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THE CARDINGTON RAINFALL EXPERIMENT

By D. J. HOLLAND

Introduction.—In the mid-1950's the Meteorological Office undertook, with the Road Research Laboratory and the Hydraulics Research Station, a programme of research aimed at providing improved data and methods for the design of urban storm water drainage systems. The research was co-ordinated by a Committee set up by the Ministry of Housing and Local Government. It is estimated that the total cost of a new urban drainage system is of the order of £3 million and that average annual expenditure on new and reconstruction work in England and Wales is of the order of £30 million. No figures are available on the damage caused by flooding of such systems but clearly overall expenditure is sufficiently high to warrant examination of design practices from time to time.

That part of the work falling to the Meteorological Office was the specification of heavy rainfall intensities. The designer requires to know the frequency or return period of intense falls of rain over the area to be drained and the typical time profile of an intense fall of rain. The area of interest may vary from a few tens of acres to a few square miles depending on the particular scheme, and the operative time interval (the time of concentration — time from rain-water entering the upper end of the system to the outfall) from about 15 minutes to an hour or more.

Instruments to measure rainfall give directly only the rainfall over the area of the gauge aperture, hereinafter called point rainfall. The rainfall work therefore fell into two parts :

(i) Specification of the return period of heavy point rainfall in time periods varying from a few minutes to 1–2 hours.

(ii) The relationship between point and areal rainfall for areas from a few tens of acres up to a few square miles together with typical time profiles of build up and decay of heavy rain.

For (i) the present practice is to use an empirical formula derived by Bilham,[1] viz.

$$\log n = 5{\cdot}08 + \log t - 3{\cdot}55 \log (r + 2{\cdot}54)$$

where n = number of occurrences in 10 years
t = time in hours
r = rainfall in millimetres

except that for intensities greater than 30 mm per hour a modification due to Holland[3] is used. The Bilham formula was obtained using autographic records difficult to analyse for periods below about 15 minutes and is assumed to apply in all parts of the U.K. The collection of data from sufficient areas of the country in a form suitable for analysis over shorter time steps, in order to check the validity of this formula both for short time intervals and for geographical location, is continuing and will not be further discussed here. This paper is concerned with the work under (ii) above.

Site, instruments, data collected.—The site chosen for the experiment was one of about 10 km^2 in relatively flat country about 30 metres above mean sea level near Cardington in Bedfordshire. This is an area with fairly high thunderstorm frequency and the necessary support facilities were readily available there. The instruments used were Dines tilting-siphon rain-gauges with strip charts running through at 14 cm per hour so permitting analysis in