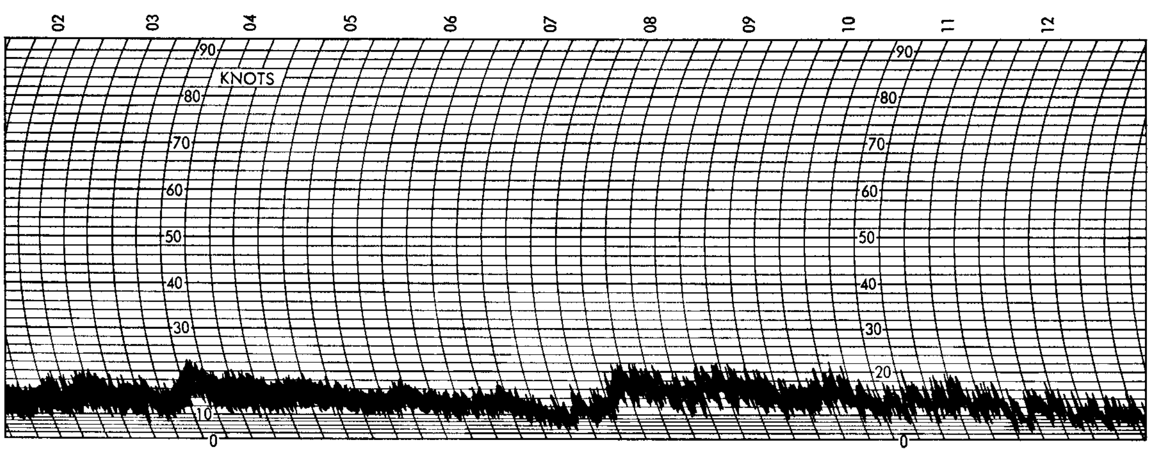

Figure 1. Example of a wind speed trace recorded on a chart used in conjunction with a Mk 2 and Mk 4 anemograph.

Table I. *Changeover and control stations used in the analysis*

Changeover station		Control station
Name	Date of changeover	Name
Boscombe Down	23 June 1964	Abingdon
South Farnborough	6 February 1964	Heathrow
Abingdon	8 January 1964	Boscombe Down
Valley	22 April 1963	Speke
Kirkwall	15 March 1962	Wick

3.2 *Data*

All ranges of wind speed have been included in the analysis. Although the accuracy of estimated speeds below about 5 kn is low, for the reasons already outlined, they have not been omitted. If systematic differences between the anemographs do occur in the 0–5 kn range, which contains a significant proportion of recorded speeds in the UK, then the long-term mean difference for all wind speeds would be considerably modified. However, the nature of the estimation procedure for these low speeds means that any differences in this range may not be directly associated with the anemometers.

Results of the analyses are presented in section 4. In sections 4.1 and 4.3 hourly mean values are used and PTA speeds are compared with Mk 2 and Mk 4 CGA observations over relatively long time periods. Section 4.2 relates to 10-minute means and compares PTA and Mk 2 CGA speeds over shorter periods of time.

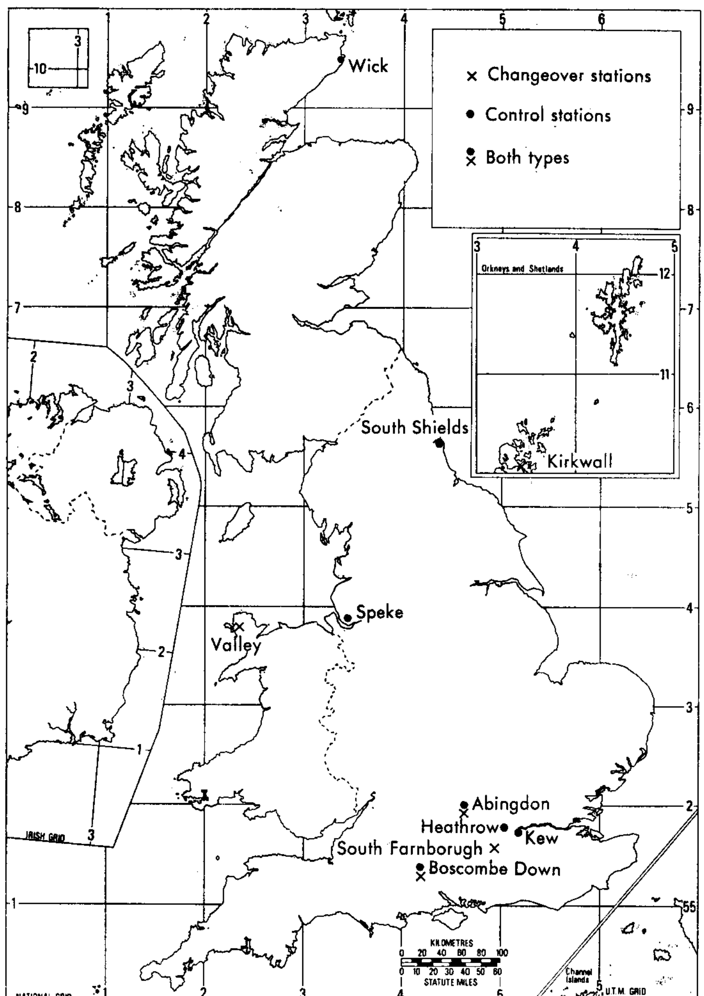

Figure 2. Location of stations used in the comparison.

4. Analysis and results

4.1 *Annual averages*

Annual averages of hourly means are readily available from 1956 onwards. These values have been plotted in Fig. 3 for the three changeover stations found to give the greatest difference between CGA and PTA annual averages. Values are also shown for a control station, Kew. The plots for the changeover stations strongly suggest that the introduction of the CGA has caused a discontinuity in the time series.

For each changeover station, means of the annual averages were calculated for the PTA and CGA periods separately, ignoring years in which the changeover took place. Means were also determined for Kew and South Shields over the corresponding periods. The relative wind speed change at the changeover station, $\bar{V}'$, was calculated as

$$\bar{V}' = (\bar{V}_{HC} - \bar{V}_{OC}) - (\bar{V}_{HP} - \bar{V}_{OP}),$$

where $\bar{V}$ represents a mean of the annual wind speed averages, H and O denote cHangeover and cOntrol station values respectively, and C and P indicate CGA and PTA periods respectively.

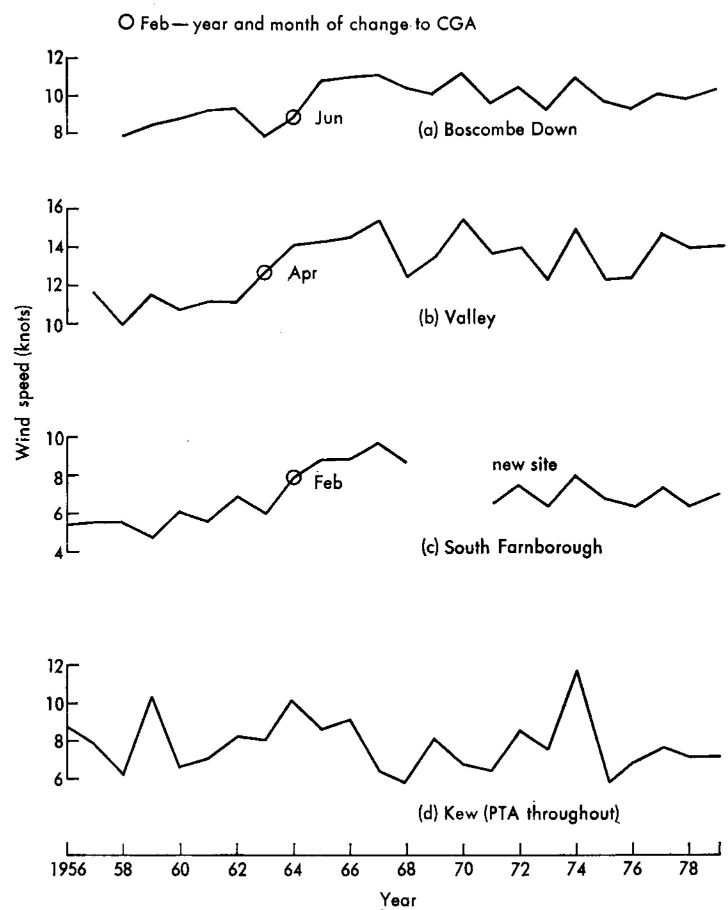

Figure 3. Mean annual wind speed at three changeover stations (a, b and c) and one control station (d).

Results for each combination of changeover and control stations are shown in Table II. The CGA values are seen to be more than 1 kn greater than PTA means at four of the five stations (cols 10 and 11). Values of 'Student's' t were calculated for $\bar{V}'$ to determine the statistical significance of the differences (see Appendix). They were found to be highly significant for all but Kirkwall and Abingdon when South Shields was the control. With Kew as the control, all stations except Abingdon gave a significant or highly significant result. The mean of $\bar{V}'$ over all five changeover stations is about 2 kn.

Table II. *Averages of annual mean hourly speeds (knots) for PTA and CGA periods (numbers rounded to one decimal place)*

Changeover station	PTA period averages (1) CS	(2) K	(3) SS	No. of years	CGA period averages (4) CS	(5) K	(6) SS	No. of years	CGA–PTA differences (4)–(1) (7) CS	(5)–(2) (8) K	(6)–(3) (9) SS	Relative changeover station differences (7)–(8) (10) K	(7)–(9) (11) SS	t values and their probabilities of occurrence by chance (12) K	(13) SS
Boscombe Down	8·5	7·5	9·2	7	10·2	7·3	9·2	13	1·7	−0·2	0·0	1·9	1·7	7·9 (<0·1%)	4·4 (<0·1%)
South Farnborough	5·7	7·7	9·2	8	9·0	7·6	9·1	4	3·3	−0·1	−0·1	3·4	3·4	7·9 (<0·1%)	11·4 (<0·1%)
Abingdon	7·7	7·6	9·2	8	7·7	7·3	9·1	11	0·0	−0·3	−0·1	0·3	0·1	1·5 (>5%)	0·6 (>5%)
Valley	11·0	7·7	9·2	7	13·9	7·3	9·2	14	2·9	−0·4	0·0	3·3	2·9	9·1 (<0·1%)	6·3 (<0·1%)
Kirkwall	12·1	7·4	8·8	4	13·6	7·3	9·2	15	1·5	−0·1	0·4	1·6	1·1	2·5 (<5%)	1·6 (>5%)

Key to headings in Table: CS = changeover station, K = Kew, SS = South Shields.

4.2 *Observations at three-hourly intervals*

Comparisons were next made between 10-minute mean speeds recorded at each changeover station and its control station both before and after the changeover. For reasons of convenience and availability of homogeneous control data, 167 days of observations made at three-hourly intervals were used for the PTA and CGA periods, a total of 1336 observations in each period. The relatively short comparison period ensures that factors such as gradual changes in exposure do not affect the analysis. A complete year of observations before and after the changeover was also analysed for Kirkwall and it was found that differences between the results for 167-day and one-year periods were negligible. It is therefore concluded that using periods of less than a year (i.e. less than the period of the annual cycle) has not distorted the results.

4.2.1 *Histograms.* Histograms were drawn of recorded speeds at the changeover and control stations before and after the changeover. Those for South Farnborough and Heathrow are shown in Fig. 4. Two features common to most of the histograms were:

(a) Tendencies for certain speeds, such as those that are a multiple of 10, to receive higher counts than adjoining values. Observer bias in recording wind speed has been documented by Reed (1978).

(b) Fewer observations at the changeover stations in the 1–3 kn range (1–4 kn at South Farnborough) for the CGA compared to the PTA.

4.2.2 *Changes in frequency distribution.* The relative percentage frequency change, $F'(i)$, between the CGA and PTA periods at the changeover stations was calculated for different wind speeds, V_i, where

$$F'(i) = \{F_{\mathrm{HC}}(i) - F_{\mathrm{OC}}(i)\} - \{F_{\mathrm{HP}}(i) - F_{\mathrm{OP}}(i)\},$$

with $F(i)$ representing a percentage frequency of occurrence at speed V_i and the subscripts having the same meaning as defined earlier.

Values of $F'(i)$ are shown in Fig. 5, where a positive result implies a larger number of CGA speeds at

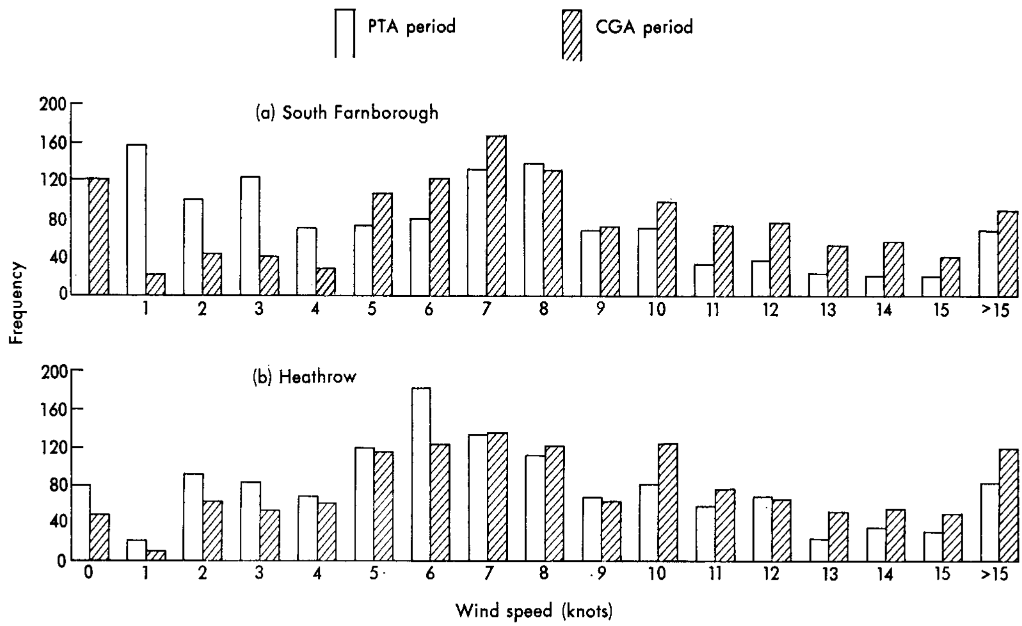

Figure 4. Histograms of wind speeds at South Farnborough and Heathrow.

the changeover station relative to frequency changes at the control station. There are fewer CGA observations in roughly the 1–3 kn range. Except at South Farnborough, the number of calms is also less for the CGA, which is rather unexpected in view of the CGA's relatively high starting speed. The frequency of CGA readings is generally greater for speeds between 5 and 7 kn and between 11 and 12 kn.

Values of $F'(i)$ were also plotted (but not shown) for hourly mean speeds at Boscombe Down and Valley. Results were similar to those obtained for 10-minute means although the numbers of 1–3 kn CGA speeds were even less than those observed for 10-minute means.

4.2.3 *Changes In speed.* It was considered worth while to determine the difference between the CGA and PTA observations for individual wind speeds. To achieve this, cumulative frequency histograms (i.e. plots of the number of observations less than or equal to each recorded speed) were drawn for the changeover and control stations before the changeover and after the changeover. The method is illustrated in Fig. 6. For each speed V_i between 0 and 20 kn at the changeover station the difference in speed $S_{H\text{-}O}(i)$ between the two curves was estimated for the PTA period and for the CGA period. (By subtracting the values of $S_{H\text{-}O}(i)$ from the observations at the changeover station the distributions at the two stations would be made more compatible.) The difference between the sets of $S_{H\text{-}O}(i)$ values from the CGA and PTA periods was then obtained, giving

$$S'(i) = \{S_{HC}(i) - S_{OC}(i)\} - \{S_{HP}(i) - S_{OP}(i)\},$$

where the two expressions in brackets are $S_{H\text{-}O}(i)$ for the CGA period and PTA period respectively.

$S'(i)$ can be interpreted as the difference in speed at V_i kn between the CGA and PTA. Plots of $S'(i)$ are displayed for each changeover station in Fig. 7. Positive values indicate a relative increase in CGA

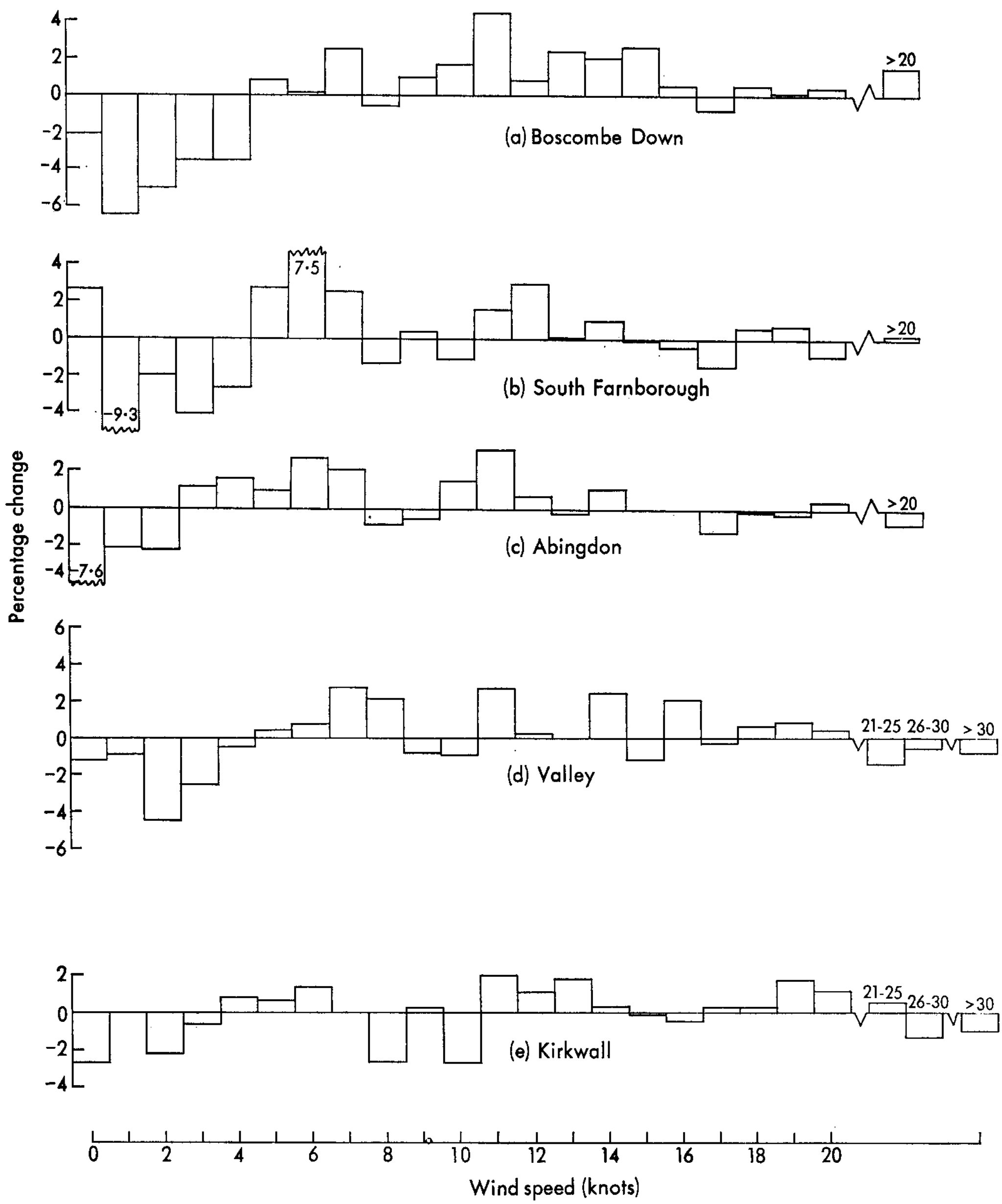

Figure 5. Relative percentage changes in frequency for different wind speeds.

speed. Most of the differences are positive, with the largest values occurring at the lowest speeds. Averages of $S'(i)$ over all five stations are also presented in Fig. 7. The graphs suggest that the CGA reads higher than the PTA by amounts ranging between about 2 kn at the lowest speeds to nearly zero at 15–20 kn. The large difference for the low speeds results from the few CGA speeds recorded in the 1–3 kn range.

4.3 *Monthly extremes*

It was not feasible to compare speeds above 20 kn in the 167-day period analysis because there was an insufficient number of observations. Therefore, to investigate these higher speeds a comparison was made between extreme hourly mean speeds recorded each month by the PTA before changeover and by the CGA after changeover. For each changeover station the highest speed was extracted for each 'winter' month from November to March such that, where possible, 50 values (i.e. about 10 winters) were obtained for immediately before the changeover and 50 immediately following. (Non-availability of suitable data limited the number of observations used from South Farnborough and Kirkwall to 27 and 24 in each period respectively.) The same procedure was performed for the summer months of June to August using a maximum of 33 extremes, although only 15 were available for South Farnborough and Kirkwall.

The extremes were plotted on extreme-value probability paper separately for each station and for each season. The plot for Boscombe Down winter months is shown in Fig. 8. It is observed that for a specified probability of occurrence the speed given by the CGA curve is about 2–4 kn more than the corresponding PTA value.

Results for all changeover stations are presented together by estimating, for various probabilities of occurrence, the difference between CGA and PTA values from the extreme-value curves. The confidence limits on these curves are considerably greater at both tails and hence values were not obtained for probabilities where fewer than three observations lay above or below the line. The estimated differences are shown in Fig. 9. Most of the values are positive, again indicating that the CGA reads higher than the PTA. The average difference is about 1–2 kn and this appears to vary little with speed. No reason could be established for the apparent anomalous results for Abingdon, or at Kirkwall for speeds below 40 kn in winter.

Similar plots were also derived for the control stations Kew and South Shields to verify that the observed differences were not due to secular changes in the pattern of wind speeds. It was concluded that the differences did not arise from such a change.

It should be pointed out that the differences in hourly mean speeds for the 15–25 kn range (Fig. 8) appear rather higher than might be expected from the results for speeds between 15 and 20 kn in the 10-minute mean analysis (Fig. 6). Further investigation revealed that mean differences between the CGA and PTA over the 167-day period were about 0·5–1·0 kn greater for hourly means compared to 10-minute means. There is also a relatively high uncertainty about the results for these particular ranges because they lie towards the tails of their respective distributions.

4.4 *Possible explanation of results*

An increase in CGA speeds over PTA values has been found, more especially for (a) speeds below about 8 kn and (b) speeds above about 20 kn. It is probable that the latter is the result of the over-estimation error of cup anemometers discussed in section 2.1.2. This may also in part account for (a) but another possible cause arises from the non-linearity of the CGA chart. Observers or tabulators determining the hourly speed when it is in the 1–3 kn range may, on some occasions, have inadvertently

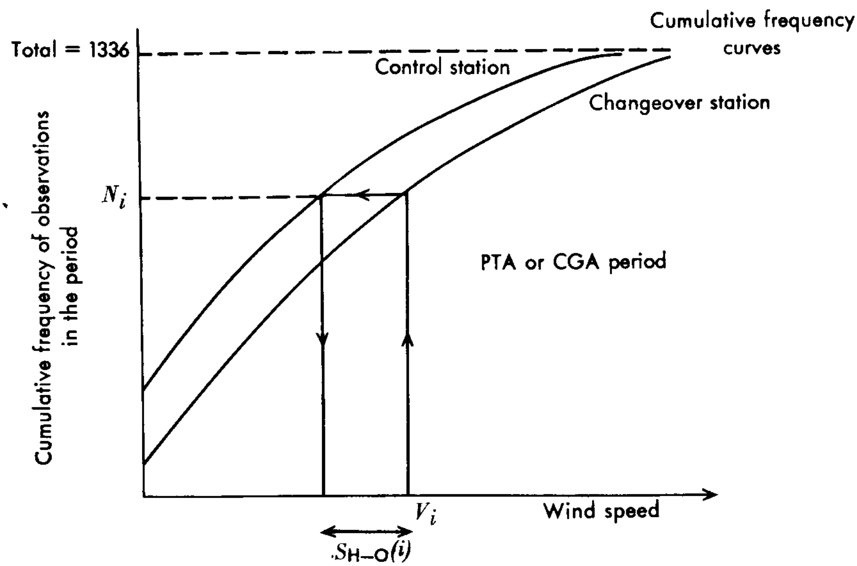

Figure 6. Illustration of method used to determine changes in speed.

