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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 $\Delta = \partial q_s / \partial T$
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 ($\approx 30 \text{ s m}^{-1}$) 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

$$H_i + \lambda E_i = R_N(i - 1) - R_N(i) \quad \ldots \quad (3)$$

and at the soil surface is

$$H_n + \lambda E_n = R_N(n - 1) - G \quad \ldots \quad (4)$$

The potential of the ith layer for heat transfer is

$$P_i = \Theta_i \rho c_p \quad \ldots \quad (5)$$

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

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

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

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

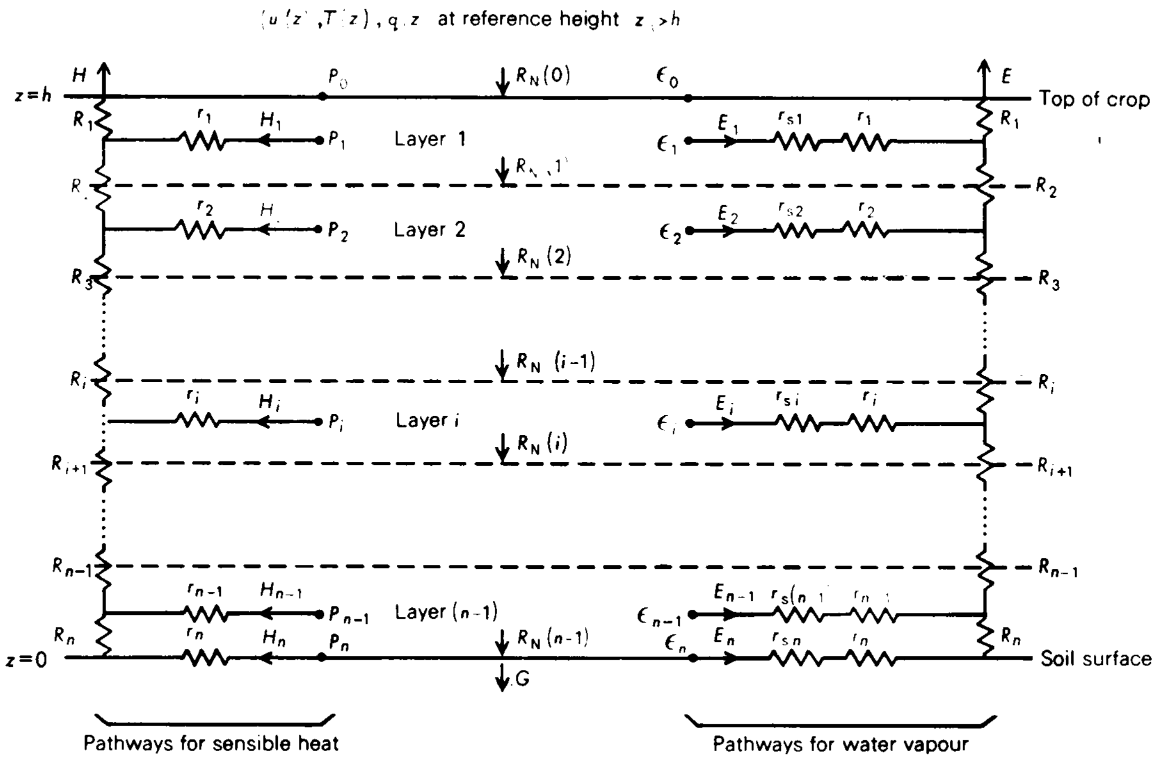

Figure 1. Outline of canopy model.

These equations become after expansion:

$$\left.\begin{aligned}
\rho c_p\Theta_1 &= H_1(r_1+R_1)+R_1H_2+\ldots+R_1H_n\\
&\ldots\ldots\ldots\ldots\\
\rho c_p\Theta_i &= H_1R_1+H_2(R_1+R_2)+\ldots+H_{i-1}(R_1+\ldots+R_{i-1})+\\
&\quad+H_i(r_i+\sum_{p=1}^{i}R_p)+H_{i+1}\sum_{p=1}^{i}R_p+\ldots+H_n\sum_{p=1}^{i}R_p\\
&\ldots\ldots\ldots\ldots\\
\rho c_p\Theta_n &= H_1R_1+\ldots+H_{n-1}(R_1+\ldots+R_{n-1})+H_n(r_n+\sum_{p=1}^{n}R_p)
\end{aligned}\right\} \quad \ldots \quad \ldots \quad (8)$$

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)):

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

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)

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

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)

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

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

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

(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

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

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

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

where ν 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_{s_i} 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

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

(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 $h \ll 10$ 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	Time (GMT) 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*

		Time (GMT) 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.

