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A NOTE ON THE ACCURACY OF RAINFALL FORECASTING USING EXISTING TECHNIQUES IN THE RIVER DEE CATCHMENT AREA

By C. A. NICHOLASS

Summary. Rain data collected as part of the Dee Weather Radar Project over a two-year period have been used to test the accuracy of some existing forecasting techniques. It is shown that the method of Holgate has a fairly high success rate, and that of Lowndes is able to predict heavy rain from westerly types but is less successful with predictions of heavy rain from other types in summer. The method of Benwell is reasonably successful in predicting very heavy frontal rain, but is not applicable to the more frequent, less heavy rainfalls.

Introduction. Recently there has been increasing interest from hydrologists in improved accuracy of forecasting areal rainfall over river catchments and subcatchments (see for example Dee Weather Radar Project, Operations Systems Report[1]). The analysis in this note shows the accuracy which is at present attainable in parts of the River Dee Catchment using three rainfall forecasting techniques.

Techniques investigated. Holgate[2] described the synoptic rules used at the Main Meteorological Office at Preston to forecast rainfall for a number of areas in north-west England and North Wales. The forecasts of rain amounts for the Dee Catchment above Bala are divided into three categories, 5–15 mm, 15–30 mm, and more than 30 mm each within a 21-hour period. The accuracy of these forecasts has been investigated for the period from 1 April 1972 to 31 March 1974 using data collected from the relevant part of a network of 63 rain-gauges distributed over 1000 km^2 of the River Dee Catchment, which were installed by the former Water Resources Board as part of the Dee Weather Radar Project. These data provided a unique opportunity for assessing the techniques.

Lowndes[3,4] has defined the meteorological conditions which should exist if heavy rain is to be expected in the River Dee area. The accuracy of his rules is investigated.

Benwell[5] showed that the jet stream at 500 mb could be used as an indicator of very wet days (days with more than 63·5 mm). Although the number of days with such large amounts is small in the two-year period, on these and other wet days the position of the 500-mb jet stream has been investigated.

Results

Rainfall forecasts for the Dee Catchment above Bala, issued by the Meteorological Office (Holgate[2]). Forecasts for the Dee Catchment above Bala (see Figure 1) are issued as routine by Preston Main Meteorological Office. 'No forecast' implies that less than 5 mm of rain is expected. The synoptic rules used to make these forecasts are summarized in Holgate's paper.

The areal rainfall over the Dee Catchment above Bala has been computed using the interpolation techniques of English.[6] To allow for slight timing errors in the forecasts, the areal rainfall was also calculated for periods displaced by both plus and minus three hours from the issued forecast period.

Table I is a contingency table of forecast and actual rainfall during the period from April 1972 to March 1974, taking the best of the three possible forecast periods. Forecast periods when snow fell or was lying in the gauges, thus making the rainfall estimates unreliable, have been excluded. Also shown in the first column are the occasions when no forecast was issued but more than 5 mm of rain fell.

The table shows that the correct category of rainfall event (excluding forecasts of less than 5 mm) was predicted in 100 out of 198 forecasts issued. Additionally the rain which occured was within one category of that which was forecast on 193 out of 198 (97 per cent) occasions. However, on three occasions more than 15 mm of rain fell when no event was forecast. The table does not show the large number of forecasts of less than 5 mm, the vast majority of which were correct.

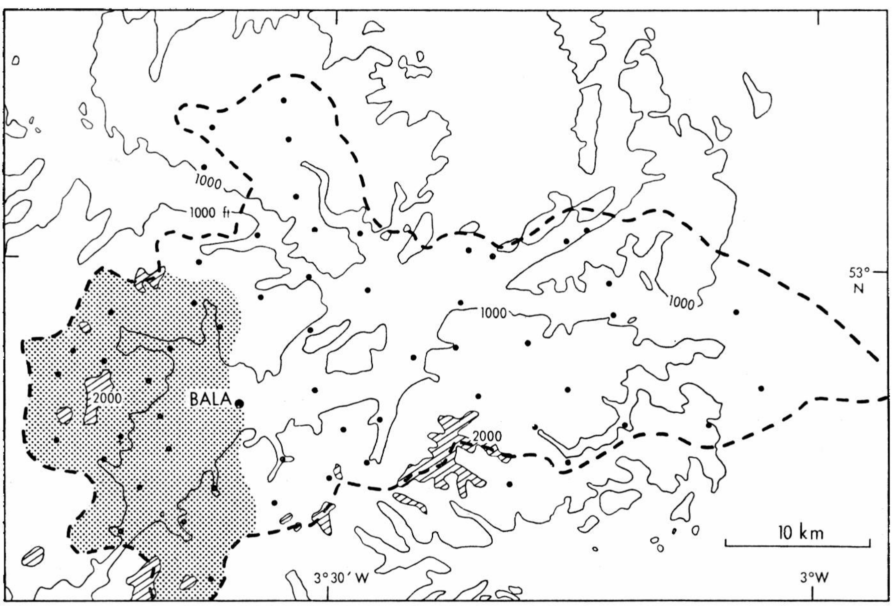

FIGURE 1—LOCATION OF RAIN-GAUGES IN THE DEE CATCHMENT AREA
The area above Bala is stippled. Contours are 1000 and 2000 ft above sea level (approximately 305 and 610 m). Hatching shows land above 2000 ft.

TABLE I—SUMMARY OF PRESTON FORECASTS FOR THE DEE CATCHMENT ABOVE BALA, 1 APRIL 1972–31 MARCH 1974

		Forecast rainfall			
Actual rainfall	No forecast	5–15 mm	15–30 mm	30 mm	Total
<5 mm		43 (53)	4		47
5–15 mm	32	70 (60)	20	1	123
15–30 mm	3	17	27	2	49
>30 mm			11	3	14
Total	35	130	62	6	233

The figures in brackets show the changes to the table which result if no allowance is made for timing errors.

The figures in brackets in the table (column 2) show what results would have been attained had no time correction been applied. It is apparent that timing errors of 3 hours are not a significant problem with these forecasts.

The range of rainfall amounts in each category is an important factor influencing the high success rate of this forecasting technique. However, it should be emphasized that this success rate was achieved in routine forecasting, whereas the other two techniques investigated below are verified against the observations and not forecast indicators.

Forecasting heavy rainfall in the Dee area using Lowndes's criteria. Lowndes has specified the meteorological conditions which should be satisfied if heavy rainfall is to occur at any point in the Dee Catchment area. He defined heavy rainfall as more than 50·8 mm (2 in) in winter (September to February inclusive) and more than 38·1 mm (1·5 in) in summer (March to August) falling in a rainfall day (09–09 GMT). Using 'readily available data' Lowndes analysed 16 occurrences in 55 winters and 45 occurrences in 57 summers.

He specified seven conditions which should be satisfied if heavy rain is to accumulate from westerly weather types. The summer and winter conditions show detailed variations, but they are broadly similar. Also, for summer rain he defined five conditions which should be satisfied for heavy cyclonic rains, with or without thunder, to occur.

Lowndes's criteria have been investigated using data from the entire Dee rain-gauge network. Because of the greater density of gauges compared with those available to Lowndes, heavy rainfall days were relatively more common—5 in winter and 11 in summer in the two-year period. Table II shows the number of criteria which were satisfied on these occasions. If it is assumed that 5 out of 7 criteria (or 4 out of 5 for summer cyclonic rains) should be satisfied before a forecast is issued, and if the criteria themselves were correctly forecast, then 4 out of 5 winter, and 4 out of 6 summer westerly occurrences would have been correctly forecast. However, none of the heavy cyclonic or thundery rains would have been correctly forecast.

For all other days in the two-year period, the number of days when 5 out of 7 criteria for westerly (or 4 out of 5 for summer cyclonic) rain were satisfied and the maximum 24-hour point rainfall on these days are shown in Table III.

To summarize Tables II and III, if a 24-hour rainfall total greater than 1 in (25·4 mm) is considered to be a wet day, then out of the 36 days when 5 out of 7 criteria for westerly types and 4 out of 5 for summer cyclonic types were satisfied, 28 were wet days. It should be noted that the method has been assessed using observations rather than forecast indicators.

TABLE II—RAINFALL DAYS EXCEEDING 50·8 mm IN WINTER AND 38·1 mm IN SUMMER

Type	Date	Maximum 24-h rainfall total	Number of Lowndes's criteria satisfied
		mm	
Winter westerly	9/11/72	62·2	6 out of 7
	2/9/73	67·2	5 out of 7
	9/11/73	63·4	3 out of 7
	4/1/74	60·4	6 out of 7
	29/1/74	74·6	5 out of 7
Summer westerly	28/4/72	49·4	7 out of 7
	26/5/72	49·0	0*
	3/7/72	51·6	6 out of 7
	1/4/73	51·4	7 out of 7
	12/5/73	39·8	4 out of 7
	5/8/73	80·2	6 out of 7
Summer cyclonic or thundery	9/6/72	39·8	3 out of 5
	31/7/72	66·2	3 out of 5
	15/7/73	53·2	3 out of 5
	31/7/73	52·6	0†
	27/8/73	52·6	0†

* Showery westerly
† Isolated thunderstorms

TABLE III—RAINFALL ON OTHER DAYS WHEN THE LOWNDES'S CRITERIA WERE SATISFIED

Type	Total number of days	Number of days with specified rainfall totals	
Winter westerly	14	≥38·1 mm	6
		25·4–38·0 mm	6
		<25·4 mm	2
Summer westerly	7	≥25·4 mm	5
		<25·4 mm	2
Summer cyclonic	7	≥25·4 mm	3
		12·7–25·3 mm	1
		<12·7 mm	3

Use of the 500-*mb jet stream as a predictor of heavy rain.* Benwell, after investigating occurrences of more than 63·5 mm (2·5 in) falling at a point within a rainfall day concluded that two criteria connected with a jet stream at 500 mb should be satisfied if heavy frontal rain was to occur. The criteria were not defined specifically for the Dee Catchment but for North Wales as a whole (and other areas). He evaluated his criteria by seeking falls of heavy intensity (greater than 4 mm per hour) at *Daily Weather Report* stations in areas satisfying the criteria. This approach has not been used in this note. Instead, the three occurrences of frontal rain of 63·5 mm or more in a rainfall day have been identified from Table II, and the positions of jet streams on these days investigated. Of the three days, two had jet streams with wind speeds greater than 70 kt at 500 mb near or over Wales and the other had a wind of 65 kt. However, the position of North Wales with respect to the exit of, or a perturbation within, the jet stream at the time of the heavy rain, was hard to judge.

If all days in the two-year period when more than 38·1 mm (1·5 in) of frontal rain fell are examined, it is found that on 16 out of 19 days there is a 500-mb jet stream with wind exceeding 70 kt affecting one or more of the radiosonde stations in the United Kingdom. In many cases, the jet stream was not directly over Wales, nor was the pertubation or left-exit criterion obviously satisfied. This association of wet frontal systems with 500-mb jet streams is well known, but it does not lead to the conclusion that whenever a jet stream is present, heavy rain will result.