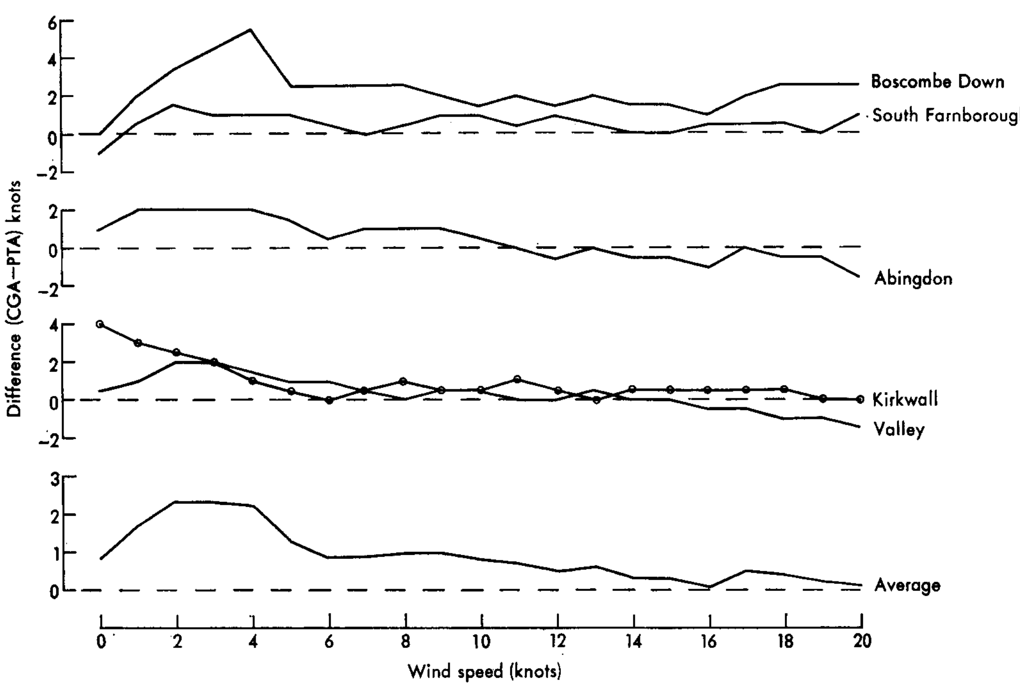

Figure 7. Difference between CGA and PTA speeds relative to control station values.

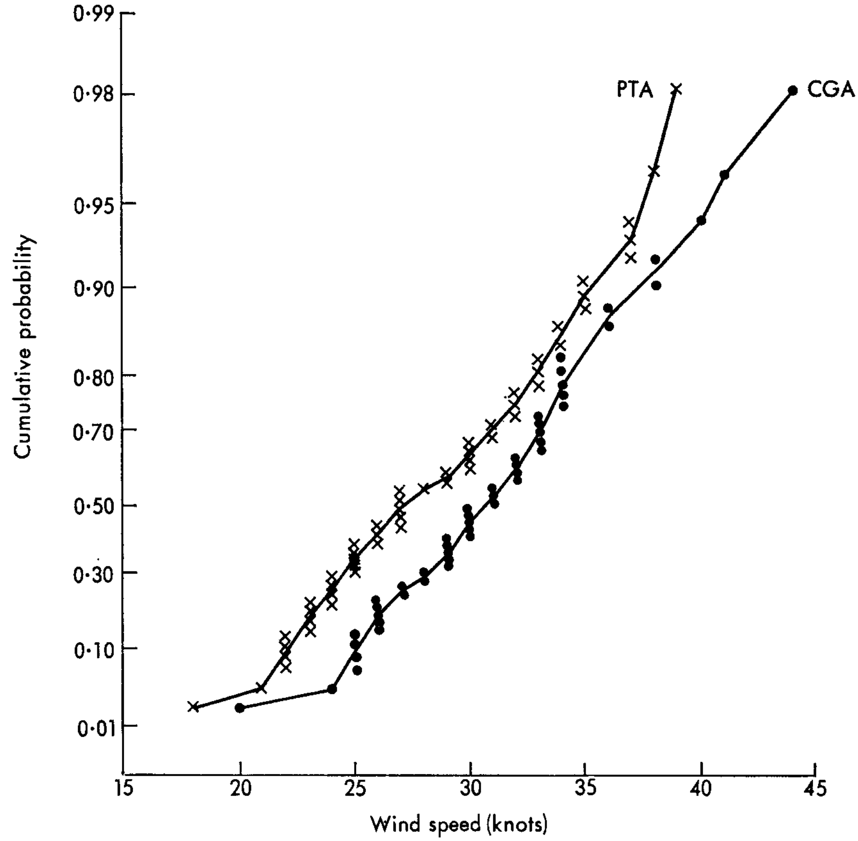

Figure 8. Plots of cumulative probability of occurrence in each period against highest speed for winter months at Boscombe Down.

ascribed such speeds to values between 5 and 7 kn. It is of note that the instructions for the analysis of such anemograph records do not mention the effects that the non-linearity of the chart can have on the estimation of wind speed.

It was also noted that in general there were fewer calms tabulated from CGA records despite its higher starting speed. It is Meteorological Office practice to record a non-zero speed if the wind direction trace fluctuates even when the speed trace registers a calm. Because of its construction and mode of operation, the CGA vane is probably more responsive to changes of wind direction in light winds than its PTA counterpart. If this is so, it may account for the reduction in the number of calms recorded by the CGA. It should also be pointed out that when the above conditions occur the speed is assumed to be 1 kn for the PTA and 2 kn for the CGA. This difference, however, is not thought to have affected the results significantly.

5. Conclusion

Results presented in this paper indicate that mean speeds derived from the Meteorological Office Mk 2 and Mk 4 electrical cup generator anemographs (CGA) exceed those obtained from the pressure-tube

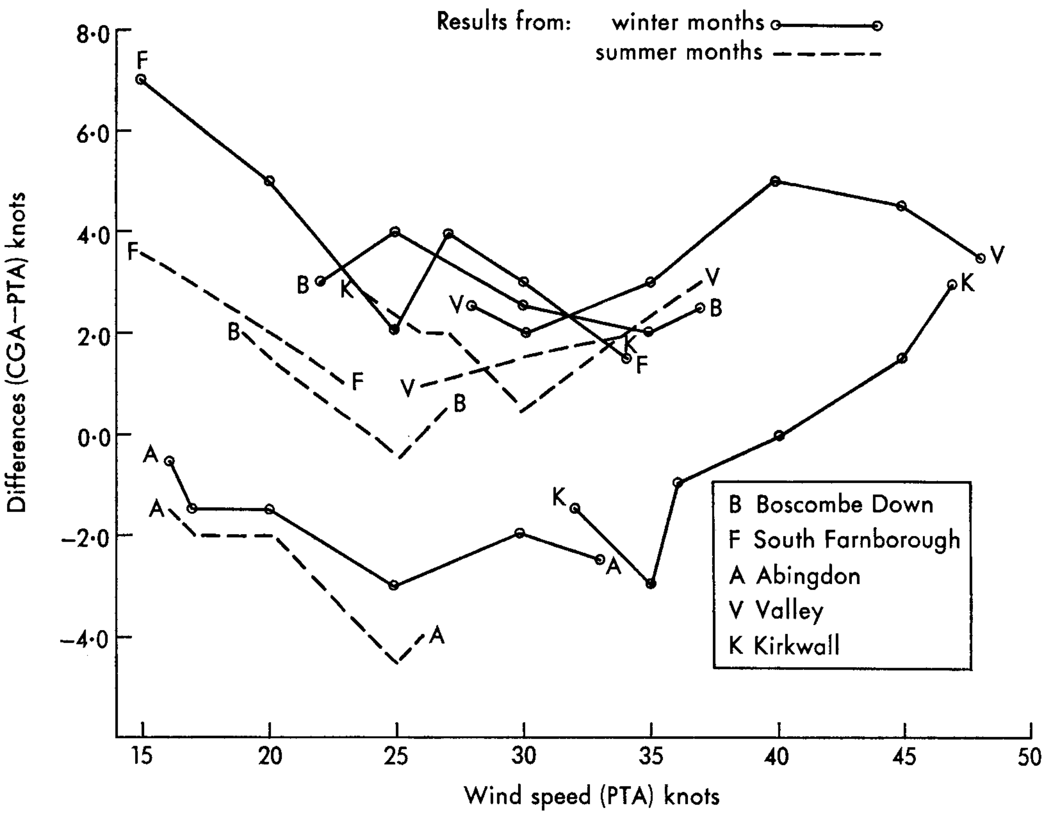

Figure 9. Differences between CGA and PTA speeds for winter and summer months at the five changeover stations.

anemograph (PTA) by 1–2 kn, with the greatest differences occurring at speeds below 8 kn and above 20 kn. It is considered that the differences for the low speeds are mainly due to observer error whereas those for higher speeds are a consequence of the inherent tendency for cup systems to overestimate the wind speed in variable winds.

In most cases where a PTA has been replaced by a CGA the site has changed and it is quite possible that this would have a greater effect on the recorded speeds than would the instrument change. However, to remove the effect of instrument variation it is proposed that, for analyses involving observations from the Mk 2 or Mk 4 CGA and the PTA, PTA readings should be increased by the following amounts:

$$(24 - x)/12 \text{ for } x \leqslant 15 \text{ kn}$$

$$\text{and } x/20 \text{ (i.e. } 5\%) \text{ for } x > 15 \text{ kn,}$$

where x is the PTA reading. This adjustment is equivalent to, for example, adding 2 kn to PTA speeds at 0 kn, 0·75 kn at 15 kn and 1·5 kn at 30 kn.

The following points are also noted:

(a) Results in this paper for speeds above 20 kn suggested a constant absolute difference between anemographs rather than a percentage difference. However, the latter is more reasonable on physical grounds and follows the findings of other workers on the overestimation error of CGAs.

(b) Non-integer speeds are introduced by the adjustment but values could be rounded to the nearest knot if desired. No speeds below 2 kn are obtained although it is unlikely that this would be important for most climatological applications, provided that the mean was acceptable. If necessary, a random number generator could be used to assign 0 and 1 kn PTA speeds to values between 0 kn and, say, 4 kn.

(c) It is emphasized that the adjustment relates to readings derived from PTA and CGA charts. It may not be valid for speeds recorded by other indicators.

Acknowledgements

I am grateful to colleagues within the Climatological Services and Operational Instrumentation Branches of the Meteorological Office for their comments and advice while this study was being undertaken.

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Appendix

Calculation of values for 'Student's' t (section 4.1)

The value calculated for each station pair and shown in columns 12 and 13 of Table II was

$$t_n = \frac{|\bar{V}'|}{s(1/n_{\mathrm{P}} + 1/n_{\mathrm{C}})^{\frac{1}{2}}},$$

where t_n is the t-statistic with degrees of freedom $n = n_p + n_c - 2$, n_p and n_c are the numbers of years comprising the PTA and CGA periods respectively,

$$|\bar{V}| = |(\bar{V}_{HC} - \bar{V}_{OC}) - (\bar{V}_{HP} - \bar{V}_{OP})|,$$

and s^2 is a pooled variance of the differences in the means:

$$s^2 = \frac{(n_p - 1)s_p^2 + (n_c - 1)s_c^2}{n_p + n_c - 2},$$

with $(n_p - 1)s_p^2 = \sum_{t=1}^{n_p} \{V_{HP}(t) - V_{OP}(t)\}^2 - (1/n_p)\left[\sum_{t=1}^{n_p} \{V_{HP}(t) - V_{OP}(t)\}\right]^2$

and similarly for s_c^2.

Award

We note with pleasure that the twenty-sixth International Meteorological Organization (IMO) Prize has been awarded to Professor Bert Bolin, Director of the International Meteorological Institute in Stockholm. Professor Bolin, one of the world's leading experts in meteorology, has carried out research in the fields of dynamical meteorology and numerical prediction, and latterly in atmospheric chemistry. From 1965 to 1967 he was Scientific Director at the European Space Research Organization, and from 1969 to 1971 he was first chairman of the WMO/ICSU Joint Organizing Committee for the Global Atmospheric Research Program.

Correction

The article on 'Lightning fatalities in Singapore' by Pakiam *et al.* (*Meteorol Mag*, **110**, 1981, 175–187) contained a number of errors.

Page 179, section 7, line 1. For '47' read '54'.

Page 183, 4th line after Table VI. For '28' read '29'.

Page 183, Table VII. The Table as printed was incorrect and should have read as follows:

Table VII. *Recreation/Work ratios for* 1965–72 *and* 1972–79

	Work		Recreation		Indefinite			
Period	No.	Percentage of total	No.	Percentage of total	No.	Percentage of total	Total No.	Recreation/ Work ratio
1965–72	16	62	7	27	3	11	26	0·44
1972–79	13	42	10	32	8	26	31	0·77

The total number of deaths (57) exceeds that of Table IV by 3 because of the addition of 2 deaths with no circumstances available, and the overlap in 1972.

Page 184, Fig. 8. The wrong figure had been supplied by the authors. The correct one is as follows:

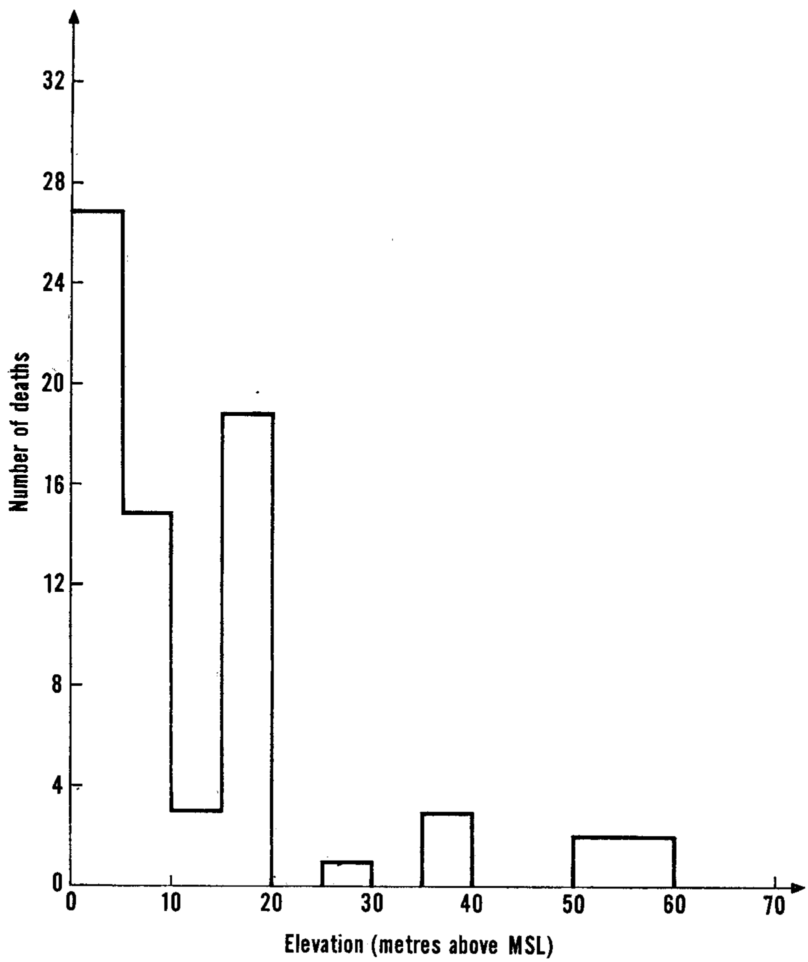

Figure 8. Relationship between lightning fatalities and elevations.

Page 187, Conclusion 6. The two percentages (33% and 67%) should be interchanged.

THE METEOROLOGICAL MAGAZINE

No. 1311 | October 1981 | Vol. 110

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
Her Majesty's Stationery Office

£1.80 monthly
Dd 716670 K15 10/81

Annual subscription £23.80 including postage
ISBN 0 11 726287 0
ISSN 0026-1149

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

November 1981

Met.O. 942 No. 1312 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1312, November 1981, Vol. 110

551.521.31 : 551.593.54

The measurement of atmospheric turbidity

By R. J. Armstrong and C. J. Richards

(Meteorological Office, Bracknell)

Summary

Measurements of atmospheric turbidity have been made at the National Radiation Centre on an irregular basis since 1968, based upon measurements of the normal incidence solar irradiance. They were originally carried out at Kew Observatory, but since 1974 they have been made at the Meteorological Office's experimental site at Easthampstead Park near Bracknell. This article defines several coefficients of turbidity and describes how they are derived from measurements of direct solar irradiance.

1. Basic definitions

The intensity of direct solar irradiance, I, at sea level, measured at normal incidence in the absence of cloud, clearly depends upon the attenuation of the solar beam as it passes through the atmosphere and this is determined largely by the optical air mass, molecular scattering and aerosol content, or 'turbidity' of the atmosphere. The optical air mass, m, is the effective path length taken by the incoming solar radiation through the atmosphere and is expressed as the equivalent number of atmospheres through which the radiation travels before reaching the observer (usually at sea level). If θ is the apparent elevation of the sun above the horizon then,

$$m = (p/p_0) \operatorname{cosec} \theta \qquad (1)$$

where p is the atmospheric pressure at the observing station and p_0 is the standard atmospheric pressure at mean sea level (1013·25 mb). The factor cosec θ is often referred to as the 'relative air mass', m_h, and can be determined by Bemporad's function (see Table 4 in *IGY instruction manual* (CSAGI 1958) which includes a correction for the effect of atmospheric refraction, especially for elevation angles of less than 10°.

The turbidity of the atmosphere can be expressed in terms of a mean attenuation coefficient, $\bar{a}$, (integrated mean over all wavelengths) which is a measure of the fractional attenuation of the solar beam due to absorption and scattering processes in the presence of water vapour, dust, smoke and the constituent gases of the atmosphere. It is defined by the exponential relationship,

$$I = S^{-1} I_0 \exp(-m\bar{a}), \qquad (2)$$

where I_0 is the extraterrestrial intensity of solar irradiance (i.e. at the top of the atmosphere) and S is defined below. The greater is the optical air mass (i.e. decreasing θ) and the greater is the turbidity, the smaller is the intensity of the transmitted radiation at sea level. Hence the attenuation coefficient $\bar{a}$ can be derived from measurements of the normal incidence irradiance.

Since the attenuation of solar radiation is a function of wavelength, λ, equation (2) may be written in the more general form,

$$I = \int_0^\infty I(\lambda).\,d\lambda = S^{-1}\int_0^\infty I_0(\lambda)\,\exp\{-ma(\lambda)\}.d\lambda, \quad \text{.. .. .. ..} \quad (3)$$

where

- $I(\lambda)$ = intensity of the normal incidence irradiance at the observing station, as a function of wavelength (units W m^{-2} per unit waveband at wavelength λ),
- $I_0(\lambda)$ = extraterrestrial intensity of the normal incidence irradiance at the mean earth–sun distance similarly expressed as a function of wavelength,
- $S\ (=R^2/R_m{}^2)$ = correction factor to allow for the variation in the actual earth–sun distance, R, from the orbital mean, R_m, and
- $\exp\{-ma(\lambda)\}$ = the transmission factor for solar radiation of wavelength λ.

The total attenuation coefficient, $a(\lambda)$, may be split into three separate components as follows:

$$a(\lambda) = a_R(\lambda) + a_D(\lambda) + a_w(\lambda), \quad \text{.. .. ..} \quad (4)$$

where a_R = the attenuation of solar radiation in clean dry air according to Rayleigh's theory of scattering by air molecules,

a_D = the attenuation by the atmospheric aerosol content, and

a_w = the attenuation due to water vapour.

Elterman (1964) provides values of a_R as a function of wavelength and altitude above sea level and Fröhlich (1977) gives the following equation to calculate the Rayleigh scattering coefficient for wavelength λ and pressure p:

$$a_R(\lambda) = (8{\cdot}69 \times 10^{-6})p\lambda^{-4{\cdot}09},$$

where p is in millibars and λ is in micrometres. Usually an allowance must be included for a given concentration of ozone. Equation (3) can therefore be rewritten thus:

$$I = S^{-1}\int_0^\infty I_0(\lambda)\,\exp\,[-m\{a_R(\lambda) + a_D(\lambda) + a_w(\lambda)\}].d\lambda \quad \text{.. .. .. ..} \quad (5)$$

Several methods have been devised for parametrizing the turbidity of the atmosphere and the three most common are described below. Two of them, those of Linke and Ångström, were developed during the 1920s.

2. The Linke turbidity factor, *T*

One of the first turbidity coefficients was introduced by Linke (1922) and it is a relatively simple measure of the haze and water vapour content of the atmosphere. He defined a turbidity factor, T, as the equivalent number of clean dry ('Rayleigh') atmospheres required to produce the observed attenuation of solar radiation, that is:

$$T = \bar{a}/\bar{a}_R(m) = \{\bar{a}_R(m) + \bar{a}_D + \bar{a}_w\}/\bar{a}_R(m) \quad \text{.. .. ..} \quad (6)$$

The bar represents a wavelength-integrated mean over the solar spectrum and $\bar{a}_R(m)$ has been expressed as a function of the optical air mass, m, because the spectral distribution of $I(\lambda)$ changes with increasing m. Usually $\bar{a}_R(m)$ is expressed in the form of the function $P(m)$, where

$$P(m) = \{m.\bar{a}_R(m).\lg e\}^{-1}.$$

(See, for instance, CSAGI 1958, Robinson 1966, or Coulson 1975.) Table I gives $P(m)$ for values of m between 1·0 and 10·0. From equations (2) and (6) therefore,

$$I = S^{-1}I_0 \exp[-T/\{P(m) \lg e\}],$$

$$\text{i.e. } T = P(m) \lg\{I_0/(IS)\}. \qquad (7)$$

Equation (7) implies that T may be calculated from measurements of both I and solar elevation. The definition of T in equation (6) implies that T can never be smaller than unity, the limit corresponding to a perfectly clean dry atmosphere.

Table I. *The factor P(m) as a function of optical air mass m, for the computation of the Linke turbidity factor T from measurements of total irradiance I.*

m	$P(m)$	m	$P(m)$
1·0	23·2	4·0	7·55
1·2	19·8	4·5	6·95
1·4	17·3	5·0	6·45
1·6	15·5	6·0	5·72
1·8	14·0	7·0	5·18
2·0	12·9	8·0	4·77
2·5	10·8	9·0	4·45
3·0	9·35	10·0	4·19
3·5	8·33		

Originally the Linke factor was based upon measurements of the total (all-wave) irradiance intensity, I, and this has been a useful measure of turbidity under various conditions. Unfortunately the factor is prone to erratic diurnal variations which appear in the absence of any significant change in atmospheric conditions and are attributed to the different wavelength dependence of aerosol and water vapour absorption/scattering compared with that of Rayleigh's theory. One solution to this problem has been to eliminate the effects of variable water vapour absorption in the infra-red by confining measurements of I to wavelengths of less than 0·63 μm, using a red (Schott RG 2) cut-off filter. This method was introduced by Ångström (1929) and is discussed in detail below. However, this approach demands much greater accuracy in the measurement of I and, in particular, knowledge of the filter's transmission characteristics.

3. The turbidity coefficient, τ_a

A second measure of atmospheric turbidity, which is a function of atmospheric aerosol content only, has been suggested by Unsworth (1975) and is defined by the equation,

$$\tau_a = -m_h^{-1} \ln(IS/I^*), \qquad (8)$$

where $m_h = \operatorname{cosec} \theta$, as defined earlier, and I^* is the normal incidence irradiance (for mean solar distance) at the bottom of an aerosol-free atmosphere which includes a specified amount of water vapour. Unsworth (1975) has tabulated I^* as a function of both the relative air mass m_h and the precipitable water content of the atmosphere and these values are listed in Table II. (See also Rodgers, Souster and Page 1978, and Unsworth and Monteith 1972.) Mathematically, I^* is given by

Table II. *Values of the normal incidence irradiance I^* at mean solar distance below an aerosol-free atmosphere, as a function of relative air mass m_h and precipitable water content, assuming $I_0 = 1353$ W m^{-2} and a fixed ozone content of 3 mm.*

Precipitable water content (mm)	Relative air mass (m_h)						
	1	1·5	2·0	3·0	4·0	5·0	6·0
5	1100	1055	1010	940	885	835	800
10	1090	1035	990	915	860	810	775
15	1080	1020	975	900	845	800	760
20	1065	1010	960	890	835	790	750
30	1050	990	945	870	820	770	730
40	1035	980	930	860	805	755	720

$$I^* = I_0 \exp\,[-m\{\bar{a}_R(m) + \bar{a}_w\}],$$

hence equation (2) can be written in the form

$$I = S^{-1}I^* \exp(-m\bar{a}_D). \qquad (9)$$

The definition of τ_a in equation (8) is therefore equivalent to

$$\tau_a = m_h^{-1}m\bar{a}_D = (P/P_0)\bar{a}_D,$$

that is, equivalent to the mean attenuation coefficient for dust and aerosol at sea level. Values of τ_a generally lie in the range 0·0–1·0, but can exceed 1·0.

4. The Ångström turbidity coefficient, β

In order to account for the difference in transmission characteristics between aerosol and 'Rayleigh' particles (i.e. gas molecules), Ångström (1929, 1930) represented the attenuation of solar radiation by aerosols in terms of a turbidity coefficient β and a wavelength exponent α, thus

$$a_D(\lambda) = \beta\lambda^{-\alpha}, \qquad (10)$$

where λ is in micrometres. The exponent α is a measure of the particle size and varies between $\alpha = 0$ for very large particles (where scattering and absorption are independent of wavelength) and $\alpha = 4$ for very small Rayleigh particles (i.e. gas molecules). Its value therefore provides a good indication of the particle size of the aerosols.

From spectral investigations the value $\alpha = 1{\cdot}3$ has been found to be a realistic average value which can be used in the calculation of β only. (See Ångström 1930 and Volz 1956.)

The coefficient β also has a simple physical interpretation. From equation (10), the proportion of solar radiation of wavelength λ reaching the ground after attenuation by aerosols is

$$\exp\{-ma_D(\lambda)\} = \exp(-m\beta\lambda^{-\alpha}).$$

For an overhead sun at sea level ($m = 1$) and at a wavelength $\lambda = 1$ μm this reduces to $\exp(-\beta)$ which is approximately equal to $(1-\beta)$ for $\beta \ll 1$. In other words, β is the fraction of solar radiation at a wavelength of 1 μm that is scattered or absorbed by aerosols in the atmosphere for unit air mass. Similarly, since $\lambda^{-1.3} = 2$ for $\lambda = 0{\cdot}6$ μm, 2β gives the fractional attenuation of solar radiation at around 0·6 μm (i.e. in the visible spectrum). The coefficient β is defined for a standard atmosphere with a surface pressure of 1000 mb.