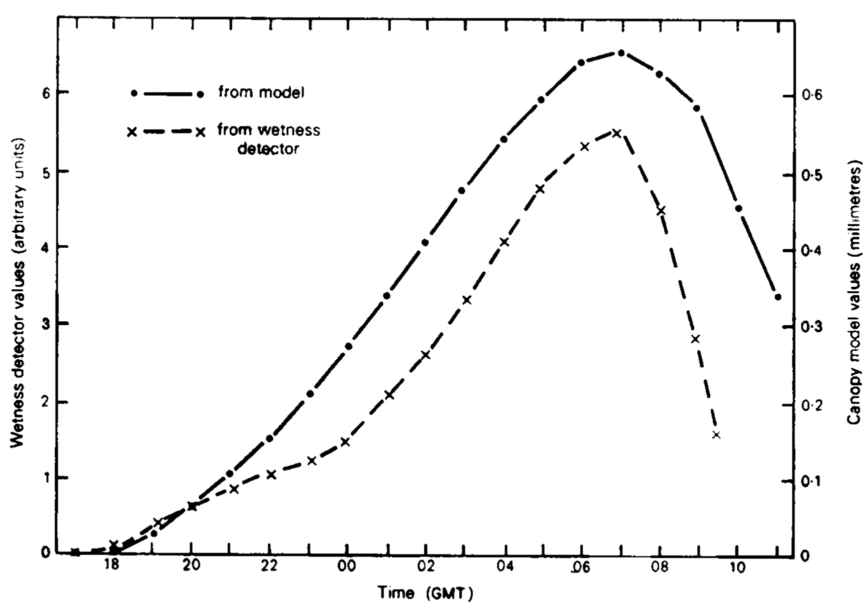

Figure 2. Measured and simulated accumulated surface water, 21–22 March 1957.

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.

References

Adams, R. J. and Seager, Judith M. 1977 Agrometeorological use of the synoptic data bank in plant disease warning schemes. *Meteorol Mag*, **106**, 112–116.

Couturier, D. E. and Ripley, E. A. 1973 Rainfall interception in mixed grass prairie. *Can J Plant Sci*, **53**, 659–663.

Denmead, O. T. 1976 Temperate cereals. Vegetation and the atmosphere, Vol. II (edited by J. L. Monteith). London, Academic Press, 1–31.

Dyer, A. J. and Hicks, B. B. 1970 Flux-gradient relationships in the constant flux layer. *Q J R Meteorol Soc*, **96**, 715–721.

Gadd, A. J. and Keers, J. F. 1970 Surface exchanges of sensible and latent heat in a 10-level model atmosphere. *Q J R Meteorol Soc*, **96**, 297–308.

Grant, D. R. 1975 Comparison of evaporation from barley with Penman estimates. *Agricultural Meteorology*, **15**, 49–60.

Hirst, J. M. 1957 A simplified surface-wetness recorder. *Plant Pathology*, **6**, 57–61.

Hirst, J. M., Long, I. F. and Penman, H. L. 1954 Micrometeorology in the potato crop. Boston, Mass., American Meteorological Society, and London, Royal Meteorological Society. Proceedings of the Toronto Meteorological Conference, 233–237.

Hughes, T., McMullan, J. T., Morgan, R. and Murray, R. D. 1977 On the optimum orientation of solar collectors. *Energy Res*, **1**, 143–156.

Lumb, F. E. 1964 The influence of cloud on hourly amounts of total solar radiation at the sea surface. *Q J R Meteorol Soc*, **90**, 43–56.

Monteith, J. L. 1957 Dew. *Q J R Meteorol Soc*, **83**, 322–341.

1958 The heat balance of soil beneath crops. *Arid Zone Research*, **11**. *Climatology and microclimatology (Proc Canberra Symp, October* 1958*)*. Paris, Unesco, 123–127.