The limitations of this technique are that it is only intended to predict very heavy point rainfall totals from frontal systems and not areal falls, and it requires accurate forecasts of the shape and position of the jet streams.

Conclusion. The rainfall forecasts, which are issued in real time using Holgate's rules, show significant success in predicting areal rainfalls over a part of the Dee Catchment.

The techniques of Lowndes and Benwell are often successful in predicting wet days from frontal systems moving from the west, which give a high proportion of the annual rainfall in the area, but neither fulfils the hydrological requirement of areal rainfall forecasts. Both methods have the limitation of not attempting to predict lesser rainfall totals which can be hydrologically important in winter, and Lowndes's technique shows little success in predicting the heavy summer cyclonic or thundery rains which can lead to flash floods.

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THE DEVELOPMENT OF THE ATMOSPHERIC BOUNDARY LAYER: THREE CASE STUDIES

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Summary. Values of the surface sensible-heat flux for specific periods are deduced from a series of temperature profiles (tethered balloon-sonde data) on each of three separate days. These flux values are compared with those obtained by more direct means using radiation, soil flux, evapotranspiration and Cardington turbulence probe measurements. Large-scale subsidence and advective effects and the application of a 'rate equation' to predict the lifting of an inversion due to heating from below are briefly discussed.

Introduction. Early theoretical work, for instance that by Ball,[1] and later experimental studies such as those of Rayment and Readings[2] have shown the need to study the development of the boundary layer below an overhead inversion. Such studies should ideally monitor the morning erosion of the nocturnal inversion and the ensuing convective development (with possible interaction between this and an overhead inversion) which dies away in the evening as the surface inversion is re-established. However, it must be admitted that, on many occasions, this ideal diurnal cycle will be only partially realized. The work described in this paper concentrates on the evaluation of the vertical heat flux at the surface and compares the results obtained from the three methods for two of the cases considered. A test of the applicability of a rate equation, for predicting the rise of inversions during dry convection, is also described.

The observations discussed here were made at Cardington during August and September 1973. On three days in this period the Balthum (tethered balloon) sonde[3] was used to provide temperature and humidity profiles. Sensible heat-flux profiles were deduced by downward summation of the flux divergences (see for example Cattle and Weston[4]) over 5-mb layers (the vertical eddy flux of potential temperature, $\overline{W'\theta'}$, was assumed to be zero above the level of the inversion top and no allowance was made for subsidence). Surface values of sensible-heat flux, Q_H, were also evaluated by the residual technique (see for example Munn[5]) that is to say $Q_H = Q_N - (Q_G + Q_E)$, the values of net radiation, Q_N, soil flux, Q_G, and evapotranspiration Q_E, having been continuously monitored at Cardington by a net radiometer, soil-flux plates and a lysimeter respectively. On two of the days $\overline{W'\theta'}$ was also measured directly using a Cardington turbulence probe mounted on top of a Clarke mast at a height of 16 metres (Readings and Butler[6]).

The three cases

24 August. Generally anticyclonic conditions prevailed during 24 August with a high 'cell' over the southern North Sea and a ridge over the British Isles. However, the upper cloud thickened at times and this explains the variation in the net radiation as shown in Figure 1. No major air-mass discontinuities were shown on the synoptic charts but the routine radiosonde ascents for the 24th indicated that small advective changes may have been occurring.

The sequence of potential-temperature profiles derived from the Balthum ascents on this day is shown in Figure 2. These four profiles indicate the changes which occurred as the nocturnal inversion was steadily 'warmed out' by surface heating as convection developed. The base of this inversion was lifted from 28 mb above ground level (AGL) at 0838 GMT to 44 mb AGL at 1031 GMT and by 1654 GMT convection was established throughout the layer monitored by the Balthum, i.e. θ is approximately constant on the 1654 plot in Figure 2.

Before applying the summation technique to the temperature profiles an attempt was made to allow for the presumed warm advection indicated above the level of 40 mb AGL (0838–1031 GMT). This was done by adjusting the 1031-GMT plot to become approximately aligned with the previous (0838) plot above 44 mb AGL. (Values of sensible-heat flux evaluated from the original unmodified profiles were large when compared with the probe and energy-balance values. It is possible that an instrumental error was responsible for this apparent warming.) The final profiles of sensible-heat flux are reproduced in Figure 2 (inset) and show the expected decrease of heat flux with

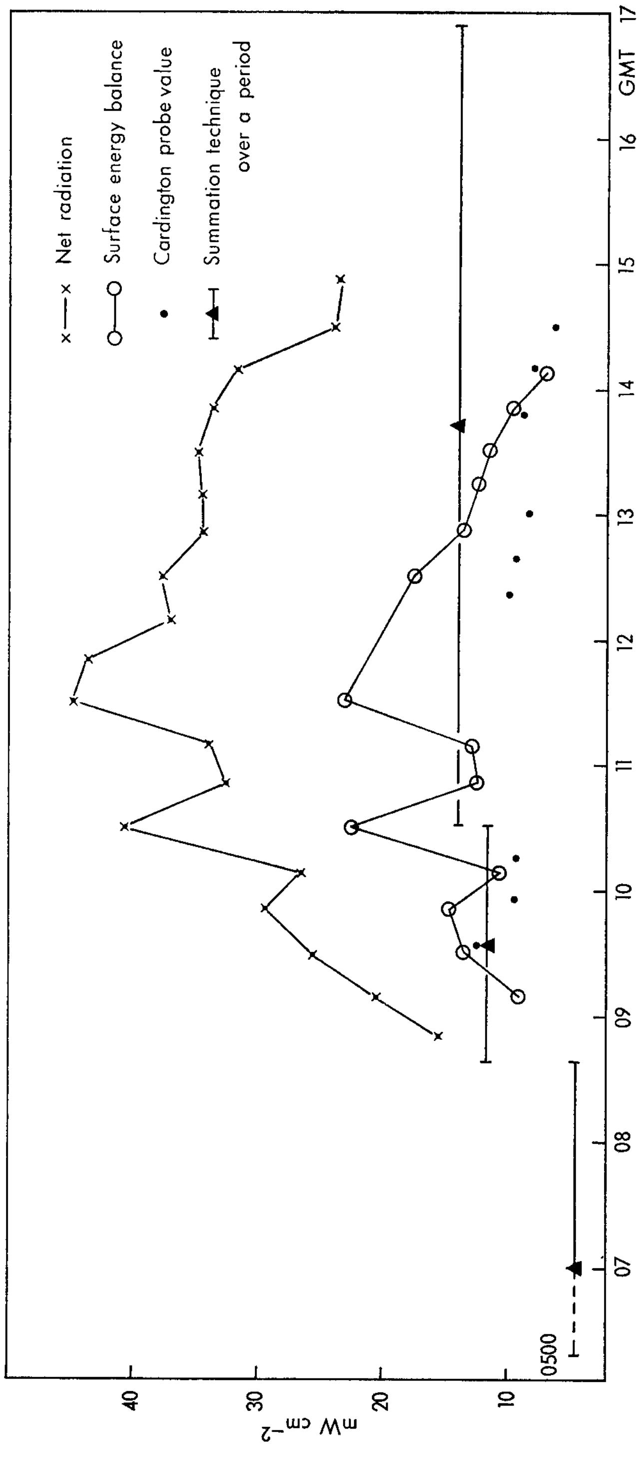

FIGURE 1—NET RADIATION AND SENSIBLE-HEAT FLUX ON 24 AUGUST 1973

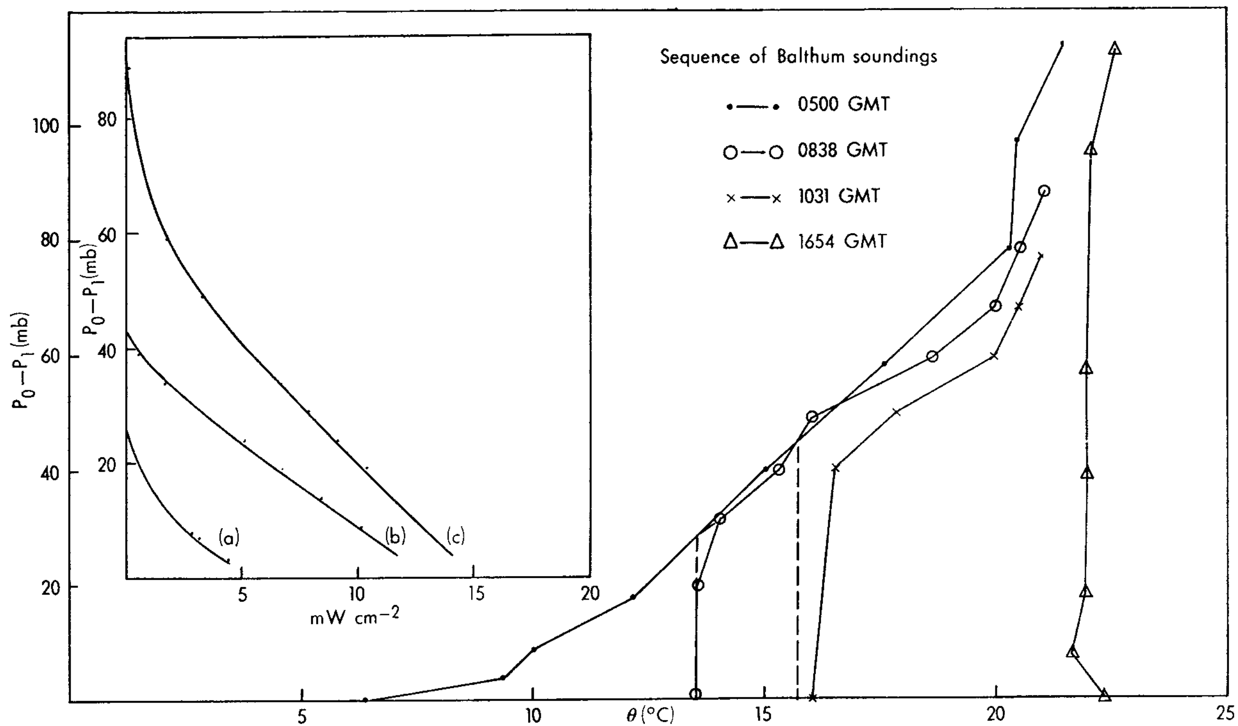

FIGURE 2—PROFILES OF POTENTIAL TEMPERATURE, θ, ON 24 AUGUST 1973
P_0-P_1 is height above the surface in millibars.
Inset shows upward sensible-heat flux in milliwatts/square centimetre.
Summation values for periods between successive soundings, (a) 0500–0838 GMT, (b) 0838–1031 GMT, and (c) 1031–1654 GMT.

height. Values of sensible-heat flux (near the surface), obtained by all three methods described in the previous section, are shown in Figure 1. Reasonable agreement is indicated and the simple correction for advection, discussed above, seems justified.