(a) *Pyrheliometric determination of* β

Owing to the considerable selective absorption of radiation by water vapour within the infra-red region of the spectrum, the determination of β from pyrheliometric measurements of normal incidence irradiance is usually restricted to the ultraviolet and visible wavebands. In practice, the coefficient β is derived by making two simultaneous measurements of the solar irradiance: one of the total irradiance I over all wavelengths and the other of the irradiance I_R in the infra-red waveband ($\lambda > 0{\cdot}63$ μm), by using a Schott RG 2 red filter over the pyrheliometer. The difference between the two measurements, I_k, gives the solar irradiance over the waveband $\lambda < 0{\cdot}63$ μm:

$$I_k = I - I_R$$
$$= S^{-1}\int_0^{0.63\,\mu\text{m}} I_0(\lambda).\exp[-m\{a_R(\lambda) + \beta\lambda^{-1.3}\}]\mathrm{d}\lambda. \qquad .. \quad .. \quad .. \quad (11)$$

The measured value of I_R, I_R', is related to I_R by the expression $I_R = D_1 I_R'$, where D_1 is a correction factor for the characteristics of the filter. Since the variation of $I_0(\lambda)$ and $a_R(\lambda)$ with λ are known, the above integral can be calculated for any value of m and β. Values of irradiance I_k have been tabulated against m (see, for instance, Table 7 of the appendix to the *IGY instruction manual* (CSAGI 1958)). This particular table is based on a mean value of $I_0 = 1{\cdot}98$ cal cm^{-2} min^{-1}. The table is entered at the appropriate value of m and from the measured irradiance I_k (corrected for the mean solar distance by multiplying by the factor S) the equivalent value of β is derived.

Although a value of $\alpha = 1{\cdot}3$ is assumed in the above determination of β, it is possible in principle to calculate the exact value of α. For this purpose an extra pyrheliometer is required so that a different simultaneous measurement of filtered irradiance can be made in addition to I and I_k for, say, the waveband $\lambda > 0{\cdot}525$ μm, using a yellow-green (Schott OG 1) filter. The integral in equation (11) can be tabulated as a function of m and β for each of the two wavebands, $\lambda < 0{\cdot}525$ μm and $0{\cdot}525 < \lambda < 0{\cdot}63$ μm, in a similar manner to that used in the table referred to above for the waveband $\lambda < 0{\cdot}63$ μm. The deduced irradiance measurements over these wavebands will generate two independent estimates of β (β_1 and β_2), assuming that $\alpha = 1{\cdot}3$. If this latter assumption is correct then these two values of β should, of course, be identical. However, this is unlikely to be the case, as α varies with aerosol size and hence will have some general value α_0, with a corresponding value of $\beta = \beta_0$ (and $\beta_0 = \beta_1 = \beta_2$).

Ångström (1929, 1930) described how one can regard the integral over wavelengths of solar irradiances as 'homogeneous' (i.e. monochromatic), which means that the integral in equation (11) can be replaced by an irradiance of fixed wavelength (the 'effective' wavelength). So, for the waveband $0 < \lambda < 0{\cdot}525$ μm the 'effective' wavelength $\lambda_1 = 0{\cdot}45$ μm and similarly, $\lambda_2 = 0{\cdot}575$ μm for the waveband $0{\cdot}525 < \lambda < 0{\cdot}63$ μm.

We can express the total attenuation of radiation due to dust and aerosols (a_D) in each waveband, not by the wavelength-dependent function (equation (10) or (11)), but by some mean weighted function. So we let

$$a_D' = \beta_1\lambda_1^{-1.3}, \qquad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (12)$$

where a_D' is the total (integrated) attenuation coefficient over the waveband $0 < \lambda < 0{\cdot}525$ μm. Similarly, for the waveband $0{\cdot}525 < \lambda < 0{\cdot}63$ μm,

$$a_D'' = \beta_2\lambda_2^{-1.3}. \qquad .. \quad .. \quad .. \quad .. \quad .. \quad (13)$$

(Note that β_1 and β_2 in equations (12) and (13) are expected to be different as we have used the assumed mean of 1·3 for α.) Now if we use α_0, the true atmospheric value ($\neq 1{\cdot}3$), then β_1 and β_2 will be the same —equal to β_0 as mentioned earlier. Therefore,

$$a_D' = \beta_0 \lambda_1^{-\alpha_0} \quad (14)$$

$$\text{and } a_D'' = \beta_0 \lambda_2^{-\alpha_0} \quad (15)$$

Equating (12) with (14) and (13) with (15),

$$\beta_1 \lambda_1^{-1.3} = \beta_0 \lambda_1^{-\alpha_0} \quad (16)$$

$$\beta_2 \lambda_2^{-1.3} = \beta_0 \lambda_2^{-\alpha_0}. \quad (17)$$

Hence, using (16) and (17), α_0 is given by

$$\alpha_0 = 1{\cdot}3 - \{\ln(\beta_1 \beta_2^{-1}) / \ln(\lambda_1 \lambda_2^{-1})\} \quad (18)$$

and, finally, β_0 can be derived from either (16) or (17) once the true value of α_0 has been calculated.

The determination of α_0 to even moderate accuracy demands great care and precision in the derivation of β_1 and β_2, which implies that the filtered irradiances must be measured with an accuracy of at least 1%. In practice it is very difficult to meet this requirement with filtered pyrheliometric measurements and erroneous values of both α and β are easily obtained, with quite unrealistic variations appearing between individual 'observations'. For these reasons the use of the sun photometer (see below) is now favoured by the World Meteorological Organization in the determination of β.

(b) *The sun photometric determination of α and β*

The sun photometer, based upon an original design by Volz, is a dual-channel device for measuring the normal incidence solar irradiance in narrow spectral regions centred at approximately 0·38 μm and 0·5 μm. The conical acceptance aperture has a half-angle of 1–2° and the detector is a photovoltaic selenium cell. The signal from the detector is amplified and is observed on an attached microammeter.

The measured irradiance can be regarded as being monochromatic at the above wavelengths, so equation (5) can be used to express the measured irradiance $I(\lambda)$ in terms of the extraterrestrial irradiance $I_0(\lambda)$, ignoring water vapour absorption which can be neglected at these wavelengths. Thus,

$$I(\lambda) = S^{-1} I_0(\lambda) \cdot \exp[-m\{a_R(\lambda) + a_D(\lambda)\}],$$

where $a_D(\lambda) = \beta\lambda^{-\alpha}$ for $\lambda = 0{\cdot}38$ μm and 0·5 μm respectively.

$I_0(\lambda)$ is the extraterrestrial irradiance which would be measured with the same instrument at air mass zero. At present this value is determined by the Langley method (World Meteorological Organization 1978). The readings over a range of air mass values are made during periods of stable turbidity and their logarithms are plotted against m and extrapolated to air mass zero to obtain I_0. Usually, sun photometers used in the field are calibrated by direct comparison with reference instruments. These instruments are stable sun photometers that have been calibrated by carefully selected Langley plots.

$a_R(\lambda)$ is normally tabulated as a function of λ for mean sea level (Elterman 1964) and as an example Table III shows sea level values of the Rayleigh scattering coefficient for 0·35 cm of total ozone for three values of λ. Since ozone absorption is not negligible at 0·5 μm the value of $a_R(\lambda)$ at this wavelength is usually increased by the absorption coefficient due to ozone at 0·5 μm.

Since $I_0(\lambda)$, $a_R(\lambda)$, m and S are known, the two measurements of $I(\lambda)$ will give the attenuation coefficient $a_D(\lambda)$ at each wavelength, producing the simultaneous equations,

$$a_D(\lambda = 0{\cdot}38) = \beta(0{\cdot}38)^{-\alpha}$$

$$a_D(\lambda = 0{\cdot}5) = \beta(0{\cdot}5)^{-\alpha}.$$

Table III. *Sea level values of Rayleigh scattering optical thickness for* 0·35 *cm of total ozone.*

λ	a_R	a_{ozone}
380 nm	0·45	0
500 nm	0·145	0·012
850 nm	0·014	0

Eliminating β,

$$\alpha = \ln\{a_D(\lambda = 0{\cdot}38)/a_D(\lambda = 0{\cdot}5)\}/\ln(0{\cdot}5/0{\cdot}38), \quad .. \quad .. \quad (19)$$

from which β can be derived by substituting for α in either of the two simultaneous equations above.

5. Practical determination of turbidity—method of measurement

At the National Radiation Centre the derivation of atmospheric turbidity has been based upon the measurement of normal incidence irradiance using an Ångström compensation pyrheliometer (see page 390 of *IGY instruction manual* (CSAGI 1958)). This is one of the most reliable instruments for measuring solar irradiance and is often used as a standard in the calibration of secondary pyrheliometers. The detector consists of two identical thin blackened manganin strips, one of which is exposed to the sun and the other shielded. An electric current is passed through the shielded strip until the temperatures of the two strips are equal. The electrical heating of the shielded strip is then equivalent to the heating produced in the exposed strip by the absorption of solar radiation. The temperature difference between the two strips is monitored by means of a thermocouple, one junction being on the back of each strip. If the temperatures are identical there can be no output from the thermocouple, thus heating equivalence is indicated by a sensitive null-detector and the heating current can be adjusted until balance is achieved.

Let i_0 = the equilibrium heating current (amperes),
r = the resistance per unit length of the shielded strip (ohm m^{-1}),
b = the mean width of the strip (m),
L = the length of the strip (m) (area of strip = bL m^2),
a = the absorption coefficient of the blackened surface of the strip (usually taken as 0·98 for the coating of camphor soot), and
I = the normal incidence solar irradiance (W m^{-2}).

The rate at which radiant energy is absorbed by the exposed strip, Q_1, is given by

$$Q_1 = IbLa.$$

The rate of electrical heating, Q_2 of the shielded strip is given by

$$Q_2 = i^2rL \text{ (current}^2 \times \text{resistance)}.$$

At equilibrium, when the temperatures of the two strips are equal, i.e. $i = i_0$ and $Q_1 = Q_2$ then

$$I = (i_0^2r)/(ba) = ki_0^2 \text{ (W m}^{-2}\text{)},$$

where $k = r/(ba)$ and is a constant for the instrument being used. In practice, k is derived by comparing the instrument with a world-wide standard instrument.

In order to derive turbidity as reliably as possible a number of irradiance measurements are normally made in quick succession over a period of, say, nine minutes. During this time each of the blackened strips is alternately exposed to the sun whilst the heating current i is passed through the other (shielded) strip.

An average equilibrium current is calculated for each strip and the mean of the two strips i_0 is then used in the above equation to derive the mean irradiance I. Given the time of the observation and the precipitable water content of the atmosphere the relative air mass can be calculated and hence the Linke turbidity factor T and Unsworth's coefficient τ_a derived according to equations (7) and (8). In order to determine the Ångström turbidity coefficient β using, say, equation (11) two simultaneous sets of irradiance measurements are required (using two pyrheliometers): one instrument measuring the total all-wave irradiance I and the second measuring the filtered irradiance I_R by isolating the waveband $\lambda < 0{\cdot}63$ μm with a red (RG 2) filter.

At the National Radiation Centre practical attempts have not proved very successful in determining the exponent α from filtered pyrheliometric irradiance measurements over different wavebands, according to the theory of section 4(a). Unrealistic values of both α and β have been obtained and these may be partly due to the interpolation error which arises from the practice of making filtered measurements alternately rather than simultaneously, since only two Ångström instruments are in service at the Centre.

A suite of computer programs has been developed for calculating each of the three turbidity coefficients for those occasions when special irradiance measurements have been made at the National Radiation Centre. A 'master' archive data set has also been created to store these parameters, together with a variety of relevant meteorological and astronomical data.

The World Meteorological Organization (WMO) which collects, stores and publishes turbidity data at the National Climatological Center (NCC), Asheville, North Carolina, USA, provides details on the operating instructions when making turbidity observations (World Meteorological Organization 1978). The Meteorological Office does not make routine measurements nor has it sent any turbidity data to the NCC but one of the new generation of sun photometers has been obtained from Japan, together with four filters at 368, 500, 675 and 778 nm ($\pm$ 5–6 nm). Of these, the 500 nm filter is mandatory for any data sent to WMO. After a test period at Easthampstead Park it will probably be installed at Eskdalemuir which is a WMO climatological station and a WMO baseline air pollution monitoring network (BAPMoN) station and is jointly run by the Meteorological Office and the Natural Environmental Research Council. As turbidity is one of the three minimum requirements from a BAPMoN station it is hoped that routine measurements will be made and sent to the NCC in the near future.

In order to test the limits of sun photometric readings an error analysis can be performed based on the following formula:

$$\Delta a_0(\lambda) = m_h^{-1}\{\Delta I(\lambda)/I(\lambda)\} + m_h^{-1}\{\Delta I_0(\lambda)/I_0(\lambda)\} + \Delta a_R(\lambda). \quad .. \quad (20)$$

Fröhlich (1977) gives a table of typical errors for an Environmental Protection Agency (USA) sun photometer, at a relative air mass of 2 and λ equal to 380 and 500 nm. For the worst case, when the temperature range of the instrument is $\pm$10 K (kelvins) and the ozone variation is $\pm$30%, $\Delta a_D(380) = 0{\cdot}05$ and $\Delta a_D(500) = 0{\cdot}03$. For the best case, with no temperature change and exact ozone values, $\Delta a_D(380) = 0{\cdot}03$ and $\Delta a_D(500) = 0{\cdot}02$.

One of the most important contributions to this uncertainty is the difficulty in determining the value I_0. For example, on a day when the turbidity gradually decreased from a midday value of $a_D = 0{\cdot}34$ to $a_D = 0{\cdot}24$ by 1800 hours, there was an error of 12% in the calculation of I_0. The degree of linearity of the Langley plot is normally taken to judge the degree of stability of turbidity although in some special cases linearity can be preserved for varying turbidity. It follows, therefore, that calibration of sun photometers can only be performed accurately during clear days at mountain stations. However, new technology using a combination of dye-lasers and absolute radiometers should make accurate calibrations possible. These new techniques should permit a calibration scheme to be developed whereby standard sun photometers are periodically compared with those instruments at the recording sites.

Errors can also be caused in the actual measurement of $I(\lambda)$ and hence $\Delta I(\lambda)/I(\lambda)$ in equation (20). Normally a 0·5% reading error is assumed together with an error due to the aureole influence which is related to the aperture of the instrument and can cause 0·8% errors at 380 nm and 0·4% errors at 500 nm. The effect of the latter is reduced by a factor of three with the new generation of sun photometers because of the more suitable acceptance geometry of the instruments. Similarly, the temperature coefficient has been reduced by a factor of typically from two to five by the use of silicon cells.

6. Future developments

The WMO has recognized the problem of obtaining reliable and comparable values between observing stations of the Ångström turbidity coefficient from filtered irradiance measurements using pyrheliometers. At a WMO meeting of experts on turbidity held at Boulder, Colorado, in the autumn of 1978, the use of the new generation of sun photometers was recommended for the determination of both α and β (according to the method of section 4(b)). Although turbidity measurements made by pyrheliometers will still be accepted, only those made by the sun photometers will be published by the WMO. However, until the time that sun photometers are installed at observing stations in the UK radiation network (probably Easthampstead and Eskdalemuir) and hence routine measurements of the turbidity coefficient β are available, work continues on the expansion of the archived turbidity data set. By exploiting the normal incidence irradiation data sets for Easthampstead and Kew it is possible to calculate the Linke and Unsworth turbidity coefficients. However, since much of these data consist of hourly irradiances, turbidity coefficients can only be calculated for those hours when sunshine was continuous and not obscured by cloud. The routine observations of cloud cover at these stations, together with the recorded sunshine durations, are therefore being used to diagnose suitable periods during which the mean hourly turbidity can be calculated. Since mid-1979 values of normal incidence irradiance, sampled at one-minute intervals, have become available for both Kew and Easthampstead. These measurements will make it much easier to detect intervals of unobscured sunshine over timescales ranging from several hours to just a few minutes and therefore will allow some measure of the diurnal variation of atmospheric turbidity to be made at those stations. Work is currently under way to produce statistical, graphical and tabular analysis of the turbidity data, together with the other parameters stored in the archived data set.

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551.515.33(423)

A Wiltshire tornado, 30 May 1979

By E. J. Smith
(Meteorological Office, Netheravon)

Summary

An account is given of a tornado that formed near Netheravon, Wiltshire, on a day during which heavy rain and thunderstorms developed over much of southern England. Use is made of rainfall radar photographs and several eyewitness accounts describe the tornado in its various stages of development.

Introduction

Moderate or heavy rain, with occasional thunderstorms, was reported over many parts of southern England on 30 May 1979. It is shown that a cold-front wave, which led to the development of a tornado near Netheravon, crossed Wiltshire in the afternoon of that day. Drawings from rainfall radar photographs are used to illustrate the areas of heavy rainfall associated with the wave. Several eyewitnesses were questioned and their accounts describe the tornado in most of its stages of development.

Fig. 1 shows that part of Wiltshire on the eastern edge of Salisbury Plain, including the main centres of population. There are many military establishments in the area and, as a result, a high density of meteorological offices and trained observers. Fig. 2 shows, in more detail, those areas affected by the tornado. The contours indicate the undulating nature of much of the county and show a ridge near Larkhill falling away to the River Avon. The ground then rises gently north-eastwards to the Wig plantation.

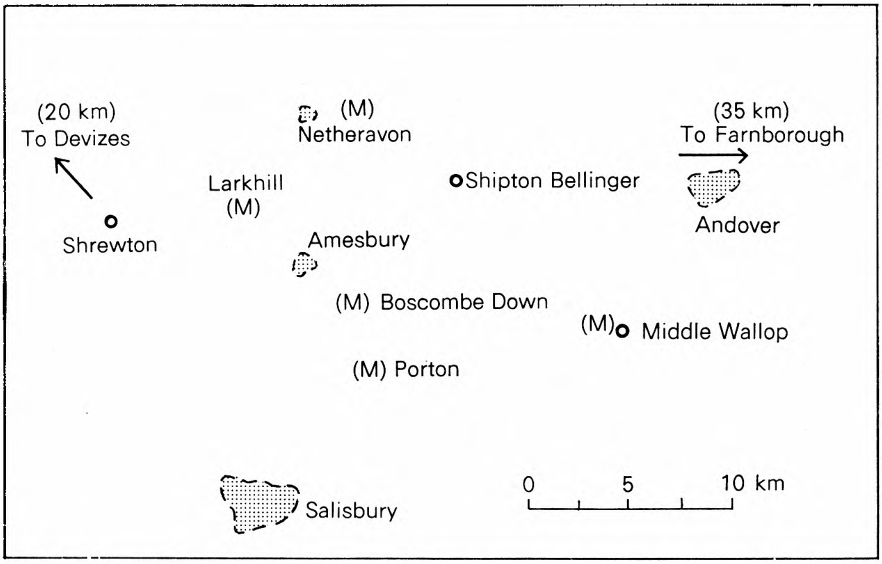

Figure 1. Part of Wiltshire on the eastern edge of Salisbury Plain showing locations of meteorological offices (M).

The formation of severe storms and tornadoes

The parameters necessary for severe storm and tornado development are well documented in the United Kingdom: Browning (1968), Hardman (1968), Hindley (1977), Lacey (1968) and Wright (1973). They are summarized as follows:

(a) Great buoyancy—necessary for a strong, persistent updraught, which is achieved if the air is potentially unstable, i.e. θ_w* decreases with height.

(b) A supply of warm moist air at low levels, i.e. a high value of θ_w in the lower layers.

(c) Mid-troposphere regions of dry air—necessary to aid downdraught development.

(d) Vertical wind shear, typically a veer of wind with height throughout the convective layer and an increase of 30–60 kn from the ground to, say, 500 mb in order that updraught/downdraught circulations may persist for long periods.

(e) Usually consideration is given to some form of trigger action—for instance, high surface temperatures, forced mechanical uplift or generally falling pressure.

(f) Development of the updraught will be more rapid if the initial energy release is restricted, say by a temperature inversion, so that the eventual energy release is more 'explosive' and leads to a stronger updraught.

It is suggested that all these factors can be identified from the meteorological information available for 30 May 1979 which is presented below.

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* θ_w—the wet-bulb potential temperature—combines water vapour and temperature data in a single parameter and is defined as that temperature at which the saturated adiabatic through the wet-bulb temperature at a particular level intercepts the 1000 mb isobar.

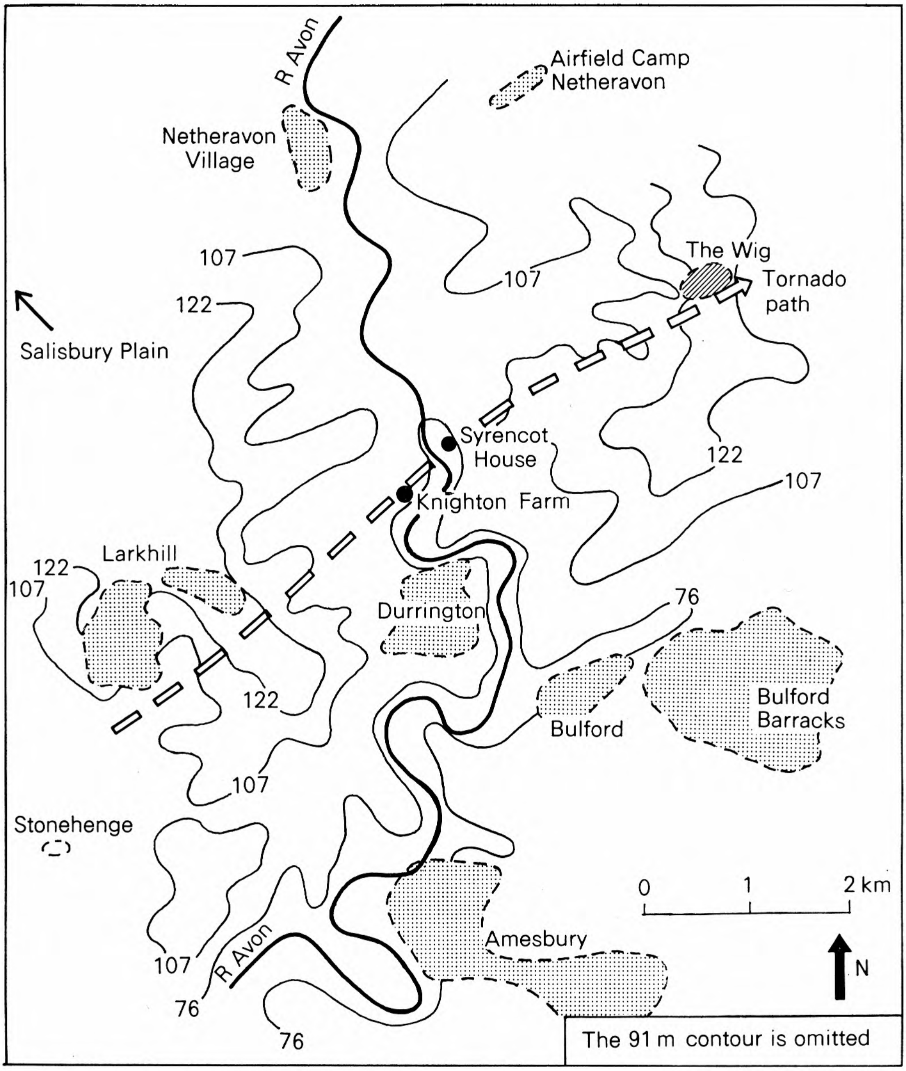

Figure 2. The path of the tornado.

The synoptic situation

Moore (1980), in an article describing the uses of pictorial satellite data, chose as an illustration the particular cold-front wave under discussion. It moved north-eastwards, crossing southern and eastern England on 30 May 1979, eventually reaching the North Sea on the 31st. Fig. 3 shows the position of the cold front at 1300 GMT on 30 May 1979 with the wave centred very near Netheravon. Rainfall radar displays (Figs 4 to 6) indicated a line of intense echoes progressing north-eastwards across Salisbury Plain between 1318 and 1403 GMT. This line represents the cold front which contained one or more severe storm cells that in turn led to the development of the Netheravon tornado. A more detailed account of the heavy rain of 30 May is given by Woodley (1981).

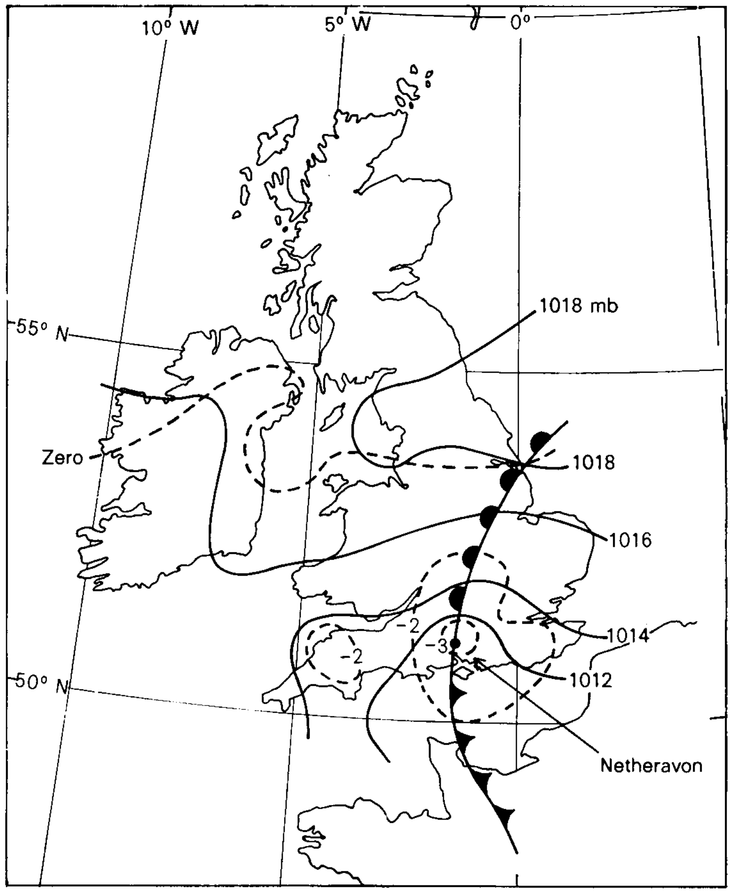

Figure 3. Surface synoptic chart for 1300 GMT, 30 May 1979.
———— mean sea level isobars
- - - - - isallobars

The weather observed on 30 May 1979

The five meteorological offices in the area each reported a squall; the time of onset varied between 1315 and 1335 GMT. See Table I.