1965 Evaporation and environment. *Proc Symp Exper Biol*, **19**, 205–234.

1973 Principles of environmental physics. London, Edward Arnold.

Monteith, J. L. and Szeicz, G. 1961 The radiation balance of bare soil and vegetation. *Q J R Meteorol Soc*, **87**, 159–170.

Monteith, J. L., Szeicz, G. and Waggoner, P. E. 1965 The measurement and control of stomatal resistance in the field. *J Appl Ecol*, **2**, 345–355.

Paulson, C. A. 1970 The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer. *J Appl Meteorol*, **9**, 857–861.

Penman, H. L. 1948 Natural evaporation from open water, bare soil and grass. *Proc R Soc*, A, **193**, 120–145.

Penman, H. L. and Long, I. F. 1960 Weather in wheat: an essay in micrometeorology. *Q J R Meteorol Soc*, **86**, 16–50.

Smith, L. P. 1962 The duration of surface wetness (a new approach to horticultural climatology). Advances in horticultural sciences and their applications, Vol. III. Oxford, Pergamon Press, 478–483.

Uchijima, Z. 1976 Maize and rice. Vegetation and the atmosphere, Vol. II (edited by J. L. Monteith). London, Academic Press, 33–64.

Utaaker, K. 1966 A study of energy exchange at the earth's surface. *Årbok for Universitet i Bergen, Mat.-Naturv. Serie*, 1966, No 1. Bergen/Oslo, Norwegian Universities Press.

Waggoner, P. E. and Reifsnyder, W. E. 1968 Simulation of the temperature, humidity and evaporation profiles in a leaf canopy. *J Appl Meteorol*, **7**, 400–409.

Webb, E. K. 1970 Profile relationships: the log-linear range and extension to strong stability. *Q J R Meteorol Soc*, **96**, 67–90.

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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 commencing 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.