The following equation (see Carson and Smith[7]) can be used to predict the rate of rise of an inversion (ignoring the effects of entrainment and the vertical velocity):

$$\frac{dZ_i^2(t)}{dt} = \frac{2\overline{W\theta_s}(t)}{\frac{d\theta^+}{dz}}$$

where Z_i is the height of the inversion base, θ^+ is potential temperature above the inversion base, and $\overline{W\theta_s}$ is the surface heat flux (the latter were taken as means of the probe values for the time intervals considered). An estimate of $d\theta^+/dz$ was obtained from Figure 2.

Using the appropriate values of Z_i, $\overline{W\theta_s}$ and $d\theta^+/dz$ for the period 0838 to 1031 GMT (i.e. the actual times at which the Balthum indicated the inversion base) the calculated rate of rise of the inversion is 5·6 mb/h compared with a measured rate of 6·1 mb/h. This order of disagreement falls well within the value corresponding to the tolerances on Z_i, $\overline{W\theta_s}$ and $d\theta^+/dz$.

7 *September.* During this period anticyclonic conditions were maintained over England; the anticyclone which was centred near the Channel Isles at 0000 GMT on 7 September changed little during the subsequent 24 hours. The routine radiosonde reports were studied to see if there were any discernible advective or subsidence effects in the light westerly airstream. The horizontal wind field and temperature distribution implied negligible advection in the 850–900-mb layer, the flow being nearly along the isotherms. Isentropic analysis methods were applied to this layer and the estimated subsidence for the Cardington area (period 0000 GMT to 1200 GMT on 7th) was $1·5 \pm 1$ mb/h compared with an estimate of 'zero to 5' mb/h obtained from the vertical-motion charts available at Bracknell. The conclusion that some subsidence was occurring is consistent with a lowering of the main temperature inversion during the 24 hour period (0000 GMT on 7th to 0000 GMT on 8th) shown on the Crawley, Sussex and Hemsby, Norfolk soundings: from 868 to 926 mb (2·4 mb/h) and from 850 to 896 mb (1·9 mb/h) respectively.

At Cardington fog had occurred overnight (6th–7th) and 7 to 8 oktas of stratus cloud, base about 100 m, was advected from the west at 0805 GMT. This cloud lifted rapidly at 1000 GMT and dispersed at about 1100 GMT. Skies thereafter remained clear apart from 1 okta of shallow cumulus, base 600 m, at 1500 GMT.

The sequence of potential-temperature profiles for this day (from the Cardington Balthum) is shown in Figure 3. The 0715 GMT sounding gives some indication of an upper inversion with a surface (nocturnal) inversion which was considerably modified by low-level cooling at 0833 GMT (associated with the advection of the low stratus cloud). This nocturnal inversion then lifted progressively, the base being at about 40 mb above ground by 1116 GMT. The next sounding (at 1241 GMT) shows an inversion base 77 mb above the surface, i.e. at 945 mb (it is suggested that this was the higher synoptic inversion

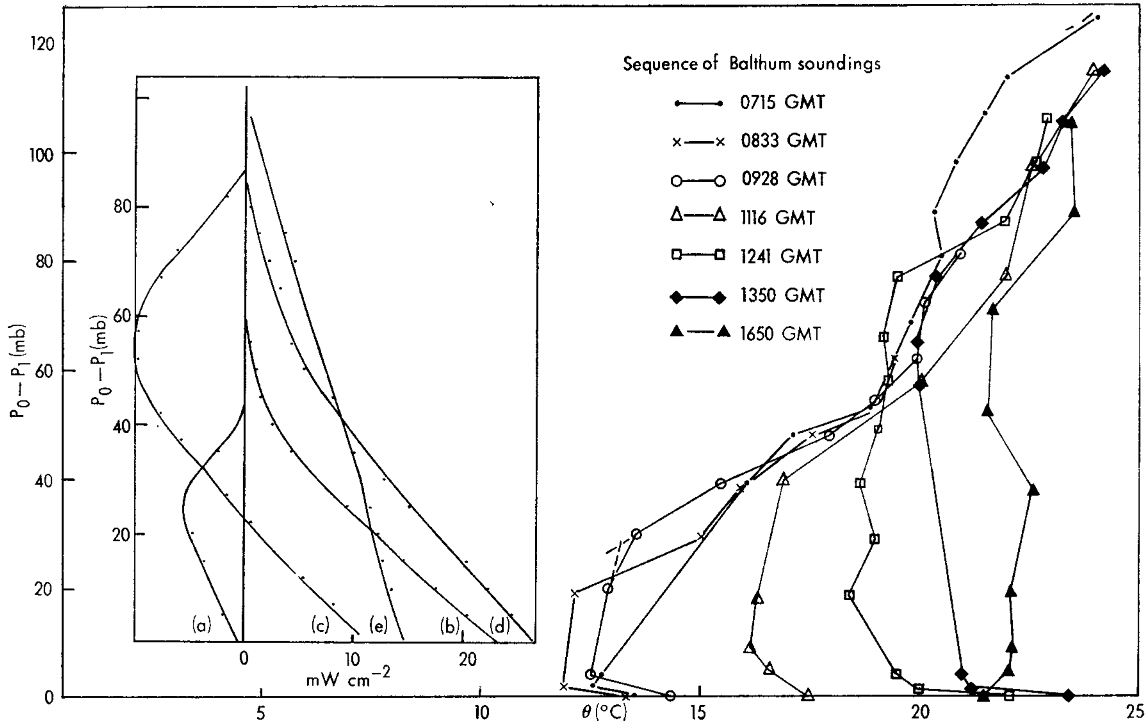

FIGURE 3—PROFILES OF POTENTIAL TEMPERATURE, θ, ON 7 SEPTEMBER 1973
P_0–P_1 is height above surface in millibars.
Inset shows upward sensible-heat flux in milliwatts/square centimetre.
Summation values for periods between successive soundings, (a) 0833–0928 GMT, (b) 0928–1116 GMT, (c) 1116–1241 GMT, (d) 1241–1350 GMT, and (e) 1350–1650 GMT.

which was not affected by the heat flux from below and which is shown at 71 mb above the surface on the 1650 GMT sounding). This lowering of the synoptic inversion corresponds to a subsidence rate of approximately 1·5 mb/h which may be compared with the similar rates previously quoted. It follows from this interpretation of the data that the lower inversion was completely eroded by 1241 GMT.

Shown in Figure 3 (inset) are the profiles of sensible-heat flux. The early downward flux may reflect the evaporative cooling and radiation from the cloud layer, factors which would vitiate the summation technique. The flux shown by curve (b) for the period 0928–1116 GMT is entirely positive and is followed by a marked decrease of surface sensible heat (curve (c)) accompanied by a large negative value about 40 mb (maximum downward flux at about 54 mb) probably reflecting the erosion of the nocturnal inversion. Thereafter the fluxes are entirely positive. The decrease in surface sensible heat flux towards midday is difficult to explain satisfactorily. However, the trend does agree with that from the other estimates, and a considerable amount of evaporation did take place during the late morning. The values of the surface flux of sensible heat obtained by all three methods are compared in Figure 4, which shows also the net-radiation curve and the downward flux of sensible heat. It may be noted that the second peak in the sensible-heat flux plot is not reflected in the plot of downward flux; presumably because by 1241 GMT the lower inversion was no longer present and the fluctuations in net radiation values before 1000 GMT were probably due to the variations in the stratus cloud cover (and presumably cloud thickness). Net radiation and sensible-heat flux increased markedly as the cloud dispersed. Heat-flux values derived from the Cardington probe measurements are unfortunately not available for the period 1100–1200 GMT but the general conclusion that there were two maxima in the sensible-heat flux curve (i.e. near 1020 GMT and 1300 GMT) is supported by the available data.

Changes in water content (below the main inversion at 77 mb) were also examined. An increase of 0·208 g/cm^2 occurred during the period 0833–1350 GMT compared with a measured (lysimeter) evapotranspiration of 0·133 g/cm^2.

It is difficult to draw any firm conclusions from these observed changes since an assumption that the changes are the result of vertical transport only is hardly justified. Although it has been stated that advection above the 900-mb level was negligible there does appear to have been some advective change affecting water-vapour content nearer the surface.

Several double-theodolite wind measurements were available for the day but only one balloon penetrated the inversion, earlier attempts being limited by stratus cloud. Wind changes with height suggest the presence of an inversion base near 76 mb which agrees well with the observed base near 77 mb above ground level.

The rate equation was applied to the data (in the same way as described in the section for 24 August), although its use on this occasion when changes of state occurred is questionable. The results were as follows:

Period GMT	Predicted rise *millibars*	Measured rise
0833–0933	4	9
0933–1151	17	12
1151–1321	8	37