Table I. *Maximum gusts recorded by the meteorological offices in the area of the tornado of* 30 *May* 1979

	Direction *degrees*	Gust speed *knots*	Time GMT
Boscombe Down	300	49	1318
Larkhill	240	41	1316
Middle Wallop	290	26	1328
Netheravon*	330	47	1335
Porton	260	50	1317

* No anemograph—wind read from anemometer dial.

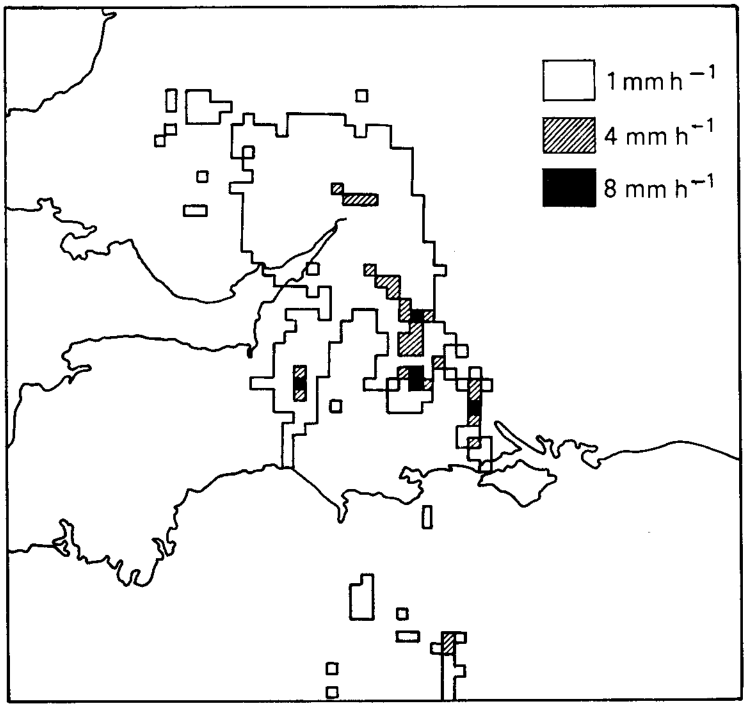

Figure 4. Drawing from photograph of rainfall radar display, 30 May 1979 at 1318 GMT.
Taylor and Browning (1974) described the versatility of radar for observing the weather. They showed that suitable calibrated radars are able to indicate the horizontal and vertical distribution of precipitation and its intensity. Such radars can be used to identify those echoes characteristic of thunderstorm development. They described how digital processing techniques had been employed to produce precipitation maps for display on a television screen. These maps may be depicted on the screen in grid form (Figs 4–6) with each box having a colour or shading to show a particular average rainfall rate. The shading often indicates precipitation intensities ranging from light rain to thunderstorms.

None of the meteorological observers reported thunder but an aircraft was struck by lightning over Devizes and thunder was heard at Shrewton. Thunderstorms had been reported earlier in the day in Somerset and Dorset and confirmed by SFLOCs (lighting flash location reports). Radar reflectivity between 1318 and 1403 GMT, although qualitative, often showed rainfall intensity of 4–8 mm h^{-1} along the cold front, with a small area of 16 mm h^{-1} north-east of Netheravon at 1403 GMT.

Upper-air data

It is unlikely that a truly representative upper-air sounding was available on this occasion but tephigrams for Larkhill at 0900 GMT and Crawley at 1200 GMT are reproduced in Fig. 7.

A sharp trough persisted to the west of Ireland throughout the period and southerly winds are shown on both ascents at middle and upper levels. With maximum upper winds across the front reported between 327 mb and 198 mb, the 250 mb level was selected to represent the jet stream (Fig. 8). Central southern England was lying under the right entrance to this jet—an area considered favourable for the intensification of low-level cyclonic circulation.

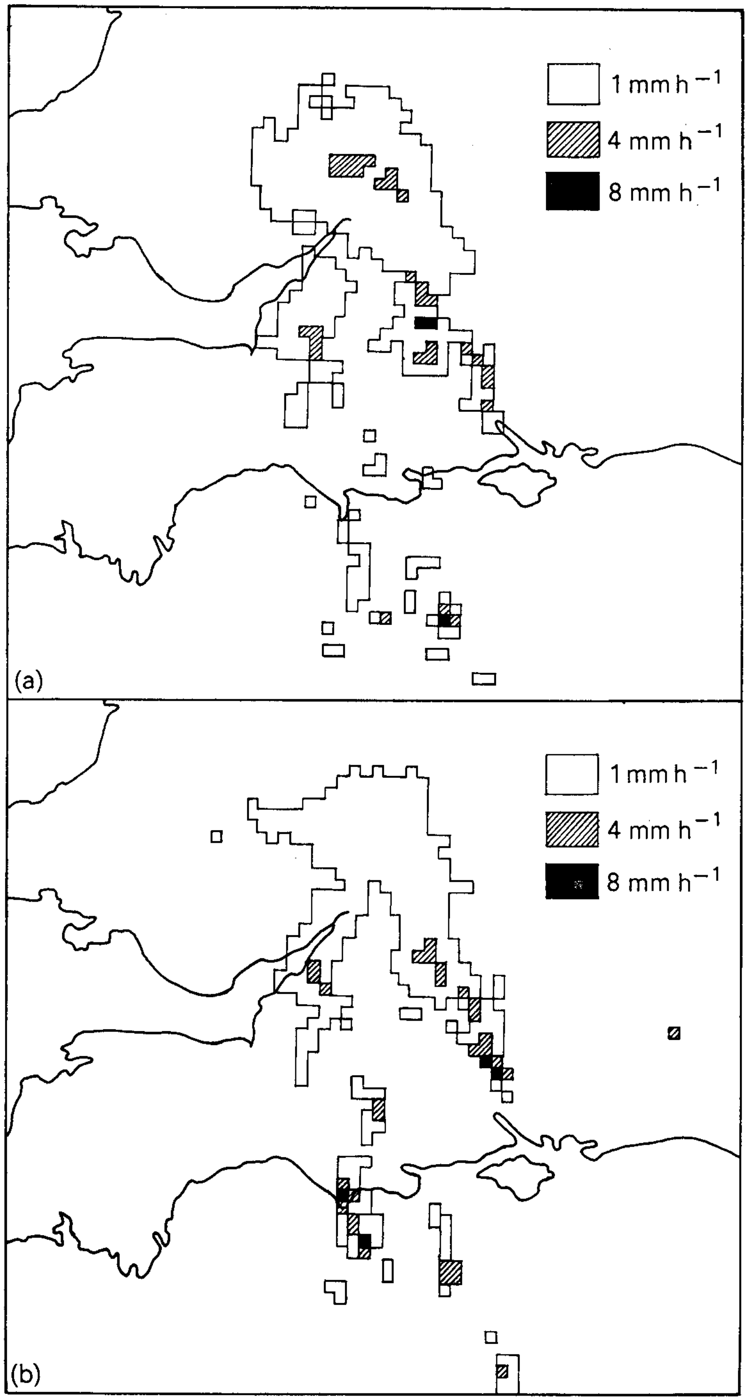

Figure 5. Rainfall radar display, 30 May 1979, (a) at 1333 GMT, and (b) at 1348 GMT.

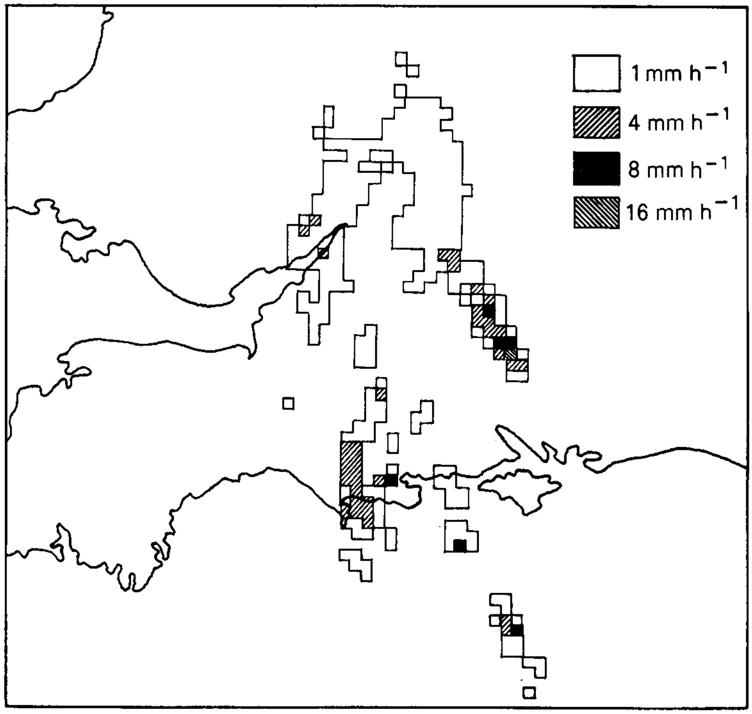

Figure 6. Rainfall radar display, 30 May 1979 at 1403 GMT.

Lower-level winds indicated a south-easterly flow ahead of the waving cold front and surface dry-bulb temperatures as high as 21 °C and dew-point temperatures as high as 18 °C were reported as far west as the Farnborough area. At Netheravon airfield, however, much lower values were observed—14 °C and 11 °C.

It is assumed that the upper-air pattern in the Netheravon area at the time of the tornado was represented by a tephigram somewhere between the two shown in Fig. 7, with a south-east wind bringing warm moist Crawley-type air below the Larkhill air of middle and high levels. Estimated θ_w values of 15 °C or 16 °C at 900 mb would fall to about 14 °C at 700 mb, then around 13 °C aloft. Dry zones were shown on both ascents.

Obviously this subjective estimate of a representative vertical temperature and humidity profile has limited value but, without a detailed multi-level trajectory analysis, was considered to be a reasonable first guess. The reduction of θ_w with height was definite, although small, but the low-level horizontal discontinuity of θ_w across the front was very marked, at least 7 °C over a few tens of kilometres.

The vertical wind shear, considered necessary for severe storm development, was confirmed by the Larkhill upper-wind profile.

The isallobaric low (the area of maximum local fall of pressure with time) was traced from a position over Brittany at 0600 GMT (not shown). Moving at 30 kn it reached the Netheravon area at 1300 GMT (Fig. 3). This area of falling pressure was considered to be the trigger action necessary to overcome the low-level temperature inversion.

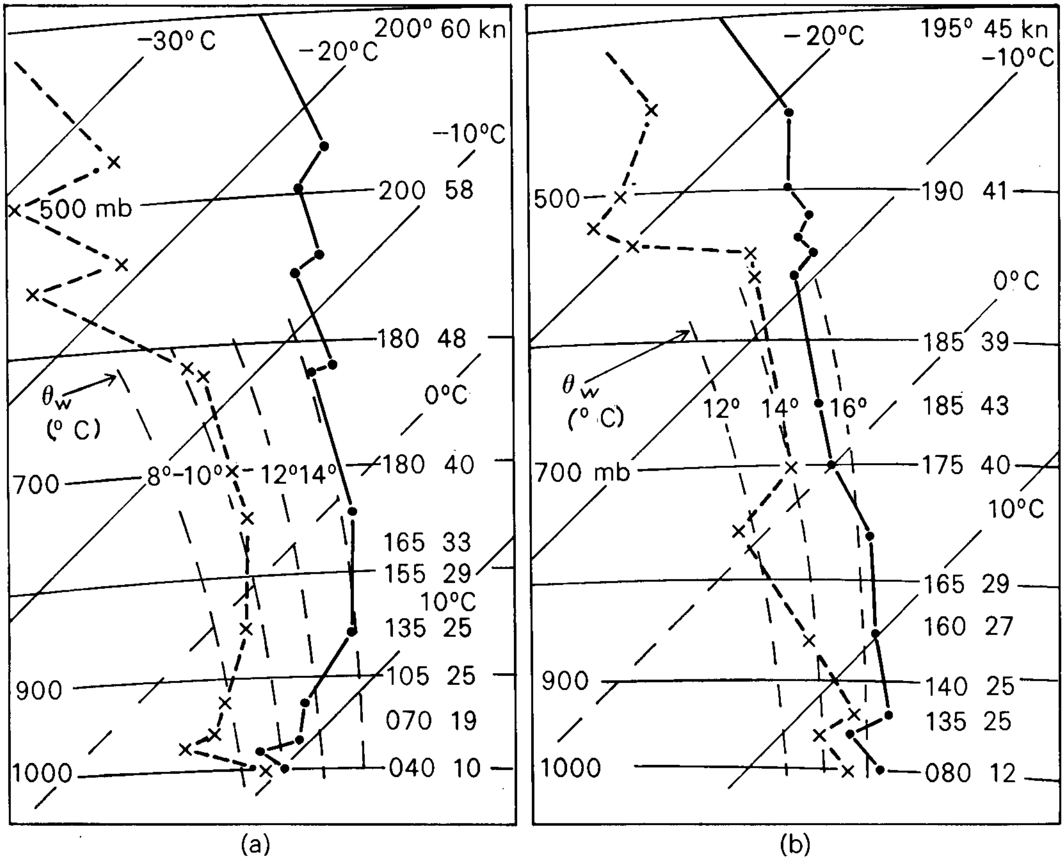

Figure 7. Tephigrams for (a) Larkhill 0900 GMT and (b) Crawley 1200 GMT, 30 May 1979.

Descriptions of the tornado

A worker from Knighton farm was interviewed and he told of working just south of Larkhill camp (Fig. 2). He had naval experience and described, without prompting, a definite funnel cloud reaching the ground, approximately 15 m wide at ground level and moving towards Syrencot House. He told of very strong winds with the funnel appearing white or light-coloured and he assumed it was filled with rain. He did not notice the rotational direction.

Office workers at Syrencot House were aware initially of a very strong wind. Their window view was towards east-north-east and it was noted that the wind was blowing from right to left, that is approximately from the south-east. Next the sky became black and a rotation was seen in the cloud but this did not reach the ground. Heavy rain followed and was being driven from left to right by the wind as viewed from the window, i.e. on a north-westerly wind. This indicated cyclonic motion in the tornado. Eventually the bad weather moved into the distance away from the window.

Mr McAllister, a Lands Agency official, observed the tornado near the Wig but did not see it hit the plantation. Initially the area became very dark; then, near to the ground, it became lighter and a funnel-type rotation was seen underneath the main cloud mass which remained black. Very heavy rain soon followed and it became very windy. Mr McAllister did not notice the rotational direction.

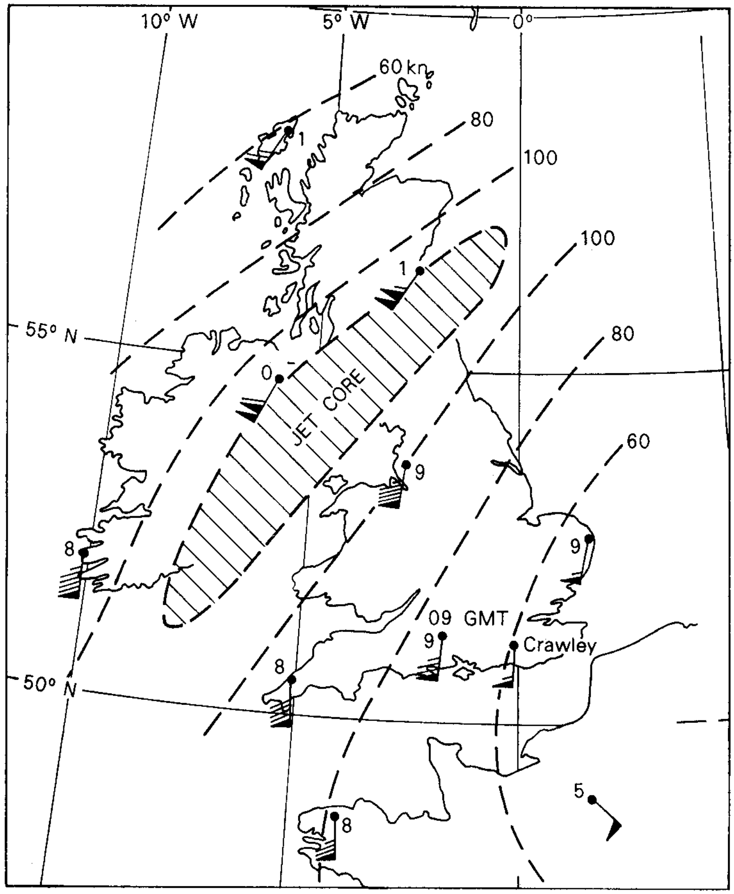

Figure 8. 250 mb plotted winds with isotachs, 1200 GMT, 30 May 1979.

Mr Loder, another farm worker, actually saw the tornado cross the Wig plantation. Once again a definite rotation was seen and Mr Loder estimated that he was about 400 m from this and that the width of the funnel was of the order of 100 to 150 m. He described the weather as being generally very dark and windy with rain. The whole sequence lasted a few minutes and Mr Loder estimated the speed of the tornado to be about 20 miles per hour (9 m s^{-1}). He saw much debris—tree pieces etc.—becoming air-borne as the tornado crossed the Wig. It became obscured by the plantation itself soon after.

The author visited the Wig on 4 June before clearing-up operations had begun. This small plantation covers an area roughly 300 m square and consists of Scots pine approximately 40–50 years old. The path of the tornado and the damage it caused are described with reference to Fig. 9 and Plate I.

The tornado came over the brow of a rise to the west of the plantation. Two trees at A were broken but the lone tree at A1 was undamaged. Approximately one-third of the plantation area, on the south side, was devastated. Several trees, including two of about 1 m base diameter, were completely uprooted and many others snapped off at some point, usually in the upper half. Some branches, up to about 25 cm in thickness, appeared to have been twisted off the trunks. The remaining two-thirds of the plantation was undamaged.

Plate I. Tornado damage to the Wig plantation. (The same tree appears at the bottom right of the upper picture and the bottom left of the lower picture.)

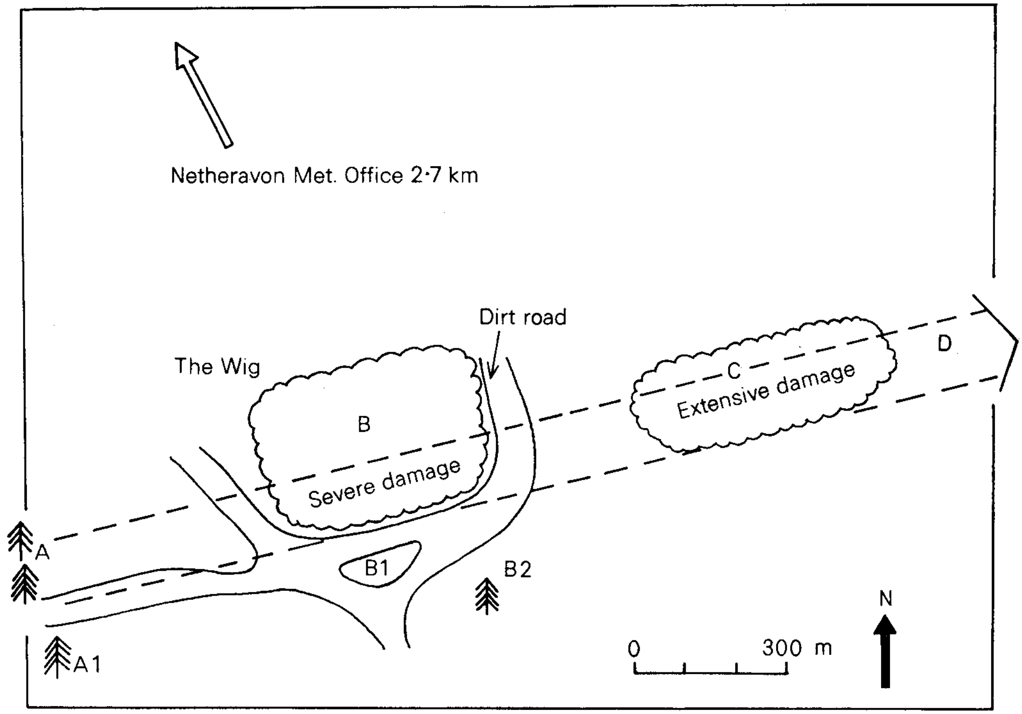

Figure 9. The track of the tornado in the area of the Wig plantation.

A notable feature was that, within an area roughly 50 m square, trees were lying in different directions, the pattern suggesting their being uprooted or snapped by winds of a small circulation. Trees at B1 were partially damaged but that at B2 was unscathed. At C, in a much less densely wooded spinney of smaller trees, extensive damage was seen—usually branches or trunks broken. Some debris from C was carried outside the spinney edge to D. From D a hedge with deciduous trees at approximately 700 m distance appeared undamaged.

A further detailed report was given by an experienced helicopter pilot who was at home at Shipton Bellinger. His view to the west was partly obscured by nearby houses but he was able to observe the squall line as it approached. A very dark vertical core appeared and fractostratus cloud at the edges was sucked up into it. He estimated that the vertical motion represented twice the rate of maximum helicopter ascent, i.e. 60 miles per hour (about 25 m s^{-1}). The storm then, suddenly, produced very heavy rain soon followed by hail, then lighter rain. The storm passed to the east within two or three minutes of the first observation.

No rotational motion within the vertical core was observed but this account appeared to present clear visual evidence of very strong local vertical motions within the cold front.

The track of the tornado

It appeared to form to the south-west of Larkhill (Fig. 2) as it is assumed to have been in an early stage of development from the description of it when just south of the camp. It moved just to the north of Knighton farm, where the tops of two or three trees were broken off, then crossed Syrencot House. It is probable that the funnel cloud, undoubtedly at ground level at Larkhill, crossed the Avon valley with the funnel above the ground, possibly by several tens of metres. The land containing Syrencot House slopes gradually upward from the river and contains many trees of different varieties, dimensions and ages. Only one of these was damaged, the top being broken. Inspection of this tree revealed that it was diseased and therefore weaker than those around it. The author considered that much more damage would have been done to the trees and buildings if the funnel had been at or near ground level. The observation by the office workers in Syrencot House seemed to confirm the assumption of an 'elevated' funnel at that stage.

The tornado then moved further eastwards out of the valley where the funnel reached the ground once more. By this time it had developed to the size indicated by Mr Loder and was of sufficient intensity to damage or destroy many healthy mature trees in the Wig. Beyond the second, smaller, copse the tornado appeared to dissipate rapidly as no evidence of further sightings or damage was obtained.

Discussion and conclusions

The Salisbury Plain area of Wiltshire is sparsely populated and it is possible that the tornado would not have come to the notice of the author if it had not severely damaged the Wig although it is only 2·7 km to the south-east of Netheravon meteorological office.

From inspection of the Wig it seemed as if the tornado came to a halt, temporarily, within the plantation, felling trees in a more or less circular pattern. It then moved on to destroy most of the trees in the second copse. Over open ground beyond this, however, the tornado apparently became a spent force and decayed quickly although the squall line, within which it was probably embedded, continued north-eastwards.

It is considered that the meteorological evidence confirmed, in a general sense, those requirements necessary for severe storm and tornado development. The weight given to particular factors can be assessed only in a qualitative way but it is suggested that the main features causing the tornado were, in combination:

(a) the strength of the front, shown by the large θ_w gradient across it at low levels, and

(b) the wave on the front, well defined by the isallobaric low, which moved, at a critical time, into the development area under the right entrance to the south-south-westerly upper jet stream.

Local topography may have played a part in the formation of the tornado as valleys are often favoured locations for tornado development (Wright 1973). It is certain that between its appearance at Larkhill and its emergence out of the Avon valley this tornado intensified in a dramatic manner.

The evidence from Shipton Bellinger indicated the possibility of other tornado-like features within what was a very active squall line.

Acknowledgements

The author wishes to thank the Principal Meteorological Officer, Upavon, and staff of the Special Investigations Branch (Met O 9) for their advice, suggestions and encouragement in the preparation of this paper, Mr P. Brown of Boscombe Down meteorological office for additional local information, and 7 Regiment, Army Air Corps for supplying the photographs that make up Plate I.