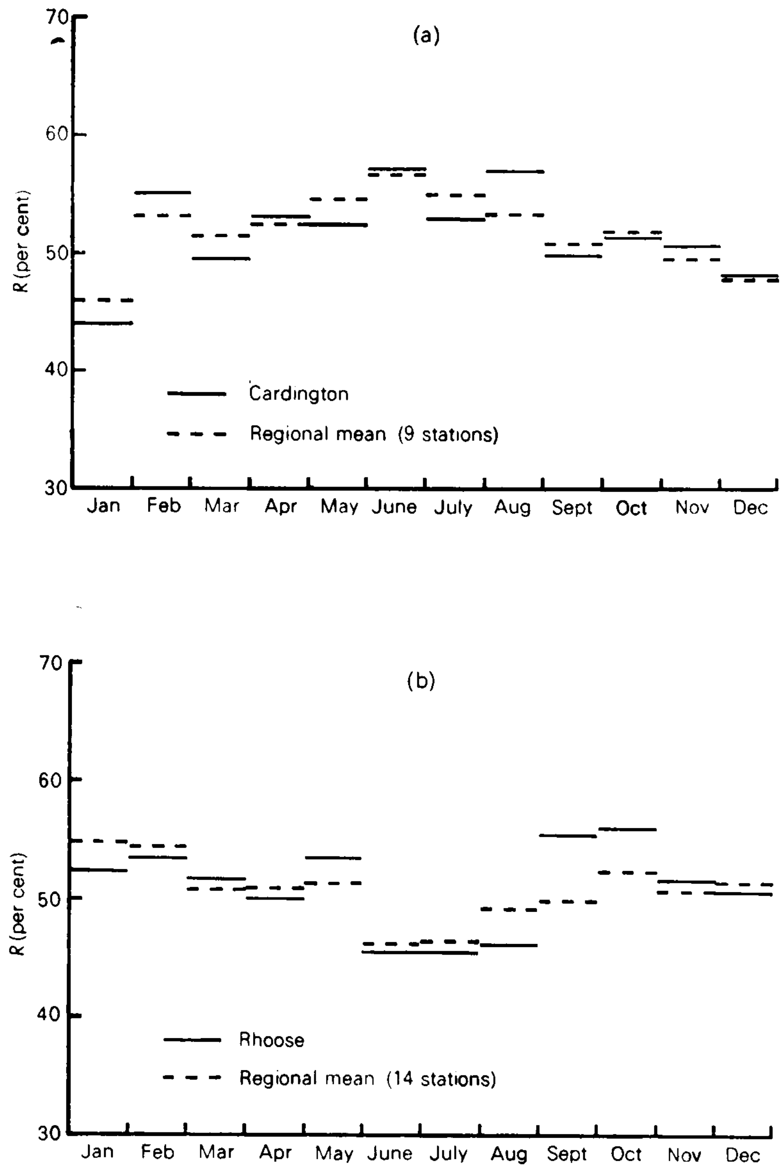

Figure 2. Month-to-month variation of percentage ratio (R) of incidence of wet working days to that of wet rainfall days: (a) inland sites, (b) coaatsl sites.

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)

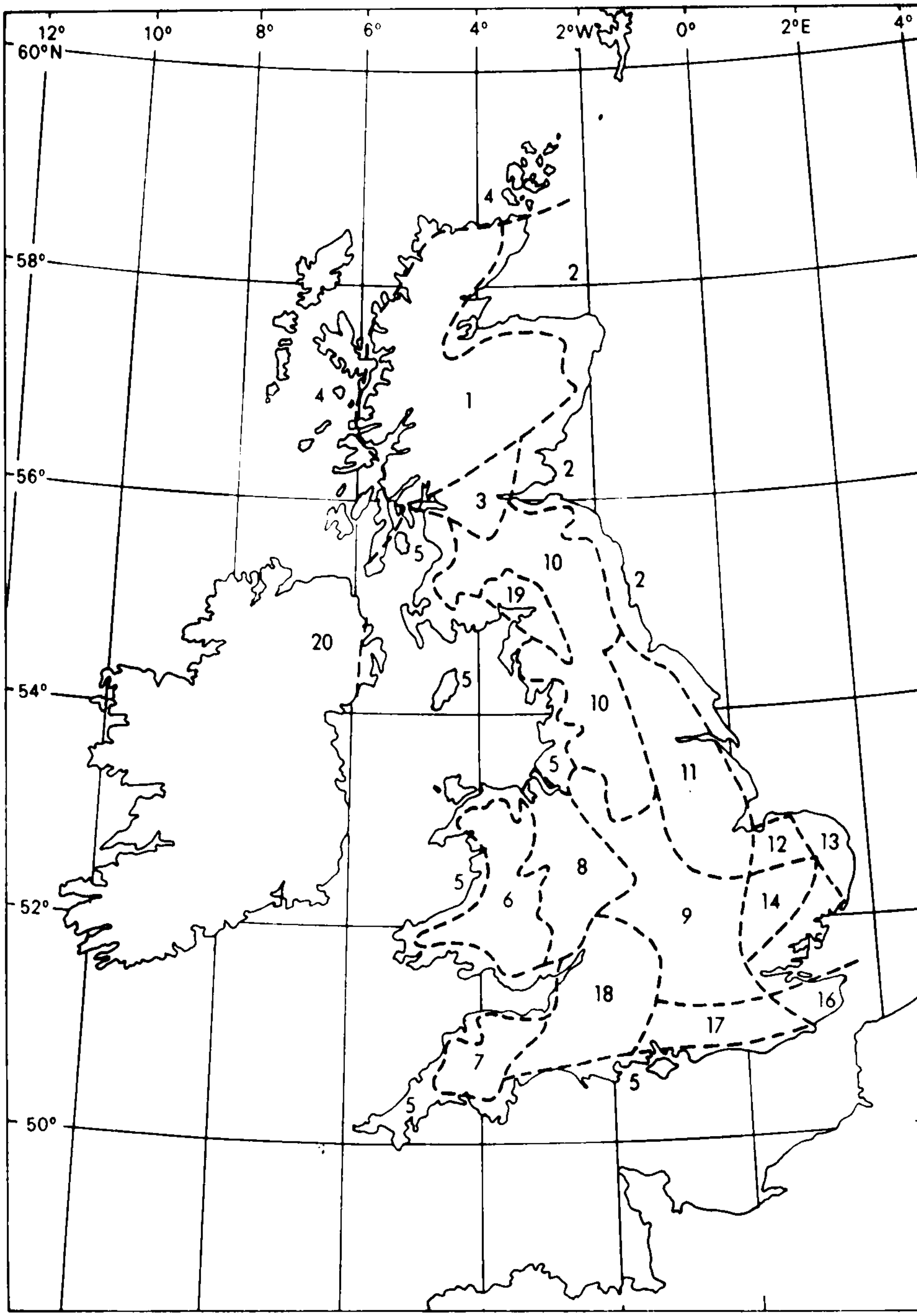

Figure 3. 0900–1800 GMT wet-day cluster analyses. (For the number of stations used for each area, see Table I).