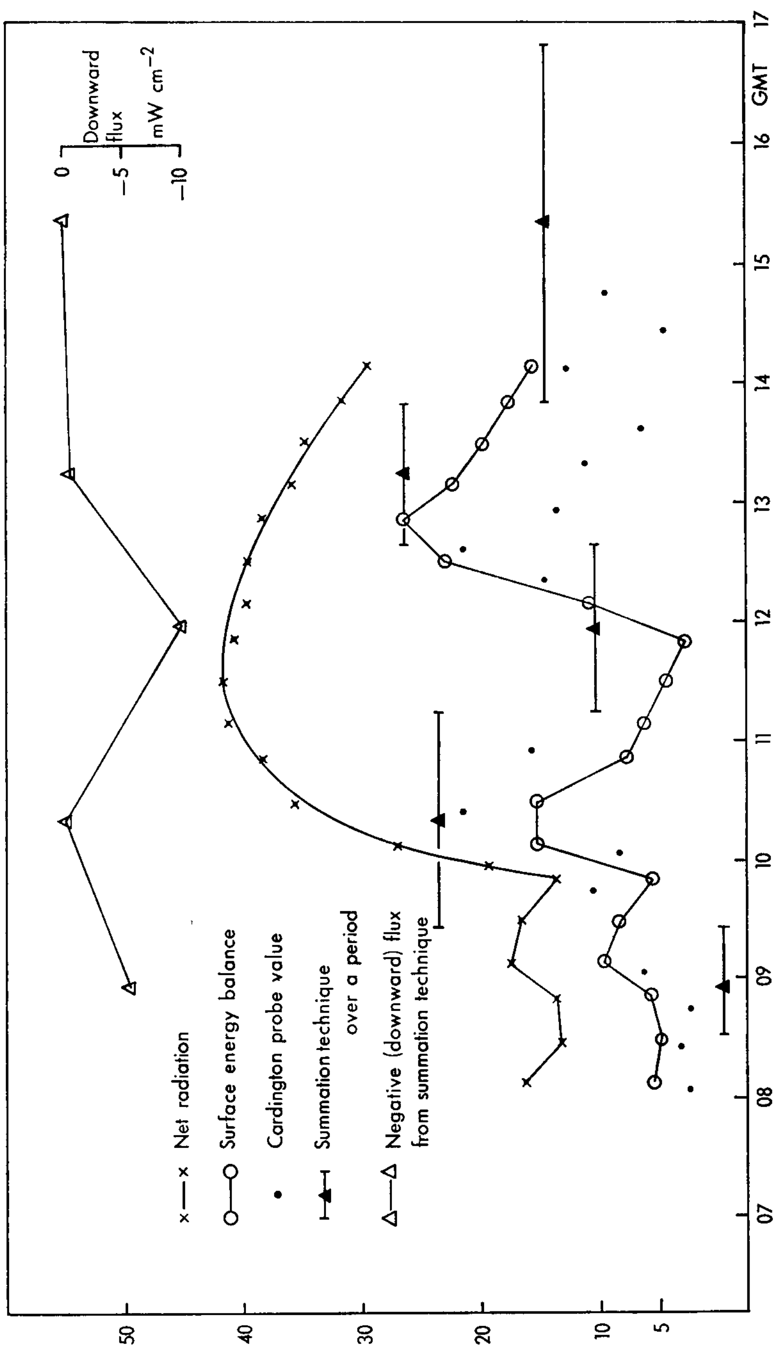

FIGURE 4—NET RADIATION AND SENSIBLE-HEAT FLUX IN MILLIWATTS/SQUARE CENTIMETRE ON 7 SEPTEMBER 1973

It may be noted that the final observed base height (at 1321 GMT) referred to the height of the higher 'synoptic' inversion, the lower inversion having been completely eroded during this latter period. Thus only the first two periods may be regarded as a test of the application of the equation, and it is of interest to note the agreement between the measured and predicted rise of the inversion, i.e. a rise of 21 mb, over the whole period 0833 to 1151 GMT. Comparing the fluctuations in surface sensible-heat flux and downward heat flux (Figure 4) it is difficult to draw firm conclusions regarding the actual ratios of the two fluxes over the period. The predicted rates of inversion rise (tabulated above) result from a straightforward application of the equation which assumes no entrainment.

12 *September*. An anticyclone over the Hebrides maintained a light easterly or south-easterly airflow over central and southern England. Near-cloudless conditions persisted at Cardington throughout the day; small amounts of high cloud were observed at times with one report, at 1000 GMT, of 1 okta of shallow cumulus, base 600 m. The only suspected advective change was that of increased moisture content near the surface during the late afternoon.

Shown in Figure 5 is the sequence of potential-temperature profiles based on three soundings from the surface to near the main capping inversion and one sounding restricted to the layer above about 100 mb (above ground level). The absence of a 'complete' sounding from the surface upwards between 0710 and 1135 GMT rules out any consideration of the lifting and erosion of a lower induced inversion which must have occurred. Thus the $W\theta$ summation is limited to the two periods between soundings (see Figure 5 inset).

The net-radiation curve and values of sensible-heat flux are shown in Figure 6 and show a reasonably smooth change with time, the two surface $W\theta$ summation values of heat flux agreeing well with the energy balance results.

Conclusions. The case of 24 August is an example of the complete 'warming out' of a nocturnal inversion finally resulting in dry adiabatic conditions within the boundary layer below the main inversion. The lower inversion warmed out 'passively' with no detected entrained heat flux. On 12 September similar 'warming out' of a lower inversion must have occurred beneath a clearly defined overhead capping inversion which was not affected by the changes in heat flux below. In each of these cases a reasonable sequence of radiative and sensible-heat flux changes is shown and the summation technique whereby sensible-heat flux may be derived from a series of temperature profiles is seen to be quite reliable.

The case of 7 September, although basically that of erosion of a low-level inversion beneath a higher capping inversion, is made more complex by the presence of the stratus cloud layer during the morning, by evaporative and condensation processes and by probable advective changes. The simple techniques described in this paper do not allow for such changes adequately.

The problem of advective and subsidence changes (or instrumental error) is difficult to resolve although the simple technique applied in the case of 24 August results in acceptable values of heat flux. The synoptic-scale techniques used to produce estimates of advection, e.g. wind shear in the vertical, cannot easily be applied to the relatively small changes within the boundary layer which may appreciably affect heat-flux estimates and water-budget calculations. Energy-balance estimates of sensible heat (the technique of residuals) depend largely on reliable evapotranspiration values. The data for

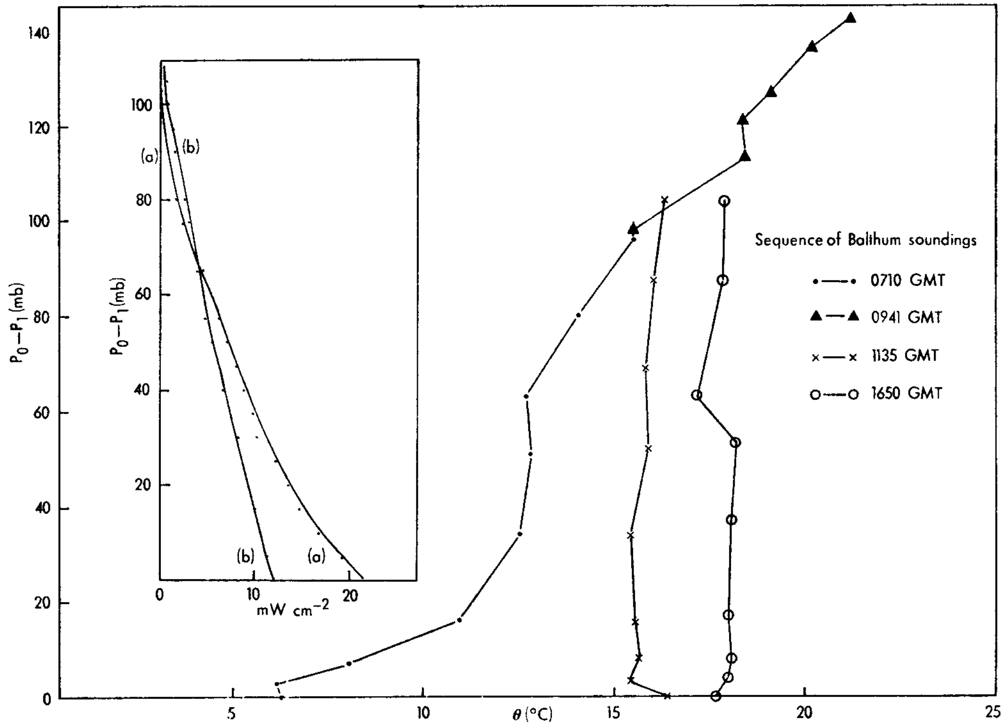

FIGURE 5—PROFILES OF POTENTIAL TEMPERATURE, θ, ON 12 SEPTEMBER 1973

P_0–P_1 is height above surface in millibars.

Inset shows upward sensible-heat flux in milliwatts/square centimetre. Summation values for periods between successive soundings, (a) 0710–1135 GMT and (b) 1135–1650 GMT.

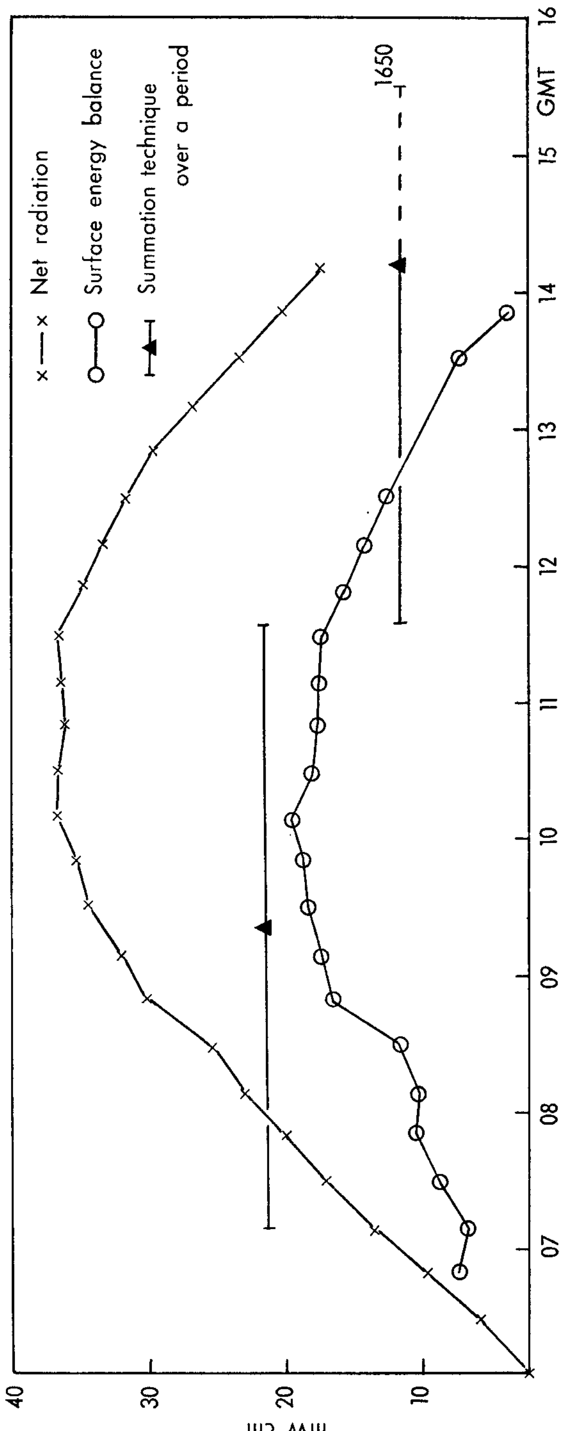

FIGURE 6—NET RADIATION AND SENSIBLE-HEAT FLUX IN MILLIWATTS/SQUARE CENTIMETRE ON 12 SEPTEMBER 1973

7 September suggest that these values are suspect if quoted for short periods when evapotranspiration is taking place at a high rate. Some difficulty was encountered regarding the reliability of soil-flux values: extrapolation of the 4-cm and 8-cm readings in order to arrive at a 'surface' value resulted in some high values. This may have been due to instrumental error. Values of sensible heat derived (using these values) were correspondingly very low. For the purpose of this analysis, the 8-cm reading was regarded as a 'surface' value. The measure of agreement between the surface-layer heat-flux values obtained by the three methods described is encouraging and could be important in planning further boundary-layer studies.

This is regarded as a 'pilot study' providing some useful guidance for the analysis of the more extensive radiosonde data which have resulted from experiment CABLE 74 (the Collaborative Atmospheric Boundary Layer Experiment) which involved Meteorological Research Unit, Cardington, Reading University (Department of Geophysics), Imperial College (Department of Physics), Meteorological Research Unit, Malvern, Chilbolton Radar and the radiosonde stations at Larkhill and Shoeburyness.

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AN INVESTIGATION INTO SPELLS OF WET AND DRY DAYS BY REGION AND SEASON FOR GREAT BRITAIN

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Summary. Distribution of wet and dry spells are considered in relation to Markov, simple logarithmic, modified logarithmic, and modified geometric models explained in this paper. Data from eight stations distributed over the British Isles show that a simple logarithmic model can usually describe dry-spell data while the modified logarithmic and geometric models describe wet-spell data. The variations in model parameters do not correlate well with region. Data considered by season for Oxford show that, on average, autumn and winter dry spells there are shorter than dry spells in spring and summer, while winter wet spells are slightly longer than those in the other seasons; these variations determine the model parameters.