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Reminiscences of the Meteorological Office, 1898-1910

By A. T. Bench

The following account was prepared by Mr A. T. Bench on the basis of his own reminiscences and those of Messrs H. E. Carter, W. Hayes and H. L. B. Tarrant; a shortened version was published in the *Marine Observer* in 1963, but we thought that the full version merited circulation among a wider audience. Mr Bench retired in March 1947 after more than 49 years' service. He entered the Office, which was then housed at 63 Victoria Street, Westminster, on 24 January 1898, as a Boy Clerk in the 'Autographic Records' Branch, and became a Probationer in the Forecast Division in September 1902. He remained in forecasting for 18 years and his memories of this period include the final telegraphic message from Victoria Street on the removal to South Kensington in 1910 and the receipt of the first wireless message from the Eiffel Tower in 1913. In October 1920 he was transferred as Principal Assistant to the British Rainfall Organization on its incorporation in the Meteorological Office, passing to the new General Climatology Branch on its formation in 1925. He remained in that Branch until his retirement.

Several accounts of the history and work of the Meterological Office have been published, notably by the late R. G. K. Lempfert but they have naturally been limited to official matters. The following notes and personal reminiscences may serve to fill in the background of the picture as seen by members of the staff in the years which immediately preceded and followed the end of the last century.

At that time the Meteorological Office was situated in Victoria Street, Westminster, and was under the direction of Dr R. H. Scott until early in 1901 when Dr W. N. Shaw succeeded him. The annual budget was £12 500. The office premises occupied the four upper floors of a building on the corner of Strutton Ground which had been originally a private residence, the ground floor having been converted into two shops—a piano dealer on the corner, with an oriental rug and carpet store next door. Mr and Mrs Drane acted as caretakers and occupied very gloomy quarters in the basement. Mrs Drane was formerly cook in the household of Dr Scott.

The boy clerks who joined the staff about the turn of the century might almost have thought they were joining a family party, several members of which were in the original 'hive off' from the Board of Trade in 1855. In a staff of just under 40 persons there were four or five sets of brothers and a pair of sisters. The sisters, Miss Rose Smith and Miss Beatrice Smith, with Miss E. A. Anderson in charge, were ensconced in a veritable 'purdah' on the top floor of the building behind double doors and were allowed to arrive 10 minutes later and leave 10 minutes earlier than the male staff in order (ostensibly) to avoid contact with the men. They comprised a section of the Marine Branch and such was their strict seclusion that permission to interview them had to be obtained from their chief.

The principal part of the library was located in the room of the head of the office, Dr R. H. Scott (succeeded by Dr W. N. Shaw), whose official designation was that of Secretary. Owing to lack of other space the regular meetings of the Meteorological Committee were held in that room, when afternoon tea was provided, the tea being a special brand at 6*s*. per pound obtained from a firm in Inverness. In the course of years the accession of books and bound volumes of observations had overflowed into other rooms and the increasing weight of these and of several thousands of marine meteorological logs, caused some of the floor joists to sag and it became necessary for iron girders to be put in to hold up the floors.

Even in a small company of individuals there can always be found some with amusing characteristics, and the Meteorological Office staff were by no means lacking in this respect. A recreation of one Marine Superintendent, Captain Toynbee, was writing evangelical pamphlets which he distributed to the staff from time to time. One of these had the intriguing title of 'Go down, proud stomach'; another was headed 'Of the dead, say nothing but good'. Captain Toynbee, when on the active list in the merchant navy, kept meteorological logs, and at one office function some of these were exhibited, as they were beautifully illustrated by coloured sketches of marine animals drawn by Mrs Toynbee, who often accompanied her husband on his voyages. On the same occasion a logbook was shown which had been kept by King George V when, as Prince George, he served as an officer in the Navy.

The Chief Clerk, James S. Harding, a short but very dignified man with a long square-cut beard, had a flair for languages and, although not much of a linguist, could read quite a few. He usually spent his annual summer leave learning a fresh one, and was discovered one year by a boy clerk at Littlehampton, where he always went, sitting on the sands by a groyne learning Russian.

A. J. Rigby was an exceptionally hairy man, which fact, he insisted, was indicative of great strength.

Around the corner from the office, in Strutton Ground, was, and still is, a public house named the Grafton and it was the invariable practice of the two senior forecasters, F. Gaster and F. J. Brodie, to pay a visit there immediately before settling down with the synoptic chart to dictate the forecasts. In those days public houses were open all day. Mr Chas Harding, brother of James Harding, and senior clerk in the Marine Branch, also had the habit of slipping out in the morning and invariably remarked on leaving the Marine Room, 'Just want to call at the Stores' (i.e. the Army and Navy which had not then become one of London's popular public stores; business was restricted to ticket holders who were members or ex-members of the armed or civil services). Mr E. J. Hood of the General Office, also used to 'pop out' for brief periods—not limited to mid-morning.

Street musicians, notably 'German' bands, often played outside the Grafton and, when they became too noisy, Dr Shaw would send Mr Snell down to request them to soften their music, as his room overlooked the side street.

Mr Gaster was also addicted to taking patent medicines for unknown complaints and the large mantelpiece in his room was completely loaded with bottles, empty and otherwise. He always had his lunch in his room, served by Mrs Drane, and had the curious habit of removing his dentures before his meal, placing them on a table-napkin beside his plate. At one period Mr Gaster had a cask of ale in the basement for his own consumption and for anyone else who would pay for a drink. This arrangement, however, did not last very long, as he found that the ale disappeared and he lost money. Mr Gaster also had a goodly row of scientific textbooks, some of them Queen's Prizes, gained for work at an evening institute. He was also Meteorological Correspondent for *The Times* and usually prepared a special account of the day's weather experienced over the country. This was sent to *The Times* office by the messenger who called each evening for a copy of the official forecast and notes which were issued to the Press. He was also a churchwarden and conducted a Bible class for young women.

Charles Thompson, a short rotund figure, was never known to wear an overcoat even during the most severe weather and always used a walking stick with a silver knob, suitable for a much taller man. He and A. H. Bell, both bachelors, were as 'David and Jonathan' in their habits and as a consequence always spent holidays together. On one occasion they took advantage of an unprecedented excursion of the Great Western Railway to Killarney for thirty shillings return. Thompson and Bell were enthusiastic members of the Old Playgoers Club and from time to time in the first decade of the present century invited members of the Meteorological Office Cycle Club to join them at dinners arranged by the O.P.C. at the Criterion Restaurant. On these occasions the after-dinner entertainments were noteworthy, the artists including many well-known singers and popular music-hall stars of the day. These visits to the 'Cri' were a generous return for hospitality of the office Cycle Club, the members of which invited Thompson and Bell to their annual dinner at a country hotel some 20 or so miles from London. These informal dinners were followed by an entertainment comprising vocal, instrumental and humorous items all presented by the cyclists, and very successful gatherings were held at the Bull at Leatherhead, the Feathers at Merstham and the Swan at Staines.

T. E. Allen, in charge of the autographic records from the first-class observatories (photographic in those days), was formerly an assistant of Glaisher, the famous balloonist, at Greenwich Observatory. He had held Grand Master's office in the Oddfellows and was Secretary of a Lodge. Quill pens were included among the stationary stores and these were invariably used by Mr Allen for his reports.

One of the junior clerks, who earlier framed pictures in his spare time, was Frank T. Bullen, who spent many years in the merchant navy, ending up as Chief Mate before entering the office. He achieved fame and fortune by his books, notably *The cruise of the Cachalot.* This publication, however, was treated with scorn by William Allingham of the Marine Branch who started his career before the mast in a sailing ship, and was the author of a standard textbook on marine meteorology. As two of the juniors who joined at this period had also graduated from naval schools (viz. Greenwich and the *Worcester*), there was a distinctly nautical atmosphere in some of the rooms.

George Francis always appeared to be in debt, both to his colleagues and elsewhere. As a result of the latter, there were occasional mysterious absences from duty owing to visits of a Sheriff's Officer. During one such two-day absence a nasty smell was noticed in his room. Toward the end of the second day this became so objectionable that an organized search was conducted, leading to a locked drawer in his table which, when broken open, disclosed some kippers wrapped in newspaper.

The 'wag' of the office staff was undoubtedly A. E. Pycock who was an excellent comic singer. Under the name of 'Fred Edwards' he was in demand for concerts and dinners and appeared on concert platforms as far away as the Grand Hotel at Eastbourne. Indeed, he earned more by his evening concert work than he did in the office. He was at all times excellent company with a fund of humorous stories. One of his office jokes was in connection with the marriage of Miss Beatrice Smith to a Mr Plank; when Pycock first heard about it he spread it around that it was young Bench whom she had actually married.

Miss Rose Smith had a great interest in music and was a member of the London Choral Society for many years. She retained an interest in choral singing until her death at the age of 91. Mr R. G. K. Lempfert was an accomplished viola player. In 1916 he married Miss Marjorie Hayward, a violinist of international repute. Another competent musician was W. G. James, flautist and organist. L. H. Powers must also be numbered among the musicians. As a violinist he entertained his fellows at staff dinners in the 1890s and even played his 'fiddle' to friends up to within a month of his death at the age of 90 in 1959. It was in the year 1900 that Powers was credited with the discovery that observers at certain seaside resorts were joining up intermittent burns on the sunshine cards by a hot wire in order to augment their daily totals.

Frank Snell was an expert telegraphist who had been transferred to the office from the General Post Office, but in common with other members of the staff in those days, was not averse to doing any other work required of him, and became the first person in the Meteorological Office to use a typewriter.

S. Call (known as 'Paddy'), who came from Armagh Observatory, was notable for his beautiful 'copper-plate' handwriting, a distinction which he retained up to his bed-ridden nineties.

Charles Heinemann was an unusual character with a reputation, which he retained to the end of his service, of never having made a mistake in his computing. He arrived at the office one morning with a very black eye, but all that he would disclose about its origin was that he had met a 'friend' at the Bull and Bush. Heinemann, who was a competent mechanic, also studied astronomy and was a very early rider of a motor cycle. At an advanced age—long after retirement from the Meteorological Office—he sailed model yachts of his own construction on the Round Pond in Kensington Gardens.

With the outbreak of the Boer War in 1899 the staff suffered the temporary loss of two of its lads who joined the City Imperial Volunteers.

The general messenger of the office was a uniformed member of the Corps of Commissionaires, whose main duty was to take the lithographic transfers of the *Daily Weather Report*, etc. to Messrs Weller and Graham in the City at 11 a.m. daily, and bring back the printed copies in the early afternoon. *Reports* posted by 5 p.m. were delivered in Liverpool, Manchester, etc. by the first delivery on the following morning.

As to sartorial matters, most of the seniors wore top hats and frock or tail coats. In those days a good silk hat could be bought for 12*s.* 6*d.* Almost everyone changed into an old 'office coat' on arrival, and some of these were very dilapidated. Behind a screen in his room Dr Scott always changed his suit for a shabby one. The consistently best dressed man of this period was Henry Harries, who changed his shoes also on arrival and stuffed them with paper to help in keeping their shape. By writing daily articles for the *Morning Post*, Harries augmented his income considerably and normally took his annual holiday on a voyage down the Mediterranean or to the Atlantic islands.

Sartorial comment would be incomplete without a reference to Mr Sargeant, a forecaster. He was completely uninhibited and dressed for comfort regardless of appearance. He wore very wide trousers to avoid bagging at the knees and in summer would come to the office wearing his black frock coat, a straw hat (known as a 'boater') with brown canvas shoes and carrying an umbrella in case the forecast 'went wrong'. He was a very likeable man, fond of chess, but had an annoying habit of whistling softly through his teeth—no tune but just audible.

Except for those of the forecasting shifts, time keeping and discipline were very strict. A red line was drawn in the Attendance Book at 9.15 a.m. and anyone who had to sign below this line twice in a week was literally had up on the carpet in the Secretary's room. Richard Curtis once reproved his brother-in-law, Charles Thompson, for exceeding the lunch period of three-quarters of an hour by a couple of minutes! Talking in the rooms except on official matters was not allowed and smoking, of course, was not even dreamt of.

Although official discipline in the office was so strict, it did not debar some of the senior clerks from sending boy clerks on personal errands almost daily; in particular to the Army and Navy Stores for such necessities as tobacco and whisky.

The situation of the office in Victoria Street was advantageous for viewing the processions of those days which passed on their way to Westminster Abbey, including those connected with the death of Queen Victoria and the Coronation of King Edward VII. For the latter occasion the office building was suitably decorated. There was also a time of great excitement when a scare caused a run on the London Penny Bank on the opposite corner of Strutton Ground. For a couple of days the Bank was besieged by hundreds of depositors making withdrawals, but the Bank of England stepped in with funds and the excitement abated.

Books and papers were circulated from floor to floor by means of a leather bag which hung on a long cord fastened to the top banister of the wide staircase by which it could be hauled up. Before the installation of house telephones communication between some of the rooms was by speaking tubes with a whistle at each end. When blown into at one end an ivory plug protruded at the other.

As there was no telephone in the office at this time, communication with the outside world was by letter, telegram or 'by hand' and boy clerks made fairly frequent trips to the Admiralty with matter for the Atlantic Charts for approval by the Hydrographer. In cases of urgency the use of a hansom cab was authorized. Some journeys could be made in part by horse-drawn buses which passed the office about three times an hour. The first telephone was not installed until after Dr Shaw had succeeded Dr Scott as Secretary. The installation of this telephone caused such excitement in the office that discipline was temporarily relaxed and a crowd of seniors and juniors stood around as the Post Office engineers fitted it to the wall in the office keeper's little room. When it was installed the Chief Clerk was called down to inspect it and with appropriate dignity he made the first call to the Royal Meteorological Society amid hushed silence, to proclaim the news that the Meteorological Office was now 'on the telephone' and would they please note that the number was 'Victoria 153'. Members of the staff rushed to use it as a novelty to ring up friends and a few expressed surprise and indignation when asked to pay for private calls.

A feature of office routine was the daily circulation of *The Times* to all the seniors; starting with the Secretary it eventually found its way to the top floor ending up in the Ladies' Room. A kitchen was situated on the top floor from which Mrs Drane supplied good satisfying dinners to the staff at the modest price of 8*d*. per head for the juniors and 1*s*. 2*d*. for seniors. Facilities for washing by some of the staff were met by the provision of a small cabinet in their room containing a basin, water jug, etc. There was, of course, no hot water circulation in the building.

For lighting purposes, tables in most rooms were supplied with Argand gas lamps which gave very good illumination, but oil lamps were used in the Forecast rooms until 1901. Mr Francis, who was rather bald, used to say that he lost his hair because for years he had to sit under a powerful hanging oil lamp when the Forecast Room was on the first floor. The rooms were warmed in cold weather by coal fires which were kept well stoked by the boy clerks.

For the reception and transmission of telegrams the office was connected by a direct telegraph line to the Central Telegraph Office and this could be switched to instruments (Siemens tape printers) in different rooms. When there was an occasional breakdown it must have been surprising to passers-by to see an almost continuous procession of telegraph messengers from the South-west District Office in Howick Place bringing telegrams addressed 'Weather London' to the building.

The Annual Leave of four weeks was generous compared with other offices. Salaries were paid by monthly cheque on the Western Branch of the Bank of England to those 'on the staff' and weekly in cash to boy clerks and temporary clerks. The wages of Boy Clerks were 12*s*. 6*d*. weekly at 15 years of age increasing by 1*s*. 6*d*. annually to a maximum of 20*s*. weekly. Junior clerks rose to a maximum of £150 per annum, Seniors to £275 and the Chief Clerk to £333. The senior clerk in the Forecast Division (F. Gaster) received £309 per annum for a nine-hour day. Other members of the Forecasting Branch received additions to their pay as compensation for time worked before 9 a.m. and after 5 p.m. and Sunday duty. The salary of the Marine Superintendent was £350 per annum and that of the Secretary £800.

The office hours were originally 10 a.m. to 4 p.m. but an agitation for some increase of the previous low salaries had been met by additions to the salary scales (as quoted above) and an addition of two hours to the working day, i.e. from 9 a.m. to 5 p.m. At one time alternate Saturdays were worked as full days, but in 1901 this was altered to a regular half-day every Saturday. On Sunday mornings the telegraph line to the Central Telegraph Office was closed and the staff on duty went there to work. The junior of the shift went from his home to take the morning observations at Westminster and then walked to

Charing Cross Post Office to send them by telegram to C.T.O. For this service he received the sum of 1*s*. 6*d*.

In the Forecast Branch the hours of duty were 8 a.m, to 4 p.m. or 1.30 p.m. to 8.30 p.m., 1 p.m. to 8.30 p.m. on Saturdays and on Sunday 8 a.m. to noon at the Central Telegraph Office and 6 p.m. to 8.30 p.m. at Victoria Street. Subsequently, with the change in time of the morning observations, the day duty was from 7 a.m. to 3 p.m. A day off in lieu of Sunday duty did not come into operation until during the 1914–18 war.

Although observations were made on the roof of the Office, the published records for London for many years were those taken by Mr Gaster at his house in Acre Lane, Brixton. A station was subsequently set up in the grounds of Christ Church, opposite the Office. (Christ Church was demolished by bombing in World War II.) At the beginning of the century no electric torches were available and when it was dark at the time of the 6 p.m. observations a colza oil lantern was used to read the instruments. When windy it was difficult to keep this alight and the observers hit on the idea of using a small mirror to reflect the light from a nearby street lamp on to the thermometers. Records from St James's Park commenced in November 1904, and a master key was provided by the Office of Works in order that entry to the park could be made at any time.

The Instruments Branch was housed on the first floor of the building in one room, divided by a partition to separate the stores from the office. Richard Strachan, a small wiry old man, almost entirely bald, with a very rasping voice, presided over this Branch until 1900, when he retired. He was assisted by J. Williams, a pleasant but diminutive hunchback. It was surprising to note the ease with which Williams dealt with large packing cases. Mr Strachan had transferred to the Meteorological Department under Admiral Fitzroy, and died at the age of 90 on Easter Day 1924. He was succeeded by R. F. Wallace, who had the assistance of one of the boy clerks on one day a week. A 'highlight' of this part-time service by the boy clerk was an occasional trip to the docks to deliver a barometer to a ship, the journey being made partly by Underground Railway. In those days the Underground was very dirty and smoky due to emissions from the funnels of the steam locomotives.

The safety bicycle with its inflatable tyres in place of the former solid tyres had become popular; many of the juniors used cycles for their journeys to and from the office and the basement resembled a cycle shop. Some of the cycles had also the new free-wheel hub!

Across the front of the office building was a narrow balcony on the second floor and on this balcony boards were displayed which gave weather information from Valentia, Stornoway, Holyhead, Yarmouth and Dungeness with the state of the sea at Dover. These boards were changed each morning and afternoon. A chart showing the distribution of pressure and station reports at 8 a.m. (later 7), 1 p.m. and 6 p.m. was displayed at the door, together with the latest district forecasts.

The forecasts and remarks thereon were written and duplicated by hectograph process (gelatine plate) every evening for distribution to the newspapers and Press agencies until September 1905 when a more modern method of typing them on stencil sheets for reproduction on a duplicator was introduced.

Throughout its existence the Meterological Office has always been subject to the attention of cranks, and there was an occasion one evening when the forecast staff had a visit from a man who came from Plumstead and declared he was a 'weather chart'. Mr Brodie asked if he had come so that he could be filed away with the official charts. After some argument he was persuaded to go away and come another day. It was thought necessary to watch him off the premises.

At least two of the senior staff took a prominent part in local municipal affairs. Mr John A. Curtis, brother of Richard Curtis, was Mayor of Fulham for one year and Mr T. Duncan Bell, brother of Arthur Bell, was an Alderman of the Borough of Camberwell. Bell became an official of the London Congregational Union and was chairman for one year. He was also a popular elocutionist and lecturer on a variety of subjects. John Curtis was also superintendent of a Sunday school in Fulham for many years.

Among notable visitors to the office was Dr Alexander Buchan (of Buchan periods fame), Secretary of the Scottish Meteorological Society. He was a tall, venerable figure, with a long patriarchal beard, and came from time to time, until his death in 1907, in connection with the Scottish stations. The staff were delighted if they could bring to his notice any entry on returns where the wet-bulb temperature value was higher than the dry. He always insisted that the figures were correct.

Correspondence

Comments on 'The problems of anemometer exposure in urban areas—a wind tunnel study' (by R. A. Evans and B. E. Lee, *Meteorol Mag*, **110**, 1981, 188–199).

As the recently appointed Head of the Climatological Services Branch of the Meteorological Office I am writing to express my concern at some of the implications in the paper entitled 'The problems of anemometer exposure in urban areas—a wind tunnel study' by R. A. Evans and B. E. Lee. My strong impression upon reading this paper is that some good experimental work is spoilt by ill-informed criticism backed up by that favourite tool of the journalist, the selective quotation.

For the benefit of your readers, and for the sake of accuracy, I feel that the following points should be made:

(a) The Meteorological Office does not have a free hand in the selection of sites for climatological purposes. We are presented with offers from authorities or individuals who have a particular interest in the data but whose sites may be far from perfect.

(b) The choice between which data to publish of two or more stations in a particular area will depend partly on sites and partly upon a number of other factors. The latter may include factors such as the type of instrument being used, the standard of maintenance, the willingness of the co-operating observer to maintain the site to our standards, the interest of the observer in the data, the likelihood of the station itself being of value as a long-term climatological record, etc. These judgements are necessarily subjective.

(c) The decision to cease the publication of wind data from Weston Park Museum and to replace them with readings from the anemometer on the top of the Geography building at Sheffield University was taken, as Mr Hopkins said in his letter to *Weather*, for several reasons of which the siting was but one.

(d) Paragraph 4(d) of the paper by Evans and Lee, in quoting from the letter by Mr Hopkins to *Weather*, stops short of his critical sentence. This reads: 'The disparity between winds measured at the two sites emphasises that, until confirmatory records from a third site in the city become available, both sets of data should be used with the utmost caution'. It is quite clear from this sentence that the Meteorological Office regarded neither site as particularly ideal.

(e) The implication by the authors that the Meteorological Office was wrong to transfer its data source to the Geography building is not borne out by Fig. 7 in their paper. This figure shows, as Mr Hopkins predicted, that both sites leave much to be desired. It is by no means clear that one is better than the other. The authors do not quote the variances from the two curves in Fig. 7; my estimate is that the difference between the two variances is well within the experimental error for the wind tunnel measurements. Furthermore, the building of the Royal Hallamshire Hospital to the south of Weston Park and within the 550 metre radius from the Museum has created a discontinuity in the record for the Weston Park anemometer. There was thus no long-term climatological reason for wishing to retain Weston Park had all other factors been equal.

(f) The discounting by the authors of the effects of the 'zig-zag' profile of the Weston Park roof on the winds at anemometer height would have carried more weight had they, in fact, modelled that building on the 1:350 scale as they did the others. They may well be right in their assertions that the turbulence created by this roof profile would be minimal but surely they should have proved the point.

(g) The ill-informed criticism and selective quotation in this paper detracts from the interesting and valuable work undertaken in the wind tunnel. Would that this exercise could be repeated for all sites from which we obtain anemometer readings—including our official sites. One cannot help wishing that the Meteorological Office could choose sites for anemometers on the basis of such testing. The experimental work described in the paper does indicate the care needed when using any climatological data and wind data in particular. If any serious user of data considers that detailed knowledge of the characeristics of individual sites would be of value, then the Climatological Services Branch can supply the relevant information. The complete quotation from Mr Hopkins's letter shows the considerable care exercised by Meteorological Office staff when making decisions regarding the acceptance of sites for climatological purposes.

F. Singleton

Meteorological Office,
Bracknell

The authors reply:
In reply to the remarks made by the Head of the Climatological Services Branch of the Meteorological Office to our recent paper we would like to respond by thanking him.

R. A. Evans
B. E. Lee

Department of Building Science,
University of Sheffield

Comments on 'Rain-gauge network rationalization and its advantages' (by C. A. Nicholass, P. E. O'Connell and M. R. Senior, *Meteorol Mag*, **110**, 1981, 92–102).

I should like to comment on the article 'Rain-gauge network rationalization and its advantages'.

The article makes no reference to the 'Report of the Joint Committee appointed to consider methods of determining the general rainfall over any areas', published by the Institution of Water Engineers, 1937 Trans, Vol. 42, pp. 231–276. This report was prepared by representatives of the Meteorological Office, the British Rainfall Organization and the Institution of Water Engineers. This 1937 report covers most of the main points of the article in a much more objective and realistic manner. The present article could have been much more useful if the earlier report had been studied.

The article does mention the importance of securing a suitable site for the rain-gauge, but seems to accept the position in which some sites are used which are not as good as others. By the time I retired in 1957 we were in a position to define the extent of the exposure error, either by inspection or by examining the fit of the average on the map of average annual rainfall. The authors do not seem to have developed these examinations from the two quite separate aspects to eliminate the doubtful exposures.

The article considers the network of stations required from the user's aspect. We looked at the problem from the different types of rainfall involved. With the orographical and cyclonic types of distribution, as we studied the distributions for a number of wet days each year we felt we could manage with fewer records to define the distribution adequately. The thunderstorm rains were, however, local and infrequent and usually had little effect on the distribution on the annual, and still less on the average, maps. We thought in terms of a network of reliable records, plus a reserve which could be called upon in the case of instability rains. Indeed it seemed unlikely that we could secure enough records to define the distribution during all these local intense rains. We hoped, however, to be able to use run-off records or the maximum height of streams to add to our knowledge of the rainfall distribution.

On page 95 the article suggests the use of correlation and variances of pairs of rainfall data, without apparently realizing that changes arise from time to time in the accuracy of rainfall records, owing to leaks in the gauge, changes in the sites, etc. An example of the change in the reliability of a record is given in *British rainfall 1923*, page 243. We used the calculation of the mean deviations or correlation coefficients to test the homogeneity of records. The decrease in the correlation with distance over the British Isles was also defined in *British rainfall 1925*, pages 258–259.