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.

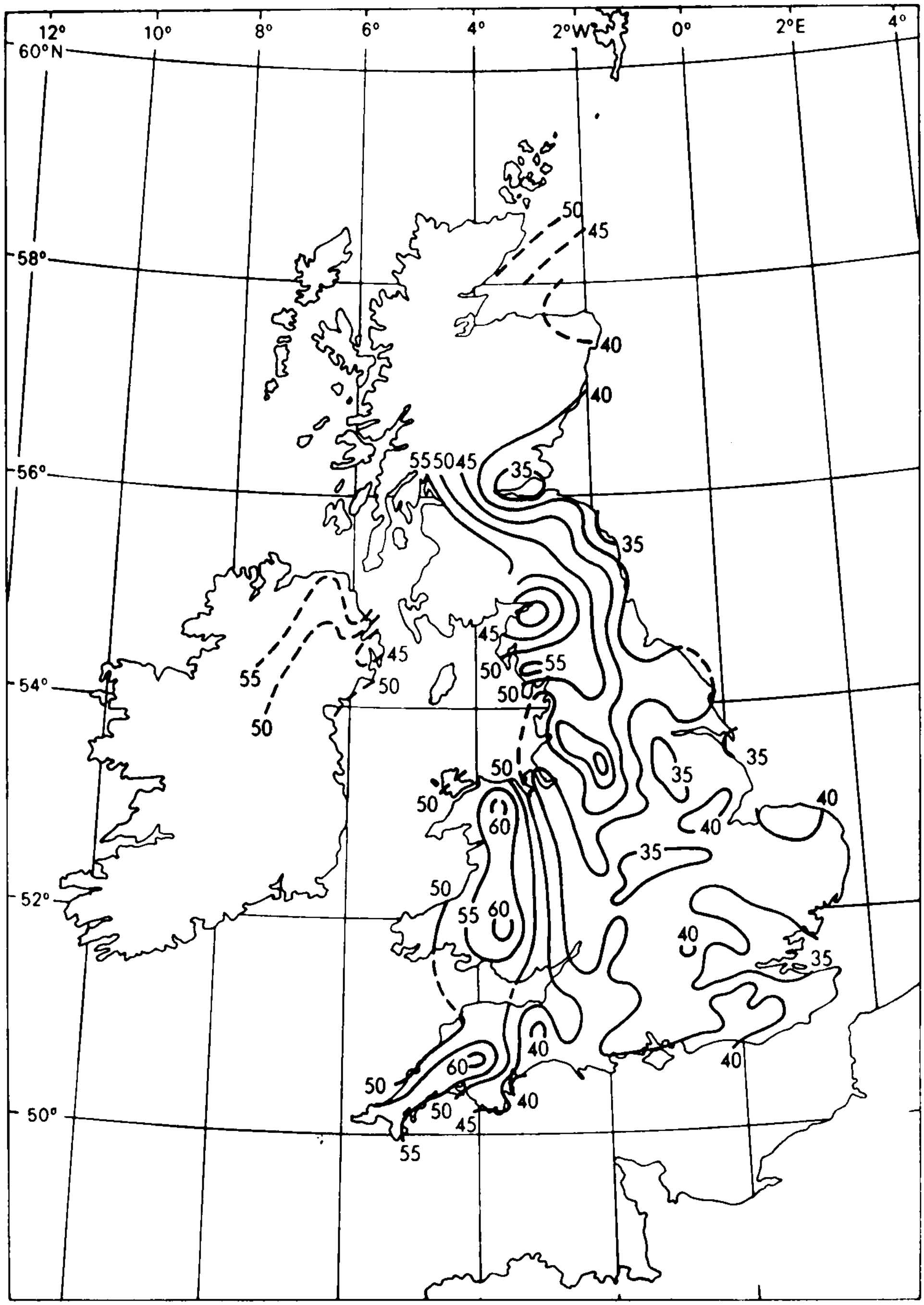

Figure 4. Percentage of wet days to total days in January, 1941–70.