Introduction. Many investigations have been conducted into the distributions of sequences of wet and dry days. The most popular model used to fit the distributions of spell lengths has been the simple Markov model which assumes that the probability of any particular day being wet or dry depends only on the character of the previous day (for instance Chatfield,[1] Gabriel and Neumann[2]). Williams[3] first suggested a logarithmic series as a fit to sequences of wet and dry days and this model has since been applied to other data (Cooke,[4] Chatfield[1]). Green[5] proposed a modified logarithmic model of which the simple logarithmic and Markov models are special cases. This model, which used two parameters, satisfactorily fitted 33 out of 36 cases collected by Green and others; these included observations of duration of rainstorms, and of intervals between them, collected by Weiss.[6] Yap[7] proposed a modification to the simple Markov model in which the probability parameter (of a wet or dry day being followed by a similar day) was a variable, though a constant within any given spell length.

New data are here investigated in relation to seasonal and regional variations. Distributions from eight stations are compared. Those for Oxford are further divided into four seasons and examined in more detail.

The models. The probabilities of spells of length 1, 2, 3 . . . r wet or dry days are defined by the various models as follows:

Model 1: Markov Chain Model

$q, q^2, \ldots q^r$, with normalizing constant $\dfrac{1-q}{q}$.

Model 2: Williams's logarithmic model

$q, q^2/2, q^3/3, \ldots q^r/r$, with normalizing constant $\dfrac{1}{\log(1-q)}$.

Model 3: Green's modified logarithmic model

$\dfrac{q}{1+a}, \dfrac{q^2}{2+a}, \ldots \dfrac{q^r}{r+a}$ with $0 \leqslant a \leqslant \infty$ and the normalizing constant determined by the requirement $\displaystyle\sum_r \frac{q^r}{r+a} = 1$. In each case the normalizing constant ensures that the total probability is unity. In order to fit models 1 and 2 from data the mean spell length is used (i.e. the total number of wet (or dry) days divided by the total number of wet (or dry) spells) to find q.

For model 1, mean spell length $= \displaystyle\sum_r \frac{1-q}{q} q^r r = \frac{1}{1-q}$.

For model 2, mean spell length $= \displaystyle\sum_r \frac{-1}{\log(1-q)} \frac{r\ q^r}{r} = \frac{-q}{\log(1-q)(1-q)}$.

For model 1, q can be found directly from the mean spell length; for model 2 it is found by a recursive process or from tables published by Williamson and Bretherton.[8]

It may be noticed that models 1 and 2 are special cases of model 3 for $a = \infty$ and 0 respectively.

To fit model 3 the method of minimum chi-square is used. We let q approach 0 from 1 and let a approach 0 from some value greater than, say, 6 in successive steps; the distribution for given a, q is tested for fit at each step by the chi-square test. The parameters a and q are altered each time the chi-square value falls as compared with the values of a, q for previous smallest values of chi-square. In applying the chi-square tests, spells of length greater than a certain value (about 15) are grouped together into one category. The program stops when chi-square falls below a certain value determined by the number of categories; the a and q values for the minimum chi-square value are taken as best fit values.

For model 4 we assume that the probability of a dry or wet spell is p, where p is a random variable having a constant value within any one run, but different values in different runs (as Yap[7]); p is assumed to be a random variate

$$\mathrm{f}(p) = \frac{p^{a-1}(1-p)^{b-1}}{B(a, b)}$$

where a, b are constants of the distribution and $B(a,b)$ is the Beta function.

The probability of a run of days is given by

$$P(r) = \frac{1}{B(a,b)} \int_0^1 (1-p)\, p^{r-1} (1-p)^{b-1} p^{a-1}\, dp,$$

where $(1-p)$ is a normalizing factor and p^{r-1} arises from $r-1$ days following the first wet (or dry) day. Then

$$P(r) = \frac{B(a+r-1, b+1)}{B(a, b)},$$

$$P(1) = \frac{b}{a+b}, \text{ and } r \geqslant 2,$$

$$P(r) = \frac{a+r-2}{a+b+r-1} P(r-1),$$

where we have used the definitions

$$B(x, y) = \frac{(x-1)!\,(y-1)!}{(x+y-1)!} = \int_0^1 p^{x-1} (1-p)^{y-1}\, dp.$$

To fit the model we take factorial moments about the origin U'_1, U'_2 for the first two moments, i.e.

$$U'_1 = \int_0^1 \mathrm{f}(p)(1-p) \sum_0^\infty p^{r-1} r\, dp$$

$$= \frac{1}{B(a, b)} \int_0^1 \frac{1}{(1-p)^2} (1-p)\, p^{a-1} (1-p)^{b-1}\, dp$$

$$= \frac{B(a, b+1)}{B(a, b)} = \frac{a+b-1}{b-1}$$

$$U'_2 = \int_0^1 f(p)\ (1 - p) \sum_0^\infty p^{r-1}\, r(r-1)\ dp$$

$$= \frac{1}{B(a, b)} \int_0^1 p^{a-1} (1 - p)^{b-1} \frac{2p}{(1 - p)^2}\, dp,$$

$$= \frac{2}{B(a, b)}\ B(a + 1, b - 2),$$

$$= \frac{2a\ (a + b - 1)}{(b - 1)\ (b - 2)}.$$

Then $b = \dfrac{2U'_1 (U'_1 - 1) - 2U'_2}{2U'_1 (U'_1 - 1)\ U'_2}$,

$a = (U'_1 - 1)\ (b - 1)$.

U'_1 is equated to mean spell length and U'_2 to the difference between mean-square spell length and mean spell length.

Persistence. As a measure of persistence we may use the ratio of the probability of spell length $(r + 1)$ to spell length, r, $F(r)$ say. For models 1, 2 and 3, $F(r) = P(r + 1)/P(r) = q\ ((r + a)/(r + a + 1))$. For the general case of model 3, $0 \leqslant a \leqslant \infty$; models 1 and 2 are special cases of model 3 for $a = \infty$ and 0 respectively. $F(r)$ is constant for model 1 for all r and equals q. In general, $F(r)$ increases with spell length r and with model parameter a; its rate of increase decreases as r increases and $F(r)$ tends to q in the limit.

For model 4, $F(r) = P(r + 1)/P(r) = (a + r - 3)/(a + b + r - 1)$ and the measure of persistence increases with spell length, tending to 1 for large r.

Model fitting for eight stations. The data used were for 40-year periods: 1921–60 for York, Cwm Dyli (North Wales), Oxford, Falmouth, March and Edgbaston, 1931–70 for Edinburgh; for Whitby, the shorter period 1921–42 was used. Difficulty was experienced in finding stations with long-term continuous rainfall records with a constant threshold for recording rainfall; threshold values were 0·01 in for all stations apart from Edinburgh and Edgbaston with 0·2 mm. These data are given in Appendix 1 (dry spells), Appendix II (wet spells); graphs of spell length distribution for Edinburgh, Falmouth, Cwm Dyli and March are illustrated as representative examples in Figures 1 to 6.

The chi-square test was used to test the fit of models 1 to 4 to the observed distribution with an acceptance level of $P(\chi^2) \geqslant 0{\cdot}05$. For dry spells the logarithmic model fitted the data for all stations except March and Edgbaston. For March the modified logarithmic model fitted the data for small a ($a = 0$ for the simple logarithmic model); for Edgbaston no model fitted the dry-spell data. Neither the Markov nor the modified geometric models produced distributions to fit any of the dry-spell data. The parameter q did not show any systematic variation among the stations.

For wet spells the modified geometric and modified logarithmic models fitted most data. The exceptions were Cwm Dyli for the geometric model,

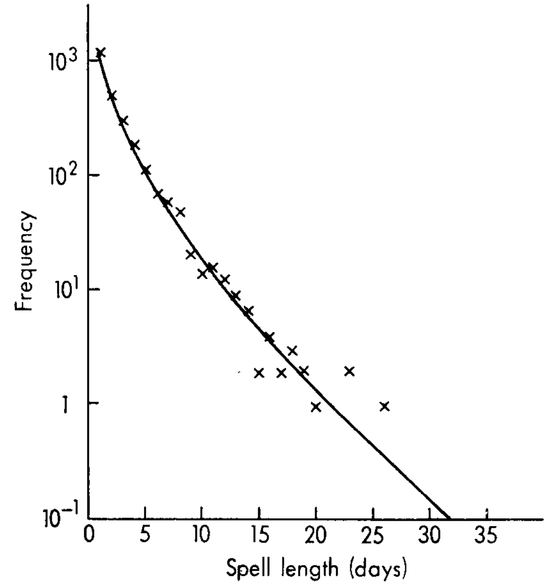

FIGURE 1—DRY SPELLS AT EDINBURGH, LOGARITHMIC MODEL $q = 0{\cdot}82$.

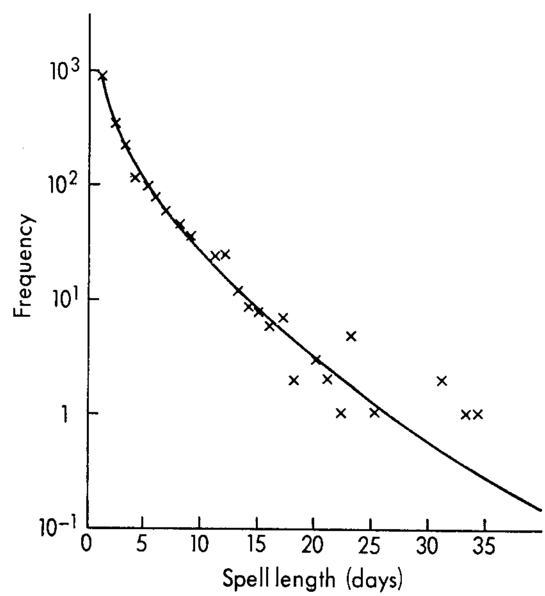

FIGURE 2—DRY SPELLS AT FALMOUTH, LOGARITHMIC MODEL $q = 0{\cdot}87$.

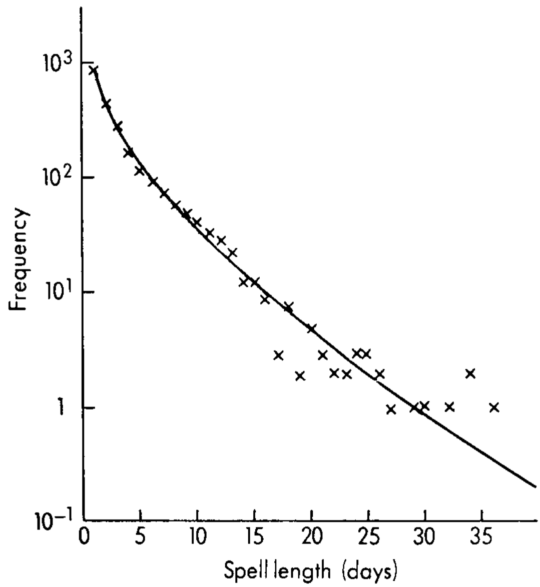

FIGURE 3—DRY SPELLS AT MARCH, MODIFIED LOGARITHMIC MODEL
$q = 0{\cdot}87$, $a = 0{\cdot}34$.