The proposals in the article for redesigning rain-gauge networks seem unrealistic. Our emphasis was on using keen observers and suitable sites. Where this gave a close network we examined the relation of rainfall to the configuration so that we could apply the knowledge gained to areas of less information. We gradually increased the distribution as observers and sites became available. We found it a waste of time to use poor observers or unsuitable sites.

We also developed a scheme for examining the station values on the annual percentage maps. As explained in *Weather*, **34**, pages 441–442, 'If a station gave a value differing by 2 per cent or more from that expected from the values at surrounding stations then the record came under suspicion. If the map for the previous year gave a similar difference then some error was likely, and if this difference had persisted for three years then clearly some change had occurred'. This examination brought to light some errors which could be eliminated. It appears that this scheme has been stopped so that the records now being accumulated may have become more uncertain.

John Glasspoole

87 Mostyn Road
Merton Park
London SW19 3LW

The authors reply:

We are grateful to Dr Glasspoole for reminding us of the Report of the Joint Committee (of which he was a member) on 'The determination of the general rainfall over any area' (1937). He will recall that in the discussion which followed its presentation there was agreement that the Report would be a useful reference work. However, the discussion also revealed a number of doubts (including some expressed by the then President of the Royal Meteorological Society) about the subjective nature of the methods used.

Our recent study attempted to apply modern statistical techniques using available computer resources to the same problems that confronted the Joint Committee, and to quantify certain aspects which were only qualitatively defined in the 1937 Report.

The conclusions of the Joint Committee were that a precise determination of the general rainfall over any area requires:

(a) an adequate distribution of suitably exposed rain-gauges,

(b) a periodic critical examination of records, and

(c) a regular preparation of isohyetal maps from which the general rainfall may be determined.

Our recent study took into account similar requirements with the following sequence of actions:

(1) All rain-gauge sites were inspected and classified.

(2) A statistical method was developed for evaluating records and interpolating rainfall values in ungauged areas.

(3) A network was designed to meet users' requirements.

(4) All sites in the design network were to be of a standard approved by the Meteorological Office and the records regularly monitored using the computer-assisted quality control procedures.

Whilst the article did not detail every stage of the project, it is inherent in (4) above that poor sites would either have to be improved or abandoned, with only approved sites being adopted in the new network. Although users' requirements form the basis upon which the network was designed, the effects of topography and variability of rainfall are taken into account in the statistical methods. On a practical level, wherever possible keen observers and suitable sites were included in preference to poor sites and/or observers. Additionally, an element of redundancy was built into the network by retaining all the good sites, even though some of them were not needed to satisfy the users' requirements.

Dr Glasspoole refers (in his fifth paragraph) to the possibility that inhomogeneities in the rainfall records could affect the calculation of correlations and variances of pairs of rainfall data. Assuming that such inhomogeneities had not been detected during the normal data checking and archiving process, the problems resulting would be most noticeable when correlating long series of data, such as for annual totals. In our study the correlations were for monthly and daily data and the periods required to give a reasonable sample size were not too long, 15 years for monthly and 6 years for daily data. This it would be hoped that the problem of data inconsistencies would not be serious.

During this period of reducing resources it is vital that users' requirements are reviewed and that, where justified, cost-effective methods of acquiring and processing rainfall data are employed. The rationalization method described in the paper represents one approach to the problem of designing raingauge networks so that they may provide the quality of data which is required by the users in a more cost-effective way compared with the former subjective and often wasteful methods.

C. A. Nicholass

Meteorological Office

P. E. O'Connell

Institute of Hydrology

M. R. Senior

Wessex Water Authority

Reviews

Air in danger, by G. Breuer. 225 mm × 140 mm, pp. xii + 189, *illus*. Cambridge University Press, 1980. Price £10 (hard cover), £3.50 (paperback).

The book sets out to provide the interested non-specialist with an account of man's technological activities on the earth's atmosphere. The account is set in the context of the development of the atmosphere on the geological time-scale, compared with which any man-made changes are both small in extent and extremely recent. The greater part of the book is devoted to the increase in carbon dioxide resulting from the burning of fossil fuels and the reduction in the global biomass. The other topics considered are the effects of oxides of nitrogen and stable chlorine compounds on the ozone layer. This balance can be justified on the grounds both of the magnitude of the effects which might be produced and the extent of the changes in man's economic activities which might have to be adopted to reverse them. The author makes it clear that there is a divergence of opinion as to the consequences of a continued growth in atmospheric carbon dioxide. There are also difficulties in estimating the global sources and sinks, particularly the source afforded by the reduction in the global biomass and the sink afforded by the transfer of carbonates to deep ocean waters.

The presentation is partly in the form of direct exposition and partly in the form of interviews with workers in the field. At least in translation, these give the impression of being very contrived. The German original was published in 1978 and this translation by Peter Fabien and W. A. Matthews, both of the Max Planck Institute, Lindau, contains references up to 1978. It is unfortunate that the layout of the combined author's notes and bibliographical references makes it very difficult to trace a publication except on the first occasion when it is cited.

The final chapter attempts to make recommendations for future policy. The only point which comes over clearly is the author's advocacy of large-scale reafforestation, particularly in the Third World, with financial aid from the developed countries. The reviewer was left wondering if such large-scale planting of trees could ever be accomplished, bearing in mind that it is only marginal land and land reclaimed from being denuded by erosion and from desertification which could conceivably be used for this purpose.

E. L. Simmons

Klimaschwankungen (*Verständliche Wissenschaft Band 115*), by C. D. Schönwiese. 185 mm × 115 mm, pp. xii + 181, *illus*. Springer-Verlag, Berlin, Heidelberg, New York, 1979. Price DM 12.

It is a formidable undertaking to write a book on climatic variations for the layman, which I think is what this is. There is, to judge from some earlier efforts which have been marketed, a temptation to dramatize the subject; this tends to result in false ideas and conclusions. Schönwiese has sternly resisted this temptation but the price is a rather pedestrian book which will, I am afraid, test the endurance of all but the most determined seekers after knowledge. Those who complete the course will be rewarded by a systematic and accurate survey of this difficult and controversial subject.

In the first two chapters he tries to say what climatic variations are—certainly not one hard winter or a hot droughty summer—and surveys the historical data which tell of variations in climate.

Then there is a chapter on the statistical treatment of climatological data, which he advises his non-mathematical readers to skip and perhaps come back to later if they feel the need.

After some more discussion of variations during the last century and the last thousand milleniums he comes to the crucial question of the causes of these variations. He stresses that cause and effect are closely interwoven in the climatic system and discusses the variety of response times, feedback effects and the autovariation of the system. He gives it as his opinion that, even with the most powerful computers, model simulation of past climatic variations is unlikely for several decades to come.

There is a thorough chapter on likely man-made effects on climate, where he makes the strange statement that the cooling in the last three decades has robbed the CO_2 thesis of its importance. He soon regains his customary balance in pointing out that changes of culture are as much if not more responsible than climatic variations for the desertification in the Sahel region of Africa.

He ends with a reminder that increased world population has increased the vulnerability of man to climatic variations which he would have readily adapted to in earlier times.

M. K. Miles

Atmospheric phenomena, with introductions by David K. Lynch. 290 mm × 215 mm, pp. 175, *illus*. W. H. Freeman and Company, San Francisco and Oxford, 1980. Price £9.50 (board), £4.90 (paper).

This most attractive addition to the series of 'Readings from *Scientific American*' contains 18 articles from that admirable magazine. Six are on 'basic considerations'—water, ice, snow crystals, the growth of snow crystals, hailstones, and fog—and twelve are on 'atmospheric phenomena' including the rainbow, glory, green flash, noctilucent clouds and the zodiacal light. Each is by an expert in his field and may be assumed to have been up to date at the time it was originally published. Publication dates vary in fact from February 1949 ('The mechanism of lightning' by Loeb) to April 1978 ('Atmospheric haloes' by Lynch); but these dates are clearly displayed and no one could be unwittingly misled. In fact, for the readership aimed at, viz. the scientifically informed general public or the scientist who is not a specialist in the topic discussed, there is little to complain of and much to admire. The whole collection has been put together by David K. Lynch who has supplied a preface and introductions to both sections. The general feeling conveyed is summed up in the closing words of his preface:

'One might justify the study of atmospheric phenomena on the grounds that it is relevant to agriculture, communications or national defense, but I'll use a simpler approach, one to which we can all respond and one which is self-justifying. The sky is absolutely fascinating, and a desire to experience its beauty fully is sufficient reason to explore it. This reader is for everyone who shares my love of the sky.'

Diagrams and photographs—many in colour—are of the high standard to be expected from *Scientific American.*

R. P. W. Lewis

The weather almanac (third edition), edited by James A. Ruffner and Frank E. Bair. 235 mm × 160 mm, pp. viii + 801, *illus.* Gale Research Company, Detroit, Michigan, 1981. Price US $48.00.

The third edition received of this interesting and comprehensive reference guide to US weather and climate, which was first published in 1974, has even more pages, about half of them devoted to a narrative and statistical description of the local climates of over 100 US cities, each with the records of 40 recent years. Other information given includes climate maps with the normals for the United States as a whole, followed by sections on various severe weather phenomena such as hurricanes, tornadoes, thunderstorms, floods, heat waves, etc., each with handy safety rules listed. To the sections on other geophysical hazards such as earthquakes and tsunamis has been added one on volcanoes, based on the Mount St Helens eruption. Some topics of current interest have been added and reviewed, such as solar power, acid rain, the carbon dioxide cycle and climate change. Altogether a volume packed with information for the interested tourist, which even contains a world-wide climate survey with details on 550 cities throughout the world.

N. S. Harrison

Corrections

Meteorological Magazine, **110**, 1981

In the article 'A mesoscale forecast for 14 August 1975—the Hampstead storm', insert 'π' in equations (2) and (3), page 150, thus:

$$S = 558 \cos(\pi t/12) + 72 \quad (\mathrm{W\ m^{-2}}) \quad \ldots (2)$$

$$S = 279 \cos(\pi t/12) + 36 \quad (\mathrm{W\ m^{-2}}) \quad \ldots (3)$$

In 'Synoptic aspects relating to the development of widespread heavy rainfall over southern England on 30 May 1979', the wet-bulb potential temperature at the bottom of Fig. 1, page 208, should be '19', not '10' as shown.

In 'The founding of the Meteorological Office 1854–55', page 223, fourth paragraph, second line should read '. . . voted, namely, 2000*l*, for the Mercantile Marine and 1000*l* for Her Majesty's ships.'

THE METEOROLOGICAL MAGAZINE

No. 1312 November 1981 Vol. 110

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
Her Majesty's Stationery Office

£1.80 monthly
Dd 716670 K15 11/81

Annual subscription £23.80 including postage
ISBN 0 11 726288 9
ISSN 0026–1149

THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S
STATIONERY
OFFICE

December 1981

Met.O. 942 No. 1313 Vol. 110

METEOROLOGICAL OFFICE Met.O.942

THE METEOROLOGICAL MAGAZINE

No. 1313, December 1981, Vol. 110

551.511.2:551.511.3:523.45

High-vorticity regions in rotating thermally driven flows*

By R. Hide, F.R.S.

(Meteorological Office, Bracknell)

Summary

The regular and irregular non-axisymmetric flow regimes of thermal convection in a rotating fluid annulus subject to differential heating in the horizontal are characterized by the presence of upper-level jet streams, where intense concentrations of vorticity and high concomitant horizontal temperature gradients are found. The main features of the upper-level flow pattern can be interpreted by straightforward arguments based on general thermodynamic considerations and the requirement that the flow should be quasi-geostrophic nearly everywhere. Thus, when the distribution of applied heating and cooling is such that the corresponding gradient of the impressed radial temperature field has the same sign at all radii, the most conspicuous feature of the upper-level flow pattern in the regular non-axisymmetric regime is a single jet stream meandering in a wavy pattern between the bounding cylinders. When, however, the impressed radial temperature gradient changes sign near mid-radius (as in the case when heat is introduced throughout the body of the fluid and withdrawn at both side-walls), the corresponding upper-level flow consists of several closed eddies, each circulating 'anticyclonically' with the horizontal flow largely confined to a narrow jet stream at the periphery of each eddy. In some respects these stable closed eddies are dynamically similar to long-lived anticyclonic eddies (including the Great Red Spot) seen in Jupiter's atmosphere in the southern hemisphere. Previous work on stable baroclinic eddies is now being extended in various directions and supporting numerical work is also being carried out.

1. Introduction

The motion of a fluid that departs but little from solid body rotation with angular velocity Ω is usually geostrophic nearly everywhere, with the relative Eulerian velocity $\boldsymbol{u}$ (as measured in a frame of reference that rotates with angular velocity Ω relative to an inertial frame) satisfying

$$2\rho\Omega \times \boldsymbol{u} = -\nabla p + \rho\nabla V. \qquad (1)$$

* Invited paper presented at the joint International Union for Theoretical and Applied Mechanics/International Union for Geodesy and Geophysics symposium on *Intense Atmospheric Vortices*, 14–17 July 1981, European Centre for Medium-range Weather Forecasts, Shinfield Park, near Reading, England.

Here ρ denotes density, p denotes pressure and ∇V is the acceleration due to gravity and centripetal effects. Equation (1) is the leading approximation to the full equation of motion,

$$\rho\left(\frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} + 2\boldsymbol{\Omega} \times \boldsymbol{u} - \boldsymbol{r} \times \frac{\mathrm{d}\boldsymbol{\Omega}}{\mathrm{d}t}\right) = -\nabla p + \rho\nabla V - \nabla \times (\nu\rho\nabla \times \boldsymbol{u}). \quad .. \quad .. \quad (2)$$

It is valid in regions where the Coriolis term $2\rho\boldsymbol{\Omega} \times \boldsymbol{u}$ greatly exceeds the relative acceleration term $\rho\mathrm{D}\boldsymbol{u}/\mathrm{D}t \equiv \rho(\partial\boldsymbol{u}/\partial t + \boldsymbol{u}.\nabla\boldsymbol{u})$ (where t denotes time), the precessional term $\rho\boldsymbol{r} \times \mathrm{d}\boldsymbol{\Omega}/\mathrm{d}t$, the viscous term $\nabla \times (\nu\rho\nabla \times \boldsymbol{u})$ (where ν denotes kinematic viscosity) and any other term that must be added to equation (2) when further effects (e.g. magnetohydrodynamic forces) have to be taken into account.

Now equation (1) is lower in order than equation (2), so it cannot be solved under the complete set of boundary conditions. For this to be possible it is necessary to include every term in equation (2) in the analysis. It follows that the flow cannot be geostrophic everywhere; the system must exhibit boundary layers and detached shear layers where $\rho\mathrm{D}\boldsymbol{u}/\mathrm{D}t + \nabla \times (\rho\nu\nabla \times \boldsymbol{u})$ is comparable in magnitude with $2\rho\boldsymbol{\Omega} \times \boldsymbol{u}$. Within these highly ageostrophic regions the magnitude of the relative vorticity $\nabla \times \boldsymbol{u}$ can be comparable with or even exceed 2Ω. Many examples of such vorticity concentrations are found in laboratory systems and in nature. They are often associated with steep gradients of temperature (thermal fronts), as in the case of jet streams and western boundary currents found in atmospheres and oceans.

Jet streams are a pronounced feature of the non-axisymmetric flow regimes of thermal convection in a rotating fluid annulus, laboratory and theoretical studies of which have elucidated many aspects of the general circulation of the atmospheres of the Earth and other planets. This paper outlines the findings of work on annulus convection produced by internal heating and mentions one particularly interesting possible application (Hide 1980) to the interpretation of long-lived anticyclonic eddies (including the Great Red Spot) seen in Jupiter's atmosphere.

2. Sloping convection in the laboratory

Laboratory experiments in thermal convection in a rotating fluid annulus which rotates about a vertical axis and is subject to axisymmetric applied differential heating were initiated by the writer over 30 years ago (for references see Hide and Mason 1975, Pfeffer, Buzyna and Kung 1980, and Tritton and Davies 1981). They show that when the rotation rate Ω exceeds a certain critical value Ω_R (which depends on the acceleration due to gravity, the shape and dimensions of the apparatus, the coefficients of thermal expansion, thermal conductivity and viscosity of the fluid and its mean density, and the distribution and intensity of the applied differential heating, see section 4 below) Coriolis forces inhibit overturning motions in meridian planes and promote a completely different kind of motion, which has been termed 'sloping convection'. The motion is then non-axisymmetric and largely confined to jet streams, with typical trajectories of individual fluid elements inclined at only very small but essentially non-zero angles to the horizontal. The kinetic energy of the non-axisymmetric flow derives from the interaction of slight upward and downward motions in these sloping trajectories with the potential energy field produced by the action of gravity on the density variations maintained by the applied differential heating. The kinetic energy of the motion is dissipated by friction arising in boundary layers on the walls of the container and in the main body of the fluid.

Provided that Ω, though greater than Ω_R, does not exceed a second critical value Ω_I (see section 4 below), the main features of the non-axisymmetric motion are characterized by great regularity. This regular flow is either steady (apart from a steady drift of the horizontal flow pattern relative to the walls of the apparatus) or it exhibits periodic 'vacillation' in the amplitude, shape and other characteristics. The number of 'waves' m around the annulus is not uniquely determined by the impressed conditions;

the flow is found to be 'intransitive' owing to the occurrence of what have come to be called 'multiple equilibrium states'. But a quantity *m*, defined as the most likely value of *m* at a point in the region of parameter space occupied by the regular flow regime (where $\Omega_R < \Omega < \Omega_I$, see Fig. 1), tends to increase with increasing Ω, until at $\Omega = \Omega_I$ the quantity *m* has that value for which the azimuthal scale of the horizontal flow pattern (namely the mean circumference of the annulus divided by *m*) is about 1·5 times the radial scale. Then the motion undergoes a transition to the so-called regime of irregular flow, where $\Omega > \Omega_I$ in parameter space, which is an example of thermally driven 'geostrophic turbulence'.

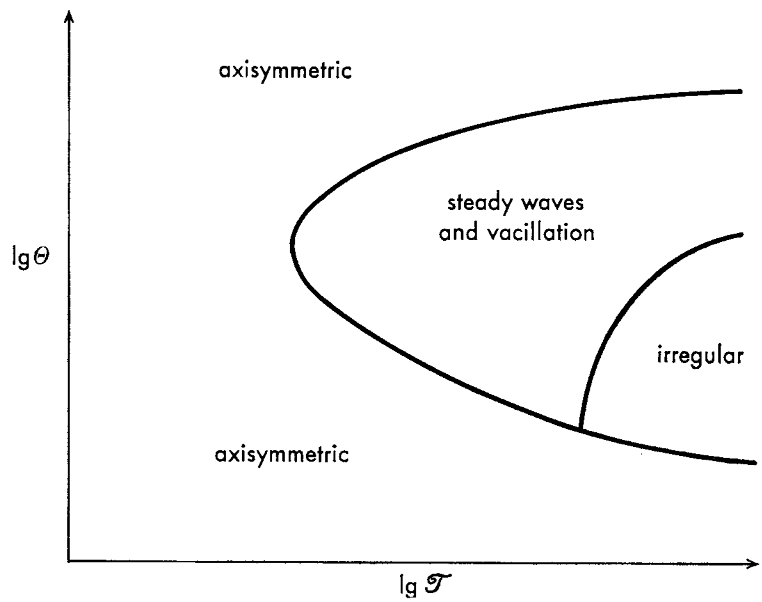

Figure 1. Schematic diagram illustrating the dependence of the mode of free thermal convection in a rotating fluid annulus under axisymmetric boundary conditions on the two dimensionless parameters found to specify the system, Θ and $\mathscr{T}$ (see equations (12) and (13)).

Many laboratory studies of various aspects of sloping convection have now been carried out. These include measurements of heat transfer, flow structure and regime transitions over a wide range of mechanical and thermal boundary conditions. Numerical studies are playing an increasingly important role in this work, and significant if more limited analytical studies have been made based on the essentially non-linear governing mathematical equations.

These equations are the equations of motion (2), together with the equations of continuity and state for a liquid, respectively

$$\nabla . \boldsymbol{u} = 0 \quad \ldots \quad (3)$$

and

$$\rho = \rho_0 \{1 - \alpha(T - T_0)\} \quad \ldots \quad (4)$$

where T denotes temperature, α denotes thermal coefficient of cubical expansion and ρ_0 is the density at the reference temperature T_0, and the equation of heat transfer,

$$\frac{\partial T}{\partial t} + (\boldsymbol{u}.\nabla)T = \kappa\nabla^2 T + q \quad .. \quad .. \quad .. \quad .. \quad .. \quad (5)$$

where κ is the thermal diffusivity (equal to the thermal conductivity divided by the product of ρ and the specific heat capacity c) and $q\rho c$ is the rate of diabatic heating per unit volume. Across any cylindrical vertical surface r = a constant, where (r, ϕ, z) are cylindrical polar coordinates of a general point, $r = 0$ being the rotation axis (see Fig. 2), and the rate of heat transfer is given by

$$H(r,t) = \int_0^d \int_0^{2\pi} \rho c\left(\kappa\frac{\partial T}{\partial r} + u_r T\right) r \, \mathrm{d}\phi \, \mathrm{d}z \quad .. \quad .. \quad .. \quad .. \quad (6)$$

where the fluid extends in the axial direction from $z = 0$ to $z = d$. It is important to notice that the geostrophic contribution to the advective heat flow term on the right-hand side of equation (6) would vanish if the flow were axisymmetric, since by equation (1) u_r, the r component of $\boldsymbol{u} = (u_r, u_\phi, u_z)$, satisfies $u_r \doteqdot (2\rho\Omega r)^{-1}\, \partial p/\partial\phi$. This result points to the *raison d'être* of the non-axisymmetric regime of flow found when $\Omega > \Omega_R$; geostrophic flow cannot convey heat perpendicularly to the axis of rotation unless it is non-axisymmetric!

The boundary conditions on $\boldsymbol{u}$ under which equations (2), (3), (4) and (5) must be satisfied are that $\boldsymbol{u} = 0$ at a rigid bounding surface and that the stress should vanish at a free surface. The thermal boundary conditions require continuity of heat flow which, at a bounding surface, is purely conductive and proportional to $\kappa\nabla T$. When the boundary conditions on the side-walls at $r = r^*$, where $r^* = a$ or b (say, with $b > a$, see section 4 below), are combined with the geostrophic relationship given by equation

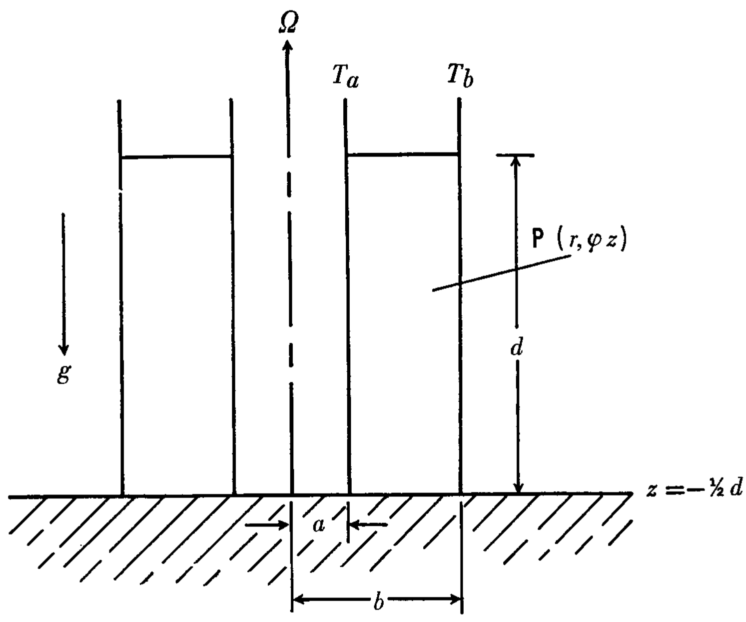

Figure 2. Schematic diagram of a rotating fluid annulus subject to a horizontal temperature gradient. (See Hide 1958 or Hide and Mason 1975 for further details.)

(1) and used in conjunction with the standard relationship for the radial flow in the Ekman boundary layers on $z = 0$ and $z = d$ to evaluate the radial heat flow at $r = r^*$ (see equation (6)), it is found (see Hide and Mason 1970) that:

$$H(r^*,t) \doteqdot -\left(\frac{\nu}{\Omega}\right)^{\frac{1}{2}}\left\{\hat{T}(r^*,d,t) - \hat{T}(r^*,0,t)\right\}\left\{\Gamma(r^*,d,t) - \Gamma(r^*,0,t)\right\}. \quad \ldots \quad \ldots \quad (7)$$

Here

$$\hat{T}(r^*,z,t) \equiv \frac{1}{2\pi}\int_0^{2\pi} T(r^*,\phi,z,t)\mathrm{d}\phi \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

and

$$\Gamma(r^*,z,t) \equiv \int_0^{2\pi} U_\phi(r^*,\phi,z,t) r\, \mathrm{d}\phi, \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (9)$$

where $U_\phi(r^*,\phi,z,t)$ is the value of u_ϕ evaluated just outside the viscous boundary layer on $r = a$ or $r = b$, as the case may be. Now it may be shown that $\hat{T}(r^*,d,t) > \hat{T}(r^*,0,t)$ (when $\alpha > 0$, see equation (4)) and that either $\Gamma(r^*,0,t) = -\Gamma(r^*,d,t)$ or $|\Gamma(r^*,0,t)| \ll |\Gamma(r^*,d,t)|$, according as the upper surface is in contact with a rigid lid or is free. Hence,

$$H(r^*,t) = (\text{negative definite quantity}) \times \Gamma(r^*,d,t). \quad \ldots \quad \ldots \quad \ldots \quad (10)$$

This relationship between the heat flow at a side-wall and the line integral of the tangential velocity near the side-wall embodies the arguments used by Hide (1958) to provide a general interpretation of the upper-level flow pattern in the case when $q = 0$ everywhere (see equation (5)), heat being introduced into the system via one of the side-walls and removed via the other side-wall. The corresponding impressed radial temperature gradient has the same sign at all values of r and the upper-level pattern of motion in the regular flow regime consists of a single jet stream meandering in a wavy pattern between the bounding cylinders, with a positive (i.e. 'westerly') azimuthal component when heat enters via the outer side-wall and leaves via the inner side-wall (so that the impressed radial temperature gradient is positive) and a negative ('easterly') component when the radial heat transfer is in the opposite direction, from the inner to the outer cylinder (see Figs 3(a) and 3(b)).