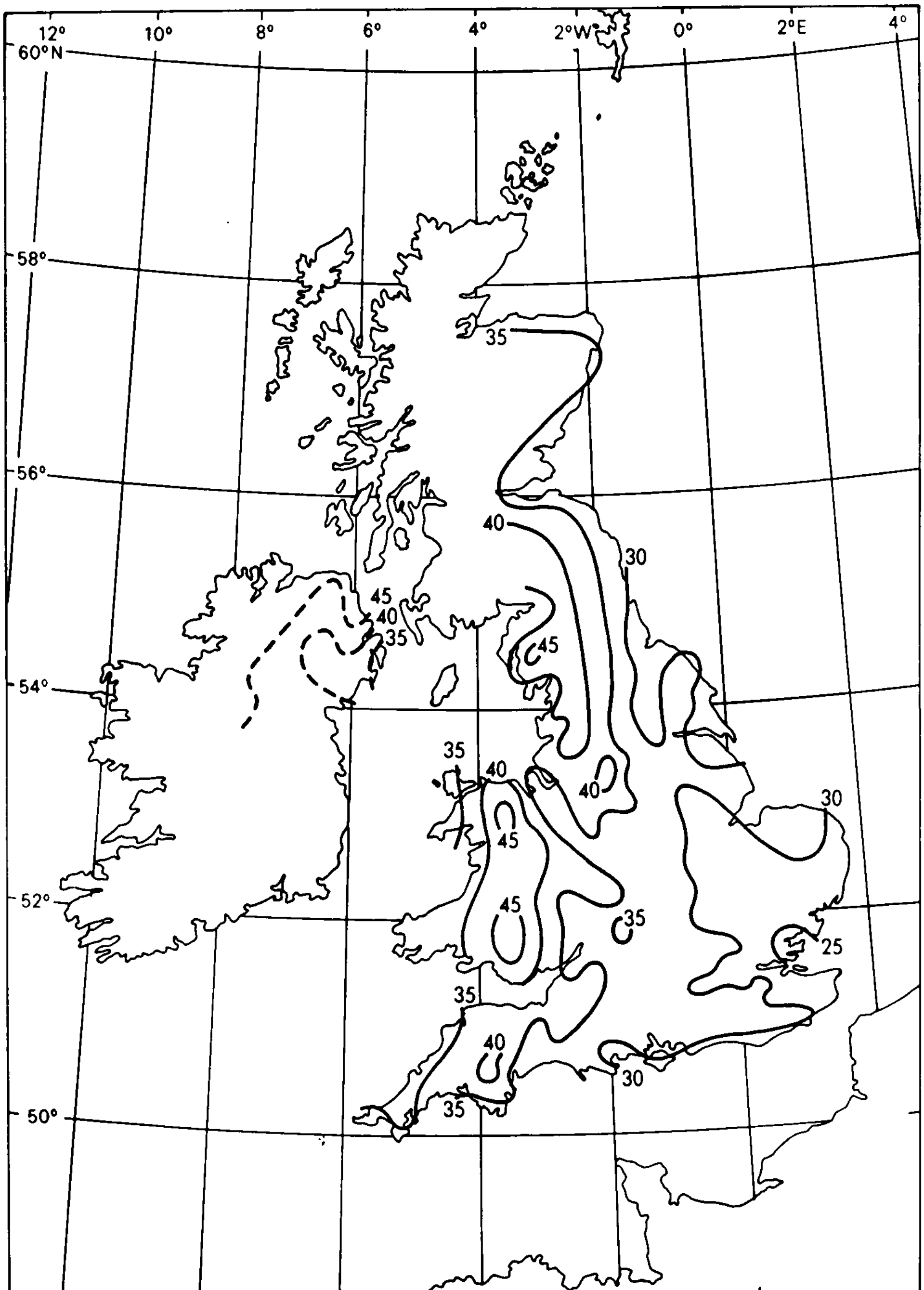

Figure 5. Percentage of wet days to total days in May, 1941–70.

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
Federal Republic of Germany

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CONTENTS

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