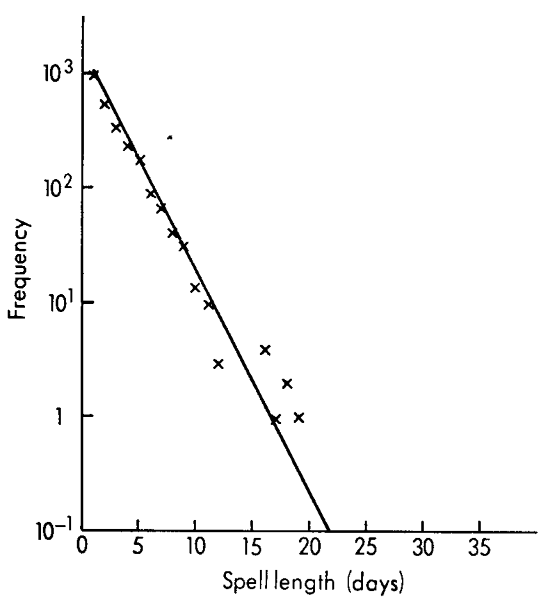

FIGURE 4—WET SPELLS AT EDINBURGH, MARKOV MODEL
$q = 0{\cdot}64$.

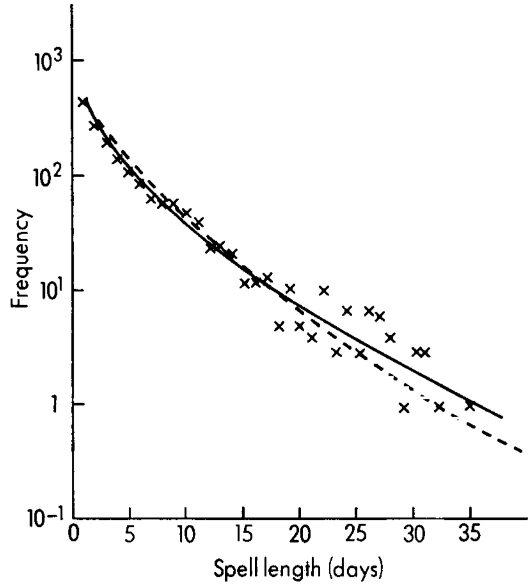

FIGURE 5—WET SPELLS AT CWM DYLI
——— modified logarithmic model, q = 0·90, a = 1·18.
– – – – modified geometric model.

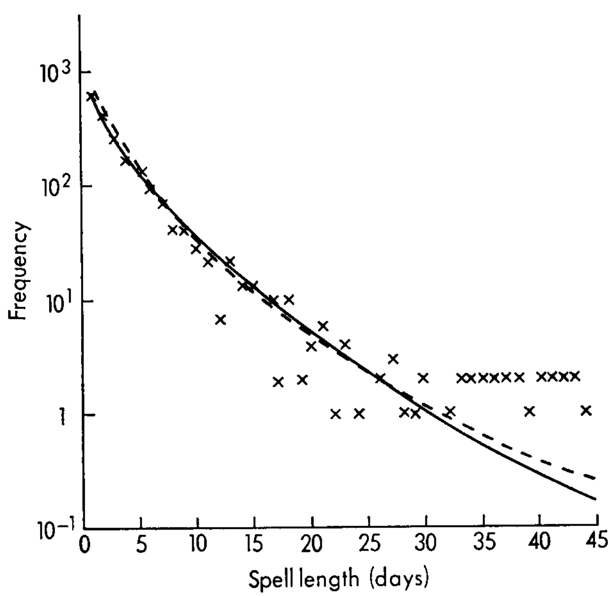

FIGURE 6—WET SPELLS AT FALMOUTH
——— modified logarithmic model, q = 0·88, a = 0·92.
– – – – modified geometric model.

Falmouth for the modified logarithmic model and Edinburgh fitted by neither modified model. However, a simple Markov model, which is a special case of both modified models, fitted the Edinburgh data. The modified logarithmic model usually produced a slightly better fit than the modified geometric model, though differences were only apparent for longer, less-frequent spells.

Variations of the parameters *a* and *q* for wet spells did not correlate well with region or with mean annual rainfall. Cwm Dyli (mean annual rainfall 140·46 in (3567·68 mm) for the period 1916–50) and Falmouth (43·00 in, 1092·20 mm), the two wettest stations, had slightly higher values of *q* than the other stations and showed slightly greater persistence of wet spells. The other stations had mean annual rainfall in decreasing order as follows: Edgbaston 30·70 in (779·78 mm), Edinburgh 27·53 in (699·26 mm), Whitby 25·66 in (651·76 mm), York 24·70 in (627·38 mm), and March 23·07 in (585·98 mm).

An examination was made of the effect of a change of threshold for the two stations which recorded in millimetres. It was found that with a threshold value of 0·1 mm the Edgbaston dry-spell data fitted a logarithmic model (no fit found for 0·2 mm), and that Edinburgh wet-spell data fitted both modified models (a Markov fit found for 0·2 mm). For Edgbaston wet-spell data and for Edinburgh dry-spell data the change of threshold was found to cause only a slight change in the model parameters.

Comparative persistence of wet and dry spells. Using models 1 to 3 the values of the measure of persistence F(*r*) were compared for wet and dry spells for each station. For March, F(*r*) was larger for all dry spells than for wet spells. For Edinburgh, York, Edgbaston and Oxford, F(*r*) was larger for dry spells of length greater than two days; for Whitby, F(*r*) was larger for dry spells longer than five days. For Edinburgh, where a Markov model produced a best fit to wet-spell data, F(*r*) was of course constant. For the wetter stations, Cwm Dyli and Falmouth, F(*r*) was larger for wet spells for all *r*. Thus we infer that dry spells are more persistent at 'dry' stations and wet spells are more persistent at 'wet' stations. For intermediate stations wet spells are more persistent for short spells only. The variations probably reflect the passage of synoptic features. Anticyclones tend to build up slowly over two or three days and last for longer periods than do individual depressions. For 'wet' stations effects of minor disturbances are greater than at other stations and wet spells tend to be more persistent than dry spells. However, analysis of spell data does not distinguish the effect of individual disturbances; a long wet spell may result from several successive depressions.

Seasonal variations (see Appendices III and IV and Figures 7–9). The Oxford data for 1852–1970 were divided into four seasons—winter (December to February), spring (March to May), summer (June to August) and autumn (September to November), the divisions between seasons being taken at the end of a spell. Each seasonal set of data was tested for the distribution of spells according to the above model. Dry spells again fitted the log model and wet spells the modified geometric model. For dry spells the mean spell lengths were similar for autumn and winter (2·875 and 2·921 days) and for spring and summer (3·498 and 3·344); the corresponding values of the parameters *q* in the logarithmic model were 0·84 for autumn and winter, 0·88 for spring and 0·87 for summer. For wet spells it was found that mean spell lengths

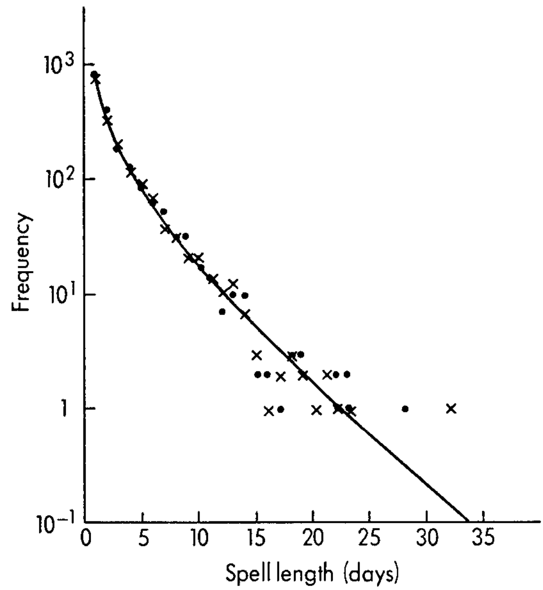

FIGURE 7—DRY SPELLS AT OXFORD, LOGARITHMIC MODEL
● Autumn × Winter

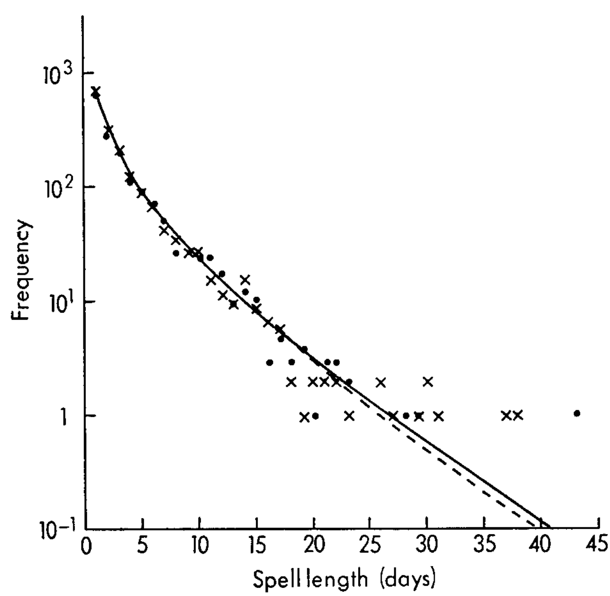

FIGURE 8—DRY SPELLS AT OXFORD, LOGARITHMIC MODEL
Continuous line and dots refer to spring; $q = 0{\cdot}88$.
Pecked line and crosses refer to summer; $q = 0{\cdot}87$.

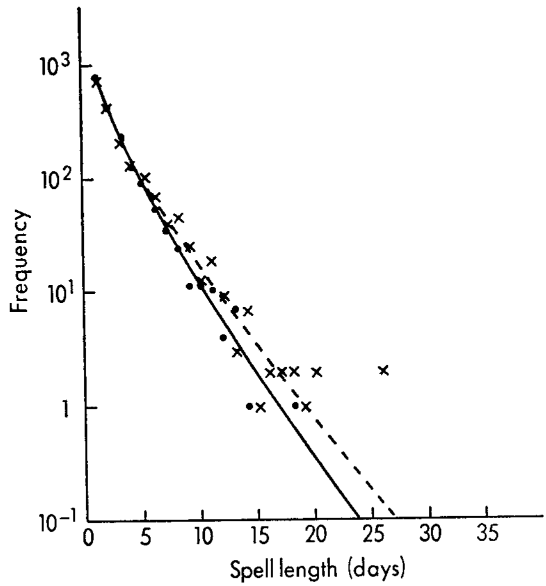

FIGURE 9—WET SPELLS AT OXFORD, MODIFIED LOGARITHMIC MODEL
Continuous line and dots refer to summer; $q = 0{\cdot}87$, $a = 1{\cdot}09$.
Pecked line and crosses refer to winter; $q = 0{\cdot}78$, $a = 1{\cdot}59$.

decreased from winter (2·932) to summer (2·621) with spring (2·783) and autumn (2·750) having similar lengths. The parameters *a* and *q* which produced the best fit to spring and autumn wet spells also produced a good (but not best) fit to summer wet spells (see table below).

	a	*q*	$P(\chi^2)$
Spring	2·075	0·75	0·50
Autumn	2·075	0·75	0·05
Summer	2·075	0·75	0·05
	1·087	0·75	0·30
Winter	1·581	0·78	0·10

Cumulative distributions. As regards extremes, a model which describes cumulative spell distributions, i.e. the number of spells of length greater than a specified value, may be of more practical value than one describing individual spells. For this reason the spell data were also considered cumulatively. For dry spells only the modified logarithmic model was found to fit the cumulative data and that at only four out of the eight stations; the parameters *a* and *q* of the model were 0·87 and 1·09 respectively for York and Oxford, 0·81 and 2·07 for Cwm Dyli, and 0·87 and 2·07 for March. On the other hand it was found that none of the models fitted cumulative wet-spell data. It was usually the rarer long spells which failed to fit the models for cumulative data since after the summation of data their relative weight in the fit was decreased.