As a further test of equation (10) Hide and Mason (1970) carried out experiments using internal heating, so that the term q in equation (5) is not equal to zero. This was done by passing an alternating electric current through the fluid. Heat could be removed via the inner side-wall, the outer side-wall or both side-walls. The observed upper-surface flow patterns (see Fig. 4) were found to be in good agreement with predictions for these three cases made on the basis of equation (10) (see Figs 3(c), (d) and (e)). In the cases where heat is removed via one side-wall only, $H(r^*,t)$ vanishes at the other side-wall and, by equation (10), the quantity $\Gamma(r^*,d,t)$ must also vanish. For this to happen, $U_\phi(r^*,\phi,d,t)$ will be positive at some values of ϕ and negative at others (or zero at all values of ϕ, as in the axisymmetric regime that occurs when $\Omega < \Omega_R$). Figs 3(c) and (d) show how this requirement can be satisfied by adding closed eddies to the wavy pattern found in the cases when $q = 0$ (cf. Figs 3(a) and (b)).

The most striking case of all studied in the experiments is the one illustrated by Fig. 3(e). Then, heat is removed via both side-walls, implying that the impressed radial temperature gradient changes sign near mid-radius. The corresponding upper-level flow consists of several separate closed eddies each circulating anticyclonically, in accordance with equation (10), with the horizontal flow confined to a narrow jet stream at the periphery of each eddy (see Fig. 4(c)).

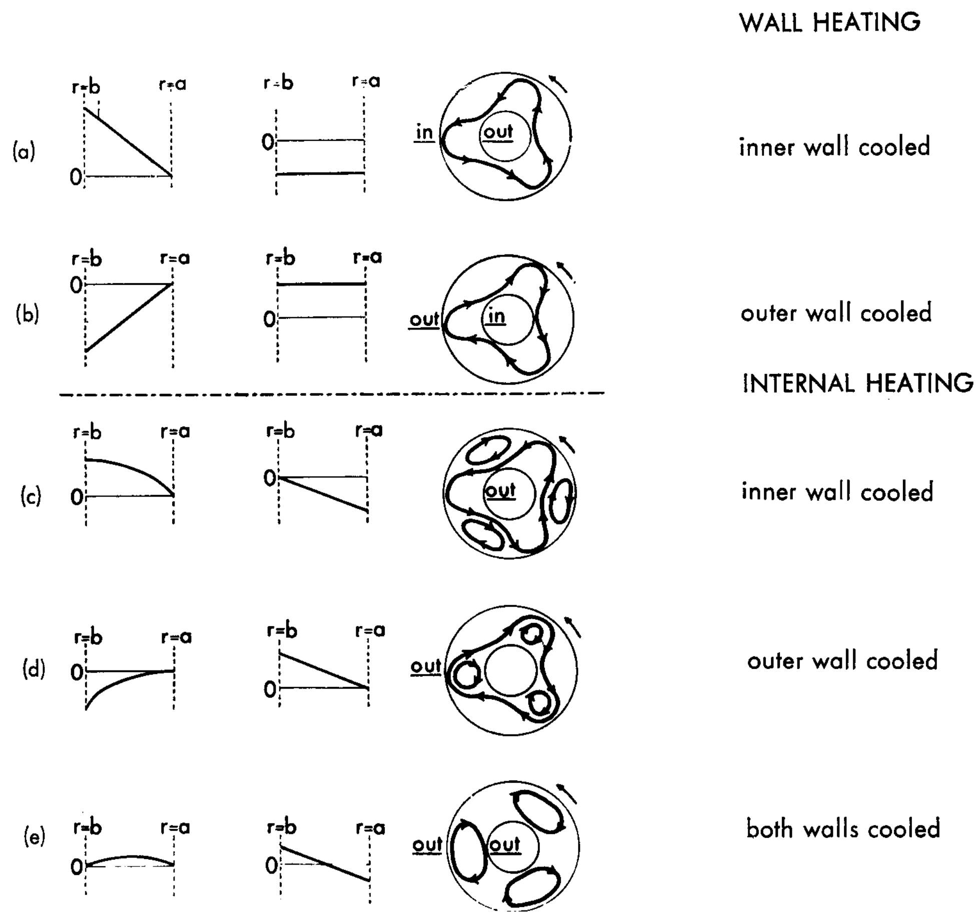

Figure 3. Schematic illustrations of the radial variation of the impressed temperature (left column), of the radial variation of the impressed radial temperature gradient (middle column), and of the corresponding upper-surface relative flow pattern in the regular regime of thermal convection in a rotating fluid annulus (right column), as predicted on the basis of equation (10). (See Hide and Mason 1970 for further details.)

3. Atmospheric flows

The meandering jet streams within which the upper-level tropospheric air flow is mainly concentrated in the Earth's atmosphere are manifestations of sloping convection produced by differential solar heating, which maintains a systematic temperature contrast between tropical and polar regions in each hemisphere. These atmospheric motions are much less regular than those depicted in Figs 3(a), 3(c) and 4(a) (cf. Fig. 5), presumably because the Earth's angular speed of rotation exceeds the critical value Ω_I, although horizontal variations of surface conditions introduce complications which are not yet fully understood.

The atmosphere of the planet Jupiter is heated from below at about the same rate as its upper reaches are heated by solar radiation. Unlike the terrestrial case (where non-solar atmospheric heating is utterly negligible), north–south temperature gradients in Jupiter's atmosphere change sign several times between equator and pole and there is no evidence of any significant systematic temperature contrast

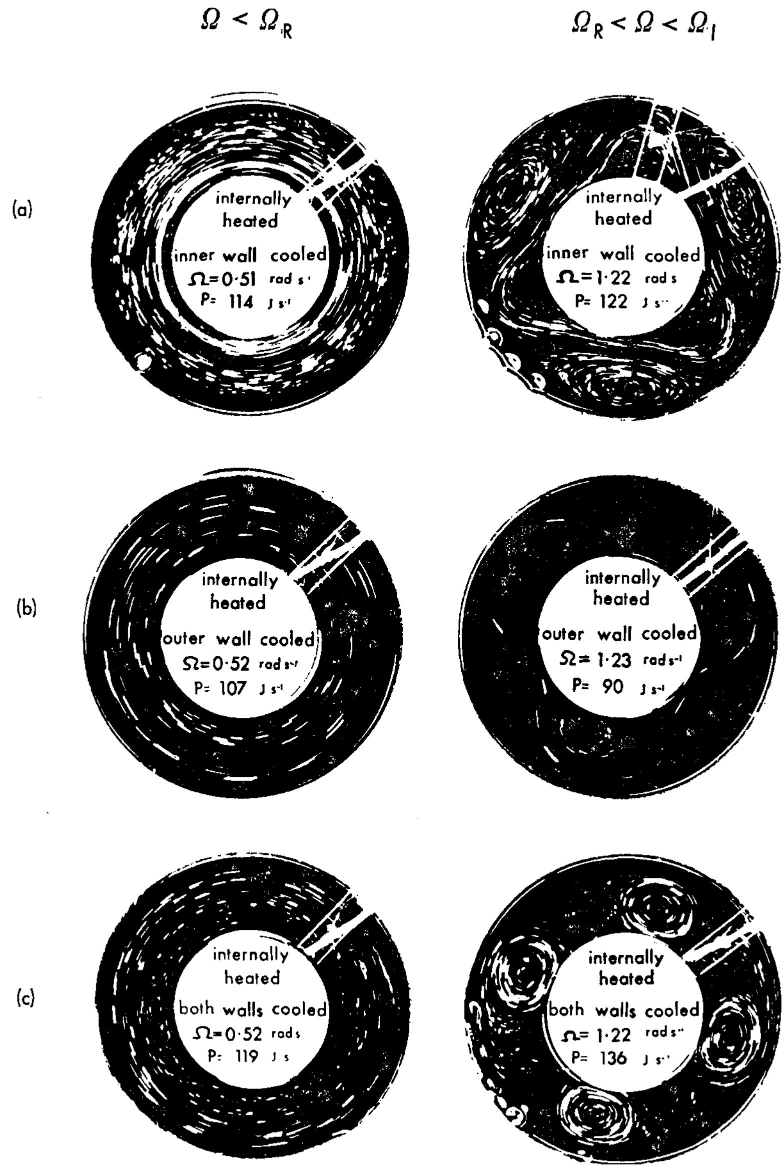

Figure 4. Streak photographs illustrating top-surface flow patterns of thermal convection in a rotating fluid annulus subject to internal heating in the axisymmetric regime (when $\Omega < \Omega_R$, see left column) and regular non-axisymmetric regime (when $\Omega_R < \Omega < \Omega_I$, see right column). They show the dependence of the general characteristics of the flow pattern on the way heat is removed from the system and confirm predictions based on equation (10). The cases (a), (b) and (c) correspond to cases (c), (d) and (e) respectively in Fig. 3. In the most striking case of all (see Figs 3(e) and 4(c)) sloping convection takes the form of closed anticyclonic eddies with the main motion concentrated in a jet stream at the periphery of each eddy. (See Hide and Mason 1970 for further details.)

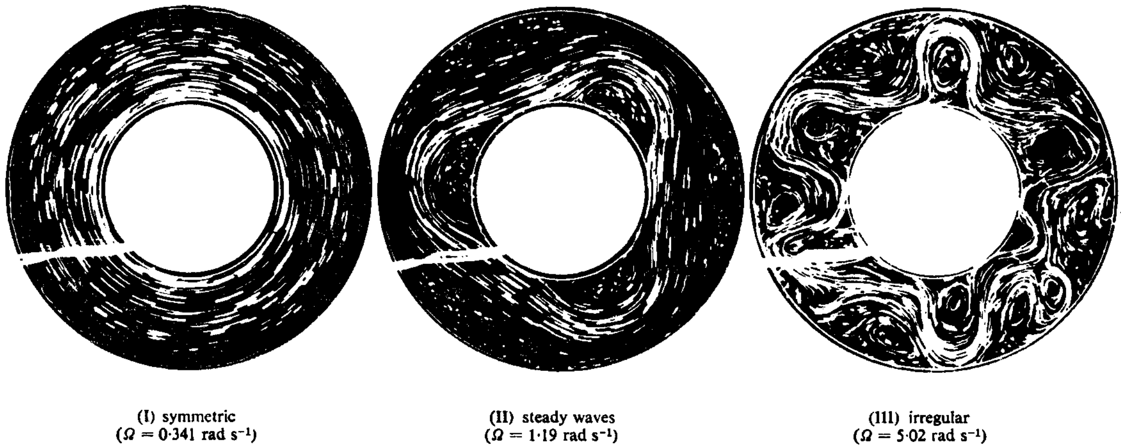

Figure 5. Streak photographs giving one example of each of the main modes of thermal convection in a rotating fluid annulus subject to a radial temperature field of the form given by equation (11), namely (I) axisymmetric flow, (II) regular (steady) non-axisymmetric flow, and (III) irregular non-axisymmetric flow.

between equatorial and polar regions (for references see Ingersoll, Dobrovolskis and Jakosky 1979). There are abundant observations of Jovian atmospheric motions at the upper-cloud level, some of which go back many decades and even longer, and the Pioneer and Voyager space probes have added further details (see Peek 1958, Smith and Hunt 1976, NASA 1979 and Mitchell *et al.* 1981). Our knowledge of what goes on below the cloud level is meagre and this produces difficulties with the interpretation of observations of upper-level atmospheric motions. Indeed, it has been argued elsewhere that the main task of the 'Jovian meteorologist' should perhaps be to use these observations to improve our knowledge of the vertical structure of the planet (see e.g. Hide 1981).

But here is not the place to discuss these observations and review the many interesting though largely controversial issues being debated by those of us who take an interest in the interpretation of the observations in terms of basic dynamical processes. There is, however, one striking phenomenon upon which laboratory experiments on sloping convection in a fluid annulus subject to internal heating might have some bearing. The highly stable closed anticyclonic eddies with the main motion concentrated in a jet stream at the periphery of each eddy that are depicted in Figs 3(e) and 4(c) are remarkably similar dynamically to the long-lived eddies to be seen in Jupiter's atmosphere in the southern hemisphere. The largest, oldest and most conspicuous of these is the Great Red Spot in the South Tropical Zone which may be at least 300 years old. Next in size and age are the three White Ovals that formed in 1939 at the boundary between the South Temperate Belt and the South Temperate Zone, apparently as the residue of the highly irregular South Tropical Disturbance that was first seen in 1901. The smallest of the long-lived eddies are clearly seen in the magnificent Voyager pictures (NASA 1979) as about a dozen oval markings somewhat closer to the pole. The motion in each of these Jovian eddies is anticyclonic and largely confined to a narrow region at the edge of the eddy. It is tempting therefore to suppose (Hide 1980) that the eddies are manifestations of sloping convection in Jupiter's atmosphere, implying that they derive their kinetic energy directly from the potential energy due to the action of gravity on density variations produced by internal and solar heating and that they transport heat from the interior to the edges of the latitudinal bands in which they arise. (See Plate I.)

Preliminary calculations indicate that there is nothing unreasonable about this hypothesis so far as its implications for the vertical structure and other properties of Jupiter's atmosphere are concerned, but a detailed examination of these implications and a critical comparison of the hypothesis with other proposals as to the nature of the long-lived anticyclonic eddies will have to be considered elsewhere. The hypothesis raises a number of fluid-dynamical questions to be resolved by further laboratory and numerical work and some of this is now in hand. Amongst these questions is that of the instability of the strongly sheared flow in the jet stream itself. Experiments with a wall-heated annulus (Hide 1958) provide some evidence that when viscous effects are sufficiently small the jet stream develops local instabilities on one side but not on the other. Pictures of Jupiter show highly irregular flow on a comparatively small scale just outside the Great Red Spot (and the other long-lived eddies), but not on the inside. It will be important to establish by experiment and theory (cf. Narasimha 1980) whether this highly irregular flow arises as a result of a 'one-sided' instability of the jet stream at the edge of the main eddy.

4. Appendix: Regimes of thermal convection in a rotating fluid annulus

The simplest system in which controlled and reproducible experiments on sloping convection have been carried out is the annular apparatus illustrated in Fig. 2 when there are no internal sources of heat (i.e. $q = 0$, see equation (5)) but the bounding cylindrical side-walls in $r = a$ and $r = b$ are maintained at different temperatures T_a and T_b respectively, so that the impressed temperature field satisfies

$$T_i = \{T_b \ln(r/a) - T_a \ln(r/b)\}/\ln(b/a), \quad \ldots \quad (11)$$

which simplifies to $T_i = \frac{1}{2}(T_b + T_a) + (T_b - T_a)\{r - \frac{1}{2}(a+b)\}/(b-a)$ when $(b - a) \ll \frac{1}{2}(b + a)$. Accurate determinations of the principal spatial and temporal characteristics of the fields of temperature and flow velocity over a wide range of precisely specified and carefully controlled experimental conditions led to the discovery of several fundamentally different free types of flow, only one of which is symmetrical about the axis of rotation (see Figs 5 and 6). The general character of the flow evidently depends largely on the values of certain external dimensionless parameters,

$$\Theta \equiv gd\Delta\rho/\bar{\rho}\Omega^2(b-a)^2 \quad \ldots \quad (12)$$

and

$$\mathcal{T} \equiv 4\Omega^2 L^4/\nu^2 \ldots \quad \ldots \quad (13)$$

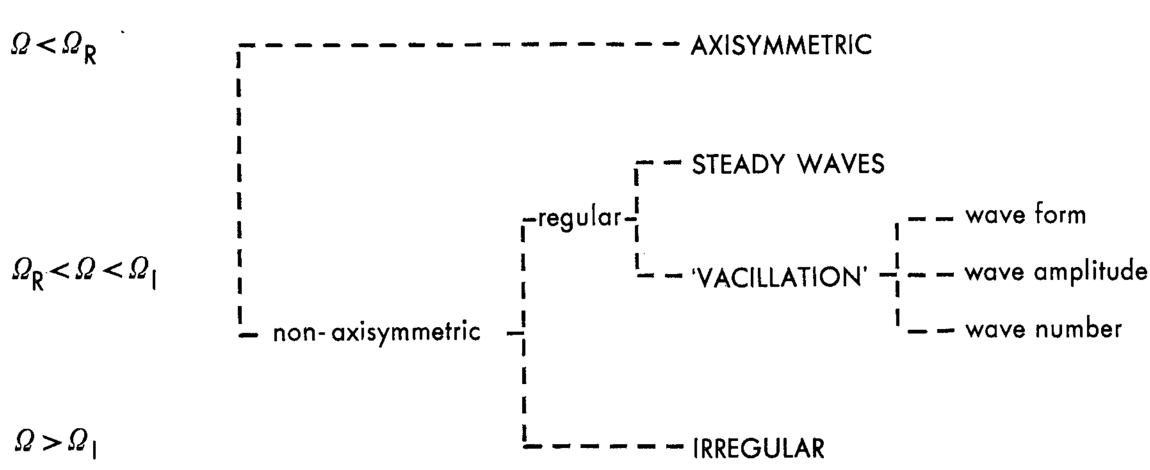

Figure 6. Broad classification of modes of free thermal convection in a rotating fluid annulus under axisymmetric boundary conditions. (See Hide 1958 or Hide and Mason 1975 for further details.)

Here g denotes the acceleration due to gravity (which is typically very much greater than $\Omega^2 b$), d is the depth of the liquid in the annular container, $\Delta\rho$ is the density contrast associated with the impressed temperature difference, i.e. $|\rho(T_a) - \rho(T_b)|$, $\bar{\rho}$ is the mean density, Ω is the angular speed of rotation of the apparatus about a vertical axis, ν is the kinematic viscosity and L, which has the dimensions of a length, is equal to $(b - a)^{5/4}/d^{\frac{1}{4}}$ over a wide range of conditions.

When $\mathscr{T}$ is less than a certain critical value of about 2×10^5 (see Fig. 1), viscosity ensures that the motion is essentially symmetrical about the axis of rotation for all values of Θ. However, when $\mathscr{T}$ exceeds this critical value there exists a range of Θ within which highly non-axisymmetric sloping convection occurs. These non-axisymmetric motions are either regular or irregular (see Fig. 5) depending on the values of Θ and $\mathscr{T}$. The regular flows often exhibit periodic 'vacillation' in amplitude, shape or wavenumber, but under certain conditions these periodic variations are so slight that, apart from a steady drift of the wavy pattern relative to the apparatus, the flow is virtually steady. In sharp contrast to this behaviour, the irregular flows exhibit complicated aperiodic fluctuations in both space and time.

Consider an experiment in which all the impressed conditions are kept fixed except Ω, which is increased in steps from low values to high values. This can be represented by a series of points on a straight line inclined at 45° to the $\mathscr{T}$ and Θ axes in the regime diagram of Fig. 1, moving from the upper left part of the diagram to the lower right. The critical value Ω_R of Ω corresponds to the point where the transition from axisymmetric to regular non-axisymmetric flow occurs and the critical value Ω_I to the point where the transition from regular to irregular non-axisymmetric flow occurs.

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Meteosat water vapour imagery

By J. R. Eyre

(Meteorological Office, Bracknell)

Summary

The Meteosat radiometer includes a channel for measuring radiation emitted mainly by water vapour in the middle and upper troposphere. The interpretation of images produced by this instrument is discussed and applications, both quantitative and qualitative, for the data obtained from the water vapour channel are reviewed.

1. Introduction

Radiometers carried on meteorological satellites can be considered as divided into two types—imagers and sounders. Conventional imaging instruments operate at wavelengths for which the atmospheric absorption is low and provide 'pictures' of the underlying surfaces—land, sea or cloud top—with very little atmospheric attenuation. Examples of such instruments on recent satellites are the visible and infra-red channels of the Advanced Very High Resolution Radiometer (AVHRR) on the TIROS-N series (Schwalb 1978), which has a resolution of *c.* 1 km, and the visible (VIS) and 11 μm infra-red (IR) channels of Meteosat, which have respective resolutions of *c.* 2·5 km and *c.* 5 km at the sub-satellite point (European Space Agency 1978). On the other hand, the wavelengths used by sounding instruments are such that most of the radiation measured has been emitted by the atmosphere itself. Emission from gases of known concentration, such as carbon dioxide and oxygen, can be used to estimate atmospheric temperature, while information on the variable concentration profiles of constituents such as water vapour can be deduced from measurements at the wavelengths of their absorption bands. The High-resolution Infra-Red Sounder (HIRS) on the TIROS-N series is an example of this type of instrument (Schwalb 1978, Smith *et al.* 1979). It has three channels principally for sounding tropospheric water vapour with a horizontal resolution of about 30 km.

However, the distinction between imagers and sounders cannot be carried too far, since the data from sounding instruments can often be built up into images (though usually with a resolution inferior to that of conventional imagers). In this way water vapour sounding channels can produce 'water vapour images', which provide opportunities for studies of atmospheric motions not previously available. Sounding instruments on several satellites have yielded water vapour images in the 6·3 μm water vapour band. (See, for example, Martin and Salomonson 1970, Steranka *et al.* 1973 and Kästner *et al.* 1980.) The Meteosat 6·3 μm water vapour (WV) channel possesses sounding characteristics similar to those of 6·3 μm channels on earlier satellites, sensing radiation emitted mainly by water vapour in the middle and upper troposphere. In addition it provides images of high horizontal resolution equal to that of the IR channel and was the first such channel to be used on a geostationary satellite (Morel *et al.* 1978). An example of a Meteosat WV image is given in Plate II.

2. Radiative transfer theory for the Meteosat WV channel

The radiance emitted at the top of a non-scattering atmosphere at zenith angle θ and wave number ν is given by the radiative transfer equation:

$$R_\nu = (I_0)_\nu\, \tau(\nu,\theta,z_s) + \int_{z_s}^{\infty} B\Big\{\nu,T(z)\Big\} \frac{d\tau(\nu,\theta,z)}{dz}\, dz \quad \ldots \quad (2.1)$$

$$= (I_0)_\nu\, \tau(\nu,\theta,z_s) + \int_{z_s}^{\infty} B\Big\{\nu,T(z)\Big\} K(\nu,\theta,z)\, dz \quad \ldots \quad (2.2)$$

$$= (I_0)_\nu\, \tau(\nu,\theta,z_s) + \int_{z_s}^{\infty} C(\nu,\theta,z)\, dz \quad \ldots \quad (2.3)$$

$B\{\nu,T(z)\}$ is the Planck function corresponding to the atmospheric temperature $T(z)$ at height z and is given by

$$B\{\nu,T(z)\} = \frac{c_1\nu^3}{\exp\{c_2\nu/T(z)\} - 1},$$

where c_1 and c_2 are constants. $\tau(\nu,\theta,z)$ is the transmittance of an atmospheric path at zenith angle θ from height z to space, $(I_0)_\nu$ is the radiance from the surface (land, sea or cloud top), and the integration is performed from the surface at height z_s to space.

In (2.2) we have defined a 'weighting function', $K = d\tau/dz$, and in (2.3) we have defined a 'contribution function', $C = BK$. It can be seen that the second term in these equations is a weighted integral of the Planck function profile and that the appropriate weighting is given by K, the derivative of the transmittance profile with respect to height.

$\tau(\nu,\theta,z)$ is related to the concentration of absorbing gas by the equation,

$$\tau(\nu,\theta,z) = \exp\{-\sec\theta \int_{z}^{\infty} k(\nu,z)\, c(z)\, \rho(z)\, dz\}, \quad \ldots \quad (2.4)$$

where $k(\nu,z)$ is the absorption coefficient ,$c(z)$ is the mass mixing ratio profile and $\rho(z)$ is the atmospheric density profile.

In spectral regions sensed by the Meteosat WV channel (*c.* 1400–1750 cm^{-1}) the dominant absorbing gas is water vapour. Therefore the transmittance profile and hence the weighting and contribution functions depend on the vertical humidity profile through (2.4). This is illustrated in Fig. 1 for an atmosphere of standard temperature profile and three different values of tropospheric relative humidity. The curves shown represent values appropriately averaged over the WV channel spectral pass-band. It can be seen that for a given temperature profile an increase in humidity decreases the transmittance to space and so raises the height of the weighting function peak. In most cases the temperature profile decreases monotonically with height in the region of the weighting function and so the result of an increase in humidity is a decrease in the measured radiance, conventionally shown by a lighter shade of grey on the image. Therefore the WV channel radiance can be used to estimate the humidity of the middle and upper troposphere (if the temperature profile is known). The images can also be used qualitatively to identify areas of high and low relative humidity (light and dark shades of grey respectively).