Conclusions. We may agree with Green's conclusion that the modified logarithmic model (of which Markov's model and the simple logarithmic model are special cases) fits most spell data. As a first approximation, we may say that the simple logarithmic model fits dry-spell data with q about 0·85; for wet spells, the modified logarithmic model fits most data, with a about 2 or 3 and q about 0·7 or 0·8 for other stations. The modified geometric model also fits most wet-spell data. The models give only a rough guide to the occurrence of infrequent long spells.

Seasonally, dry spells are slightly longer for spring and summer than for autumn and winter, one q-value for each half of the year being sufficient to describe the data. For wet spells, different values of a and q are needed for longer winter spells than those for other seasons.

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APPENDIX I—DRY-SPELL FREQUENCIES

Spell length	Edinburgh Observed	Edinburgh Log. model	York Observed	York Log. model	Whitby Observed	Whitby Log. model	Cwm Dyli Observed	Cwm Dyli Log. model
days								
1	1241	1280·9	1004	1033·4	662	689·3	886	862·6
2	524	524·7	476	444·4	287	276·8	340	359·3
3	311	286·6	228	254·8	154	148·2	170	199·6
4	194	176·1	197	164·4	92	89·3	120	124·7
5	120	115·4	107	113·1	57	57·4	84	83·1
6	74	78·8	82	81·1	51	38 4	65	57·7
7	61	55·4	60	59·8	32	26·4	59	41·2
8	50	39·7	40	45·0	19	18·6	36	30·0
9	21	28·9	43	34·4	9	13·3	26	22·3
10	15	21·3	31	26·6	13	9·6	17	16·7
11	17	15·9	24	20·8	7	7·0	17	12·6
12	14	11·9	19	16·4	4	5·2	11	9·7
13	9	9·0	11	13·0	3	3·8	6	7·4
14	7	6·9	10	10·4	0	2·8	3	5·7
15	2	5·2	5	8·4	0	2·1	3	4·5
16	4	4·0	4	6·7	1	1·6	3	3·5
17	2	3·1	5	5·5	1	1·2	2	2·7
18	3	2·4	2	4·4	1	0·9	1	2·2
19	2	1·9	4	3·6	0	0·7	1	1·7
20	1	1·5	4	2·9	1	0·5	1	1·3
21	0	1·1	1	2·4	0	0·4	0	1·1
22	0	0·9	1	2·0	0	0·3	0	0·8
23	2	0·7	1	1·6	1	0·2	1	0·7
24	0	0·5	0	1·3	0	0·1	1	0·5
25	0	0·4	1	1·1	0	0·1	0	0·4
26	1	0·3	2	0·9	0	0·1	0	0·3
27	0	0·3	0	0·8	0	0·1	0	0·3
28	0	0·2	0	0·6	0	0·1	0	0·2
29	0	0·2	1	0·5	0	0	1	0·2
30	0	0·1	0	0·4	0	0	0	0·1
31	0	0·1	1	0·4	0	0	0	0·1
32	0	0·1	1	0·3			0	0·1
33	0	0·1	0	0·3				
34	0	0·1	2	0·2				
35			0	0·2				
36								
37								
38								
39								
40								
χ^2		15·7		20·0		13·3		20·9
$P(\chi^2)$		0·40		0·30		0·30		0·20
q		0·82		0·86		0·803		0·833
a								

Spell length	Oxford Observed	Oxford Log. model	Falmouth Observed	Falmouth Log. model	March Observed	March Log. model	Edgbaston Observed	Edgbaston Log. model	Edgbaston* Observed	Edgbaston* Log. model
days										
1	1004	1034·8	904	868·9	944	951·0	1039	1068·1	1045	1076·9
2	476	444·5	358	377·9	487	476·7	460	456·9	459	454·0
3	261	254·5	216	219·2	319	291·7	261	260·7	269	255·2
4	141	164·0	116	143·0	179	196·4	154	167·3	135	161·4
5	131	112·7	92	99·5	128	139·6	141	114·5	142	108·9
6	99	80·7	73	72·1	164	102·9	81	81·6	81	76·5
7	46	59·4	53	53·8	79	78·0	73	59·9	63	55·3
8	38	44·6	47	40·9	61	59·9	39	44·8	36	40·8
9	39	34·1	36	31·6	52	46·8	43	34·1	37	30·6
10	26	26·4	29	24·8	43	37·0	34	26·3	28	23·2
11	22	20·6	24	19·6	36	29·5	23	26·4	17	17·8
12	15	16·2	25	15·6	30	23·7	18	16·0	13	13·7
13	9	12·9	12	12·5	24	19·2	10	12·7	9	10·7
14	15	10·3	9	10·1	13	15·6	8	10·1	5	8·4
15	7	8·2	8	8·2	13	12·8	10	8·0	8	6·6
16	4	6·6	6	6·7	9	10·5	8	6·4	7	5·2
17	3	5·4	7	5·5	3	8·7	1	5·2	3	4·1
18	3	4·3	2	4·5	8	7·2	3	4·2	2	3·3
19	4	3·5	4	3·7	2	5·9	2	3·4	1	2·6
20	1	2·9	3	3·1	5	4·9	2	2·8	2	2·1
21	2	2·4	2	2·5	3	4·1	0	2·3	0	1·7
22	3	1·9	1	2·1	2	3·4	3	1·8	2	1·4
23	1	1·6	5	1·8	2	2·9	0	1·5	0	1·1
24	0	1·3	0	1·5	3	2·4	0	1·2	0	0·9
25	1	1·1	1	1·2	3	2·0	0	1·0	0	0·7
26	1	0·9	0	1·0	2	1·7	0	0·8	0	0·6
27	0	0·7	0	0·9	1	1·4	0	0·7	0	0·5
28	2	0·6	0	0·7	0	1·2	0	0·6	0	0·4
29	2	0·5	0	0·6	1	1·0	0	0·5	0	0·3
30	1	0·4	0	0·5	1	0·9	1	0·4	0	0·3
31	1	0·3	2	0·4	0	0·7	0	0·3	0	0 2
32	0	0·3	0	0·4	1	0·6	1	0·3	1	0·2
33	0	0·2	1	0·3	0	0·5	0	0·2	0	0·1
34	0	0·2	1	0·3	2	0·4	1	0·2	1	0·1
35	0	0·2	0	0·2	0	0·4	0	0·1	0	0·1
36	0	0·1	0	0·2	1	0·3	0	0·1	0	0·1
37	1	0·1	0	0·1	0	0·2	0	0·1	0	0·1
38	0	0·1	0	0·1	0	0·2	0	0·1	0	0·1
39	0	0·1	0	0·1	0	0·2	0	0·1	0	0·1
40	0	0·1	0	0·1	0	0·2	0	0·1	0	0·1
χ^2		29·9		20·1		18·7		31·5		27·9
$P(\chi^2)$		0·05		0·30		0·40		0·02		0·05
q		0·859		0·870		0·875		0·85		0·84
a						0·337				

Observed denotes observed frequency; Log. denotes expected frequency (logarithmic model).
* When threshold decreased from 0·2 mm to 0·1 mm.

APPENDIX II—WET-SPELL FREQUENCIES

Spell length	Edinburgh Observed	Edinburgh Expected frequency (Markov)	York Observed	York Modified log.	York Modified geometric	Whitby Observed	Whitby Modified log.	Whitby Modified geometric	Cwm Dyli Observed	Cwm Dyli Modified log.	Cwm Dyli Modified geometric
days											
1	1003	950·8	907	895·5	882·9	523	489·4	492·8	477	495·6	413·9
2	570	612·7	520	504·2	531·2	293	302·6	309·1	322	308·6	313·2
3	336	394·9	305	307·9	327·9	182	193·7	197·3	212	213·2	239·2
4	251	254·4	204	197·5	207·2	121	127·0	127·9	153	156·3	184·2
5	195	164·0	136	130·8	133·7	74	84·8	84·2	127	119·0	143·0
6	96	105·7	92	88·7	87·9	62	57·4	56·2	95	93·0	111·9
7	68	68·1	64	61·2	58·8	40	39·4	38·0	68	74·1	88·1
8	43	43·9	41	42·8	40·0	39	27·2	26·0	63	60·0	69·9
9	33	28·3	25	30·3	27·6	12	19·0	18·0	62	49·1	55·7
10	14	18·2	26	21·6	19·3	11	13·3	12·6	51	40·6	44·7
11	10	11·7	11	15·6	13·7	13	9·3	8·9	41	33·9	36·1
12	3	7·6	9	11·3	9·8	7	6·6	6·4	25	28·4	29·3
13	11	4·9	2	8·2	7·1	4	4·7	4·6	26	24·0	23·9
14	3	3·1	6	6·0	5·2	4	3·4	3·3	24	20·4	19·6
15	0	2·0	6	4·4	3·9	1	2·4	2·4	12	17·3	16·1
16	4	1·3	2	3·2	2·9	3	1·7	1·8	13	14·8	13·3
17	1	0·8	2	2·4	2·2	3	1·3	1·3	14	12·7	11·1
18	2	0·5	4	1·8	1·6	1	0·9	1·0	5	11·0	9·2
19	1	0·3	3	1·3	1·3	1	0·7	0·8	11	9·5	7·7
20	0	0·2	0	1·0	1·0	1	0·5	0·6	5	8·2	6·5
21	0	0·1	0	0·7	0·7	0	0·3	0·4	4	7·1	5·4
22	0	0·1	1	0·6	0·6	0	0·2	0·3	11	6·2	4·6
23	0	0·1	0	0·4	0·5				3	5·4	3·9
24	0	0·0	0	0·3	0·3				7	4·7	3·7
25	0	0·0	1	0·2	0·2				3	4·1	2·8
26	0	0·0	1	0·2	0·2				7	3·6	2·5
27	1	0·0							6	3·1	2·1
28									4	2·8	1·8
29									1	2·4	1·6
30									3	2·1	1·4
31									3	1·9	1·2
32									1	1·6	1·0
33									0	1·4	0·9
34									0	1·3	0·8
35									1	1·1	0·7
36									0	1·0	0·6
37											
38											
39											
40											
41											
42											
43											
44											
χ^2		22·2		10·4	12·0		14·8	16·8		24·7	49·4
$P(\chi^2)$		0·05		0·30			0·20	0·10		0·30	0·001
q		0·64		0·78			0·76			0·90	
a				1·58			3·43			1·18	

APPENDIX II *continued*

Oxford Observed	Oxford Modified log.	Oxford Modified geometric	Falmouth Observed	Falmouth Modified log.	Falmouth Modified geometric	March Observed	March Modified log.	March Modified geometric	Edgbaston Observed	Edgbaston Modified log.	Edgbaston Modified geometric
884	873·1	865·0	628	660·8	628·9	1328	1270·3	1294·3	884	902·0	871·2
532	525·2	528·6	427	362·7	409·5	577	584·6	615·3	554	519·5	536·9
310	328·8	330·1	264	251·1	276·5	283	295·4	304·6	311	321·4	338·2
197	211·6	210·3	164	176·2	192·4	176	157·6	156·3	219	207·9	217·2
131	139 0	138 6	137	129·0	137·4	83	87·1	82·9	154	138·5	142·1
96	92·7	89·0	98	97·2	100·3	58	49·4	45·3	90	94·4	94·5
55	62·6	60·3	68	74·8	74·7	19	28·5	25·4	59	65·4	63·8
50	42·7	41·0	43	58·5	56·6	10	16·7	14·6	48	45·8	43·8
39	29·4	28·2	41	46·3	43·6	13	9·9	8·6	32	32·5	30·4
14	20·3	19·7	28	37·1	34·0	6	5·9	5·1	25	23·2	21·4
14	14·2	13·9	22	29·9	27·0	4	3·6	3·1	14	16·7	15·2
11	9·9	9·9	7	24·3	21·5	1	2·2	2·0	11	12·1	10·9
9	7·0	7·1	22	19·9	17·3	2	1·3	1·2	9	8·8	7·9
6	4·9	5·2	13	16·3	14·1	0	0·8	0·8	6	6·5	5·8
2	3·5	3·8	13	13·5	11·6	0	0·5	0·5	4	4·7	4·3
1	2·5	2·8	10	11·2	9·6	1	0·3	0·3	5	3·5	3·2
1	1·8	2·1	2	9·3	8·0	0	0·2	0·2	3	2·6	2·4
3	1·3	1·6	10	7·8	6·8	0	0·1	0·1	2	1·9	1·8
2	0·9	1·2	2	6·5	5·7	0	0·1	0·1	1	1·4	1·4
1	0·7	0·9	4	5·4	4·8				0	1·1	1·1
1	0·5	0·7	6	4·6	4·1				1	0·8	0·8
0	0·3	0·5	1	3·9	3·5				0	0·6	0·6
1	0·2	0·4	4	3·2	3·0				1	0·4	0·5
0	0·2	0·3	1	2·7	2·6				0	0·3	0·4
			0	2·3	2·3				1	0·2	0·3
			2	2·0	2·0				0	0·2	0·2
			3	1·7	1·8				1	0·1	0·2
			1	1·4	1·6				0	0·1	0·2
			1	1·2	1·4						
			2	1·0	1·2						
			1	0·9	1·1						
			1	0·7	1·0						
			2	0·6	0·9						
			2	0·5	0·8						
			2	0·5	0·7						
			2	0·4	0·6						
			2	0·3	0·6						
			2	0·3	0·6						
			1	0·3	0·5						
			2	0·2	0·4						
			2	0·2	0·4						
			2	0·2	0·3						
			2	0·2	0·3						
			1	0·1	0·3						
	11·2	12·7		50·2	21·5		14·1	1·61		4·7	5·6
	0·60	0·40		0·01	0·20		0·10	0·05		0·98	0·98
	0·75			0·88			0·66			0·78	
	3·05			0·92			1·35			1·81	

APPENDIX III—SEASONAL DRY-SPELL FREQUENCIES, OXFORD

	Winter		Spring		Summer		Autumn	
Spell length *days*	Observed	Log. model	Observed	Log. model	Observed	Log. model	Observed	Log. model
1	831	828·5	685	713·5	758	769·3	827	869·3
2	331	349·9	301	314·7	327	336·1	408	365·6
3	205	197·1	204	185·0	207	195·8	191	205·0
4	119	124·9	118	122·4	130	128·3	131	129·3
5	94	84·4	98	86·4	97	89·7	87	87·0
6	70	59·4	76	63·5	71	65·3	62	61·0
7	38	43·0	54	48·0	44	48·9	54	44·0
8	33	31·8	28	37·0	37	37·4	32	32·3
9	21	23·9	31	29·0	29	29·0	34	24·2
10	22	18·2	26	23·1	28	22·8	18	18·3
11	14	13·9	27	18·5	16	18·1	15	14·0
12	10	10·8	19	14·9	12	14·5	7	10·8
13	13	8·4	10	12·2	10	11·7	10	8·4
14	6	6·6	13	10·0	16	9·5	10	6·5
15	3	5·2	11	8·8	9	7·8	2	5·1
16	1	4·1	3	6·8	7	6·3	2	4·0
17	2	3·3	5	5·6	5	5·2	1	3·2
18	3	2·6	3	4·7	2	4·3	3	2·5
19	2	2·1	4	3·9	1	3·6	3	2·0
20	1	1·7	1	3·3	2	3·0	1	1·6
21	2	1·4	3	2·8	2	2·5	0	1·3
22	1	1·1	3	2·3	2	2·1	1	1·0
23	2	0·9	2	2·0	1	1·7	1	0·8
24	1	0·7	0	1·7	0	1·4	0	0·7
25	1	0·6	0	1·4	0	1·2	0	0·5
26	0	0·5	0	1·2	2	1·0	0	0·4
27	0	0·4	0	1·0	1	0·9	0	0·4
28	0	0·3	1	0·9	0	0·7	1	0·3
29	0	0·2	1	0·7	1	0·6	0	0·2
30	0	0·2	0	0·6	2	0·5	0	0·2
31	0	0·1	1	0·5	1	0·4	0	0·2
32	1	0·1	0	0·5	0	0·4	0	0·1
33	0	0·1	0	0·4	0	0·3	0	0·1
34	0	0·1	0	0·3	0	0·3	0	0·1
35	0	0·1	0	0·3	0	0·2	0	0·1
χ^2		20·34		23·4		12·1		11·5
$P(\chi^2)$		0·70		0·15		0·70		0·10
q		0·84		0·88		0·87		0·84

APPENDIX IV—SEASONAL WET-SPELL FREQUENCIES, OXFORD

Spell length *days*	Observed	Winter Modified log.	Winter Modified geometric	Observed	Spring Modified log.	Spring Modified geometric	Observed	Summer Modified log.	Summer Modified geometric	Observed	Autumn Modified log.	Autumn Modified geometric
1	718	697·1	680·4	680	682·3	660·9	757	816·7	734·3	762	746·6	744·8
2	409	392·6	408·9	393	386·0	392·3	404	414·2	424·9	434	422·5	435·9
3	212	239·7	252·2	211	232·4	238·5	245	234·6	251·9	241	254·5	262·0
4	142	153·7	159·8	144	145·6	148·2	150	141·4	151·9	174	159·4	161·4
5	105	101·9	103·3	90	93·8	94·0	98	88·6	93·5	84	102·7	101·7
6	69	69·1	68·2	61	61·6	60·7	56	57·1	58·6	68	67·5	65·3
7	40	47·7	45·8	44	41·1	39·8	38	37·5	37·3	46	45·0	42·8
8	46	33·4	31·3	39	27·8	26·6	26	25·0	24·2	21	30·4	28·5
9	26	23·6	21·7	23	19·0	18·0	12	16·9	15·8	28	20·8	19·3
10	13	16·9	15·3	13	13·0	12·3	12	11·5	10·5	11	14·3	13·2
11	19	12·1	10·9	4	9·0	8·6	11	7·9	7·1	13	9·9	9·2
12	9	8·8	7·9	7	6·3	6·0	4	5·5	4·8	5	6·9	6·5
13	3	6·4	5·7	3	4·4	4·3	7	3·8	3·3	10	4·8	4·6
14	7	4·7	4·2	3	3·1	3·0	1	2·7	2·3	3	3·4	3·3
15	1	3·4	3·1	1	2·2	2·2	0	1·9	1·6	1	2·4	2·4
16	2	2·5	2·4	0	1·6	1·6	2	1·3	1·2	2	1·7	1·8
17	2	1·9	1·8	1	1·1	1·2	2	0·9	0·8	0	1·2	1·3
18	2	1·4	1·4	2	0·8	0·9	1	0·7	0·6	2	0·9	1·0
19	1	1·0	1·0	0	0·6	0·7	0	0·5	0·4	1	0·6	0·7
20	2	0·8	0·8	0	0·4	0·5	0	0·4	0·3	1	0·4	0·6
21	0	0·6	0·6	1	0·3	0·4	0	0·3	0·2	1	0·3	0·4
22	0	0·4	0·5	0	0·2	0·3	0	0·2	0·2	0	0·2	0·3
23	0	0·3	0·4	1	0·1	0·2	0	0·2	0·1	0	0·2	0·3
24	0	0·2	0·3	1	0·1	0·2	0	0·1	0·1	0	0·1	0·2
25	0	0·2	0·2	0	0·1	0·1	0	0·1	0·1	0	0·1	0·2
26	1	0·1	0·2	0	0·1	0·1	0	0·1	0·1			
χ^2		19·9	29·4		11·3	15·2		13·4	10·7		19·4	21·4
$P(\chi^2)$		0·10	0·01		0·50	0·20		0·30	0·50		0·05	0·05
q		0·78			0·75			0·75			0·75	
a		1·58			2·075			1·087			2·075	

NOTES AND NEWS

Association of British Climatologists—New Directory

We have received a letter from the Association of British Climatologists informing us that the 'Second Directory of British Climatologists' (see the *Meteorological Magazine*, February 1975, page 60) is now available.

The 'Second Directory of British Climatologists' catalogues details of active research climatologists in this country at the end of 1974, their fields of interest and recent publications. It is divided into two sections: Section A consists of a list of institutions and their research interests (the section is subdivided into Institutes of Higher Education, Research Institutes and Related Bodies, and unattached Individuals); Section B lists research publications by individuals up to the end of 1974.

The 58-page Directory is available at a cost of 50 pence from the Hon. Treasurer of the Association, Dr E. M. Frisby, 10 The Larches, Headington, Oxford.

OBITUARY

It is with regret that we have to record the death of Mr E. C. W. Goldie, Assistant Scientific Officer, Met O 9, on 14 August 1975.

CORRECTION

Meteorological Magazine, September 1975, p. 258, line 29, for '0°C at 2·5 km' read '0°C at 0·5 km'.

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CONTENTS

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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