If the underlying surface is below about 800 mb, then for the majority of atmospheric profiles the first term in (2.1) may be neglected. However, if there is cloud at levels around or above the peak of the cloud-free weighting functions, then the cloud top will make a significant contribution to the radiance. For this reason high clouds such as cirrus and cumulonimbus tops stand out on the WV image as they would on the IR image, but low-level clouds do not appear.

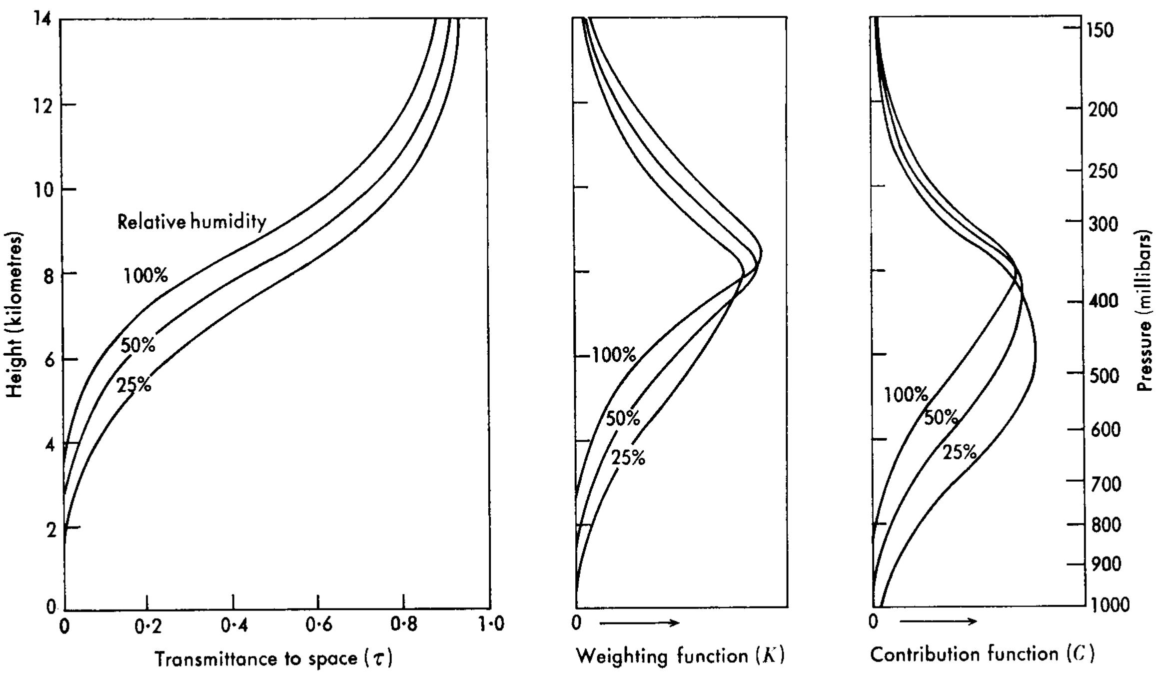

Figure 1. Meteosat water vapour channel transmittance, weighting function and contribution function for a range of relative humidities.

3. Quantitative uses of Meteosat WV channel data

(a) *Humidity of the upper troposphere*

The radiative transfer theory given above defines the relationship between radiance and humidity. From one radiance only it is not possible to retrieve a complete vertical humidity profile, but we can use it to estimate the mean relative humidity of the upper troposphere. This is the approach to be used by the European Space Operations Centre (ESOC) at Darmstadt to derive the Meteosat 'upper tropospheric humidity product' (European Space Agency 1980) and it has been used with 6·3 μm data from other satellites to estimate global water vapour budgets (e.g. Raschke and Bandeen 1967). An example of ESOC's product is shown in Fig. 2.

An alternative approach is to use a humidity profile forecast by a numerical model as a first guess and to adjust this profile until it gives agreement with the measured radiance. This method is being investigated at the Meteorological Office, using Meteosat WV channel data (Eyre 1981). Similar methods can be applied to other water vapour sounding channels such as those of HIRS.

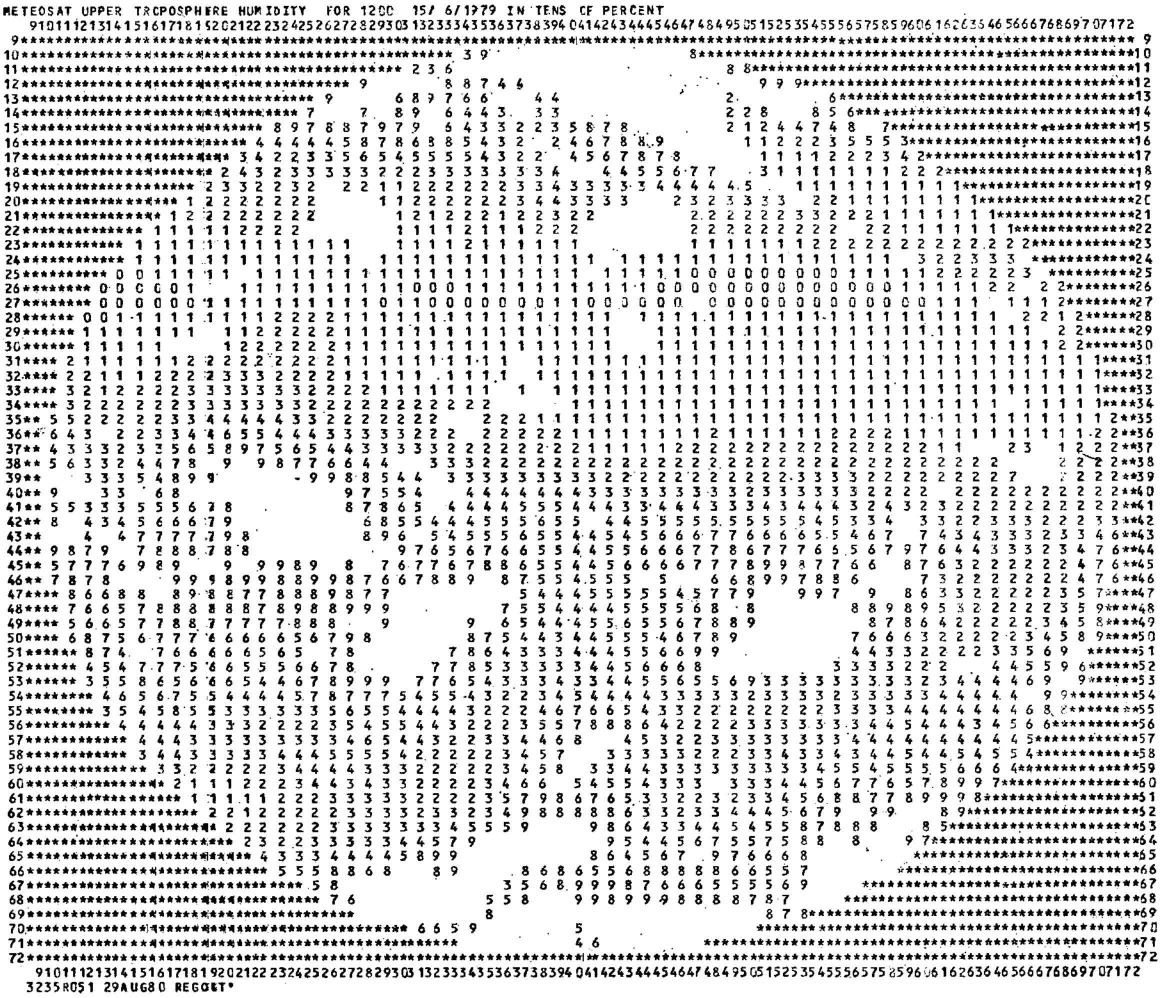

Figure 2. An example of plotted upper tropospheric humidity results.

These techniques are most easily applied in cloud-free regions. The presence of high- or medium-level cloud leads to complications, but if the cloud-top heights and radiative temperatures are known independently (e.g. using the IR channel) then the humidity above the cloud may be estimated from the WV channel radiance. For semi-transparent clouds there is the further complication of cloud emissivities differing significantly from unity, particularly around 11 μm, which makes the estimation of cloud height uncertain. In such cases accurate humidities cannot be found, but the WV channel radiance may be used to improve the estimate of the cloud height (Cayla and Tomassini 1978).

(b) *Winds*

Data from conventional imaging channels on geostationary satellites are used to follow cloud movements using sequences of images to find 'cloud motion vectors', which in many cases are directly related to winds (European Space Agency 1980). It may be possible to extend techniques to track 'features' in the WV image (Kästner *et al.* 1980, Eigenwillig and Fischer 1980). In cloud-free regions such features represent horizontal gradients in the humidity field. By tracking them and assuming that they move with the wind speed, horizontal winds in the clear air can be estimated. Difficulties arise because the Meteosat WV image is noisier than the IR image and also because the clear-air water vapour structures tend to be less clearly defined—they do not have sharp edges in the WV image. These characteristics adversely affect the calculation of motion vectors by automatic pattern correlation techniques. Also, the motion vectors calculated correspond to the average winds of rather broad layers represented by the contribution functions.

The WV channel radiances have also been used operationally in the process of assigning heights to semi-transparent high cloud tracked using the IR image since, for reasons given above, the IR radiance alone does not lead to accurate height assignment in such cases.

(c) *Vertical motion*

If it is possible to track a clear-air feature from one image to another, then the small change in the mean radiance of the feature can be used to estimate the mean vertical motion (Rodgers *et al.* 1976, Eyre 1980). If we can assume that water vapour is a conservative tracer of the motion and neglect wind shear effects, then the change in the contribution to the radiance from each element of the atmosphere is caused mainly by the change in temperature associated with the adiabatic compression or expansion which it experiences during vertical motion. Retrieval of such information is limited to areas where clear-air horizontal motion vectors have been accurately calculated and difficulties arise because large-scale mean vertical velocities in the atmosphere are never greater than a few cm s^{-1}. (1 cm s^{-1} corresponds to a change in WV channel brightness temperature of about 0·4 K h^{-1}.)

4. Qualitative uses of Meteosat WV channel data

None of the quantitative products given above was produced operationally from Meteosat 1 WV channel data. However, the images have been used qualitatively in a number of ways. They add to the data from other channels and other satellites which are available to forecasters, and since they represent radiation originating in the middle layers of the atmosphere they provide useful information on the flow patterns at these altitudes and often reveal features not apparent in conventional imagery or other meteorological observations.

At present our understanding of the synoptic interpretation of features in the WV imagery is limited. Upper tropospheric vortices can be seen and readily interpreted (Houghton and Suomi 1978). Also the long waves in the flow are usually evident from the bands in the image—bands which are often continuous over thousands of kilometres and identifiable for many days. However, a more careful analysis is required here since these bands cannot be directly associated with streamlines. Since in the clear air the water vapour is a conservative tracer of the motion, a band usually contains air originating from the same air mass. The band has been created and distorted by the divergence of the trajectories and in this way shows the recent history of the flow. Thus sequences of images reveal trajectories but a single image does not necessarily show the instantaneous flow. In addition, parts of the band will change in brightness because of vertical motion, as explained above. This complicates the interpretation but also provides qualitative information on the vertical motion field.

Of particular interest in WV images are narrow, dark bands in high and mid-latitudes associated with jet streams (Martin and Salomonson 1970, Ramond and Tjasyono 1979). Their darkness indicates that we are 'seeing' comparatively deep into the troposphere and confirms the existence of very dry bands of air, often of stratospheric origin, which have descended on the poleward side of a jet stream. Thus the images provide a new source of data for studying the development and dynamics of jet streams and can be used operationally for jet stream location.

An example of such a dark band is shown across England in the WV image of 1230 GMT on 15 August 1978 (Plate III). The jet core was around 250 mb, and the 1200 GMT 250 mb analysis is shown for comparison in Fig. 3. It can be seen that the conventional analysis is in good agreement, with respect to both the position and shape of the jet, with the assumption that the jet axis lies close to the southern edge of the dark band. In fact it may be possible in such cases to deduce the details of the jet more accurately from the WV image than from the limited number of wind observations available, even where the conventional observing network is good. In data-sparse areas the image is obviously of even greater value. For the case given here the corresponding VIS and IR images did not give a clear indication of the jet stream position.

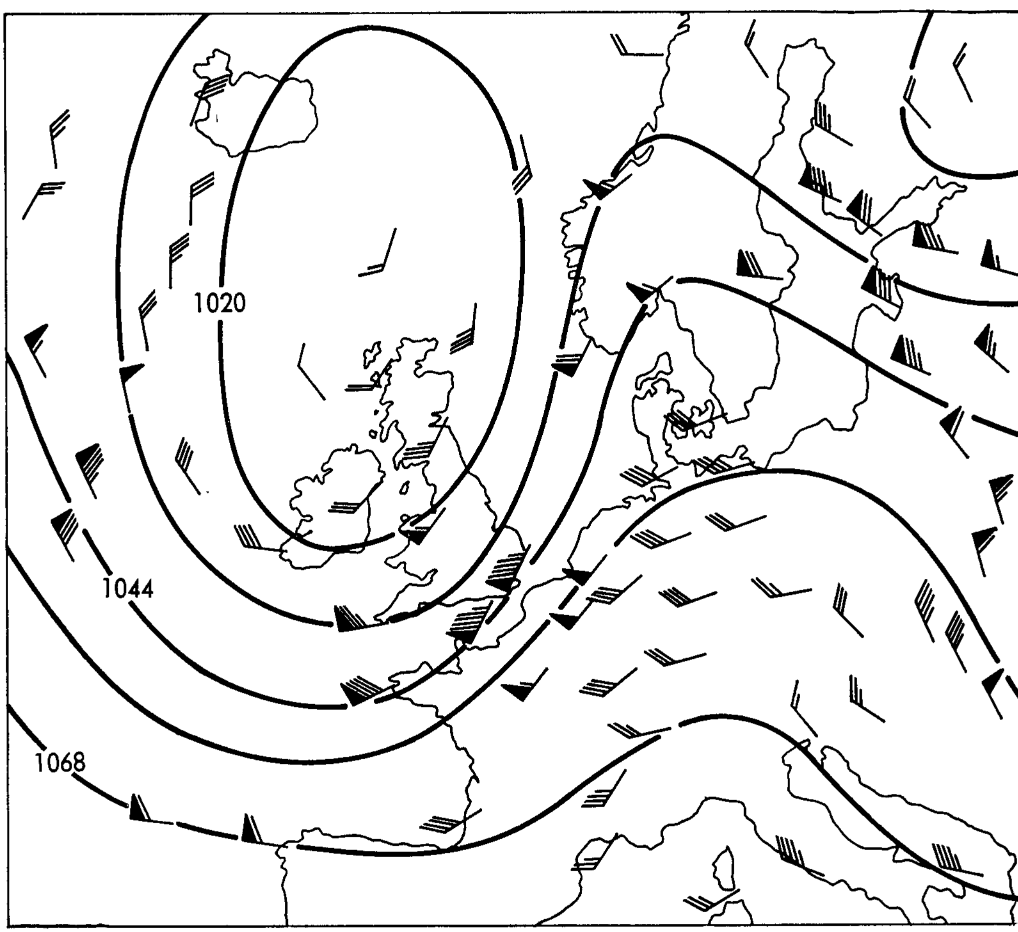

Figure 3. 250 mb analysis for 1200 GMT on 15 August 1978 (isopleths in decageopotential metres, wind speeds in knots).

5. Concluding remarks

The water vapour channel on Meteosat 1 was a considerable success, providing data of a new kind with applications in operational forecasting and research. The value of this channel on future satellites is likely to be greater still as our skill in interpreting the imagery improves and methods are developed for extracting useful products from the data.

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551.5(09):551.507.321.2

One hundred years ago: a ballooning tragedy

By R. P. W. Lewis

(Meteorological Office, Bracknell)

On 13 December 1881 Robert H. Scott, Secretary to the Meteorological Council, wrote to the War Office as follows:

I REGRET to have to inform you that on Saturday last the balloon "Saladin" was caught by a gust of wind on the coast at Bridport, broke away, and was carried out to sea.*

I enclose a copy of a report of the occurrence by Captain Templer, from which you will see that the balloon when it escaped carried with it Mr. W. Powell, M.P., who had been assisting Captain Templer in making the observations.

Up to the present time no tidings have been obtained of the balloon or its occupant.

The second half of the nineteenth century was the heroic age of exploration of the upper air when scientists ascended in manned balloons in conditions that were usually unpredictable and often dangerous. Glaisher and Coxwell, in their ascent made in 1862 for the British Association, were lucky to escape with their lives when their balloon ascended to over 30 000 feet and the cord controlling the release valve became tangled. In 1879 Captain James Templer, then of the Royal Middlesex Rifles, who was an experienced balloonist and was engaged in making experimental ascents both privately and on behalf of the War Office, expressed to the Meteorological Council his wish to make these ascents useful to meteorological science in any way he could. The Council accepted his offer, negotiated with the War Office for the loan of a suitable balloon, and sent Captain Templer a memorandum stating exactly what observations and measurements he ought to make. In the summer of 1881 the balloon 'Saladin' was available, and arrangements were made for Captain Templer to undertake several ascents, his expenses being paid by the Council.

In a full and detailed account of the ascent that ended in disaster, addressed to the Council, Captain Templer wrote:

On Friday, the 9th instant, London being enveloped in a very peculiar fog, I was anxious to ascertain the atmospheric conditions which might have produced it. On that day I was unfortunately detained in the train by the fog, but I determined to make the ascent on the following day, Saturday, December 10th. The balloon "Saladin" was at Bath, so I wrote to you that I would ascend from that place. I took Mr. Walter Powell as my assistant, for the management of the balloon.

Captain Templer had previously written to Dr R. H. Scott as follows:

SIR,

I REGRET to report that on Saturday, the 10th of December, I ascended at Bath, accompanied by Mr. Walter Powell and Mr. Agg Gardner, at 1h. 55m., for the purpose of taking the temperature of the air, and the amount of snow in the air, for the Meteorological Office. I cleared the snow clouds at 4,000 feet altitude; the temperature of these clouds was 28°, and the wet-bulb thermometer read 26°. At 4,200 feet we passd over Wells, the time being 2h. 50m. At this height I worked over Glastonbury; the temperature now rose to 41°, and the sky was perfectly clear. I passed then between Somerton and Landport, and I here found that I was in a N. ½ W. current. I asked Mr. Powell to send the balloon up to 6,000 feet, to ascertain the temperature of a small bank of cirrus. I found this temperature to be 31°, and then I asked

* The *Daily Weather Report* shows a complex trough of low pressure over England and Wales with a shallow depression centred over the Cherbourg peninsula and a ridge extending over Ireland from the west.

him to place me at 2,000 feet altitude, to regain the N. ½W. current, and we then came in view of Crewkerne. I now kept at a low altitude until I reached Beaminster. Mr. Powell here observed that we were going at 30 miles an hour, and here we first heard the roar of the sea. The balloon suddently rose to 4,000 feet. At this time I said to Mr. Powell, "Go down to within 100 feet of the earth and ascertain our exact position." We coasted along close to the ground until we reached Symondsbury. I here called to a man and asked him how far the distance was to Bridport, and he said about a mile. I asked Mr. Powell to prepare to "take in;" our pace now increasing to 35 miles an hour. To avoid the little village of Eype, Mr. Powell threw out some ballast. This took us to 1,500 feet elevation and we had still two miles to get in. I opened the valve and descended about 150 yards short of the cliff. The balloon on touching the ground dragged a few feet, and I rolled out of the car with the valve line in my hand. This caused the balloon to ascend about 8 feet, when Mr. Gardner dropped off, and unfortunately broke his leg. I found that the rope was being pulled through my hands, and I called to Mr. Powell, who was standing in the car, to come down the line. He took hold of the line, and in a few more seconds the line was torn through my hands. The balloon rose rapidly. Mr. Powell waved his hand to me, and I took his compass bearings, and found that he was going in a S. ½ E. direction. Some men coming up, I placed Mr. Gardner in their charge and sent word to the Coastguard and Bridport Harbour-master to keep a good look out, and to go out with boats. I then proceeded to Bridport and telegraphed to the Commanding Officer, Royal Engineers, Weymouth, to have a steamer in readiness for me to go in search. I proceeded to Weymouth and found the S.S. "Commodore" with steam up. I here received a telegram from Bridport Harbour-master saying that a balloon had been seen to drop in the sea south of Bridport. I at once proceeded to sea, searched the alleged place of his descent, making due allowance for the wind and current. This proving unsuccessful, I crossed the Channel till we sighted the Casquets Light, and then returned in a N.W. direction, ultimately reaching Weymouth about 5h. a.m. on Sunday morning, and have organised further search. I am of opinion that what was seen to fall into the sea was not the balloon, but part of the gear, thrown out to lighten the balloon, as the balloon could not have fallen so close to the shore as to be visible at about 5h. p.m.

I have, &c.
(Signed) JAMES TEMPLER,
Captain 7th Batt. King's Royal Rifle Corps.

R. H. Scott, Esq., F.R.S.,
Secretary, Meteorological Office.

The full account referred to above gives various observations and instrumental readings as well as additional details of the final disaster. Mr Powell was an expert and fearless aeronaut and had made more than 20 ascents in 1881; it seems from Captain Templer's account that he could possibly have saved himself by jumping out of the car, which was no more than eight feet from the ground, but perhaps he hoped to be able to land in France and save the balloon as well.

This tragedy brought an effective end to the use of manned balloons for the experimental investigation of the upper air, and development work was concentrated on the making of self-recording instruments to be carried by unmanned balloons and kites.

(Source: Minutes of the Proceedings of the Meteorological Council; 1879, 1880, 1881.)

Reviews

The glaciation of the Ecuadorian Andes, by Stefan Hastenrath. 160 mm × 230 mm, pp. xiv + 159, *illus.* A. A. Balkema, Rotterdam, Netherlands, 1981. Price Hfl 50.00, £10.00.

This attractive book describes the glacial history of the Ecuadorian Andes from the Late Pleistocene to the present, mainly concentrating on present conditions and changes documented in the past few centuries. It will serve as a valuable reference in its area because of its abundant maps, photographs and tabulations of historical sources (which will benefit multilingual readers most). The recent and continuing recession of the Ecuadorian glaciers is shown in the final chapter to be paralleled by recession in tropical glaciers elsewhere in tropical America, Africa and Papua New Guinea.

Although in Chapter 3 the author describes the atmospheric circulation and climate of northern South America, no attempt is made to relate recent glacial changes to any observed long-term meteorological fluctuations that may have taken place. Knowing the complexities of influences on glaciers, the author instead wisely proposes an observation program of glacial heat and mass budget measurements; but at least a listing of available standard meteorological data would be useful for those who might try to relate glacial recession to regional changes of temperature, precipitation and insolation.

The book is a useful contribution to the documentation of world climate and related features: the publication of books of similar quality on other tropical mountain glaciations would be welcomed.

D. E. Parker

Earth's aura: a layman's guide to the atmosphere, by Louise B. Young. 127 mm × 194 mm, pp. xi + 320, *illus.* Penguin Books Ltd, Harmondsworth, Middlesex, 1980. Price £2.50 (paperback), £7.50 (hardback).

The sub-title of this book clearly explains its nature and purpose. It is on the whole a good piece of scientific journalism by an author who is scientifically qualified herself, with research experience at M.I.T., has planned and edited several books of readings for adult education in science, and has been careful to seek the help and advice of acknowledged experts.

Topics dealt with include man's exploration of the atmosphere; the formation of rain, snow and hail; the circulation of chemical elements and compounds; man-made pollution; atmospheric wind-systems; optical effects; cosmic rays; the atmospheres of other planets; and climatic change and variability.

The book has a wealth of interesting quotations from the writings of eminent scientists such as Pascal, Newton, Franklin and Glaisher, diarists and writers such as Evelyn and Dana, glider pilots, and travellers and explorers; these give a feeling of immediate appreciation of the phenomena described as well as a sense of historical development. (The relationship between Descartes, Pascal, Périer, and the proposal and execution of the famous experiment on the Puy-de-Dôme is, however, much more complicated and murky than one would imagine from Mrs Young's rather starry-eyed account. See Middleton's *History of the barometer*, 1964.)

The general attitude is perhaps a little too uncritical: 'Some meteorologists believe that the presence of this [meteor] dust in our atmosphere affects the earth's rainfall'; perhaps some do, but many more do not. The style occasionally boils over into journalese; for example, in speaking of 1976, 'widespread fires raged uncontrolled through forests in France and Britain'; the fires of 1976, though serious, would have been much worse had it not been for the efforts of the fire brigades who, in the circumstances, succeeded remarkably well. Even—or perhaps especially—in a book for laymen, to say merely that the distances of the planets from the sun 'are not to scale' when the relevant diagram (Fig. 10) shows Pluto nine times as far from the sun as Mercury instead of 100 times is unnecessarily misleading; a simple list with actual distances would have been better.

R. P. W. Lewis

Notes and News

New Naval Liaison Officer

We are pleased to welcome Commander David Philpott, R.N., to the Meteorological Office where he has recently taken over from Commander A. S. Watt as the Naval Liaison Officer. Previously Commander Philpott was Officer in Command of the Royal Navy's School of Meteorology and Oceanography. Unfortunately, he has not brought his escort with him to Bracknell. (See Plate IV.)

THE METEOROLOGICAL MAGAZINE

No. 1313 December 1981 Vol. 110

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NOTICES

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Printed in England by Heffers Printers Ltd, Cambridge
and published by
Her Majesty's Stationery Office

£1.80 monthly **Annual subscription £23.80 including postage**

Dd. 716670 K15 12/81

ISBN 0 11 726289 7
ISSN 0026-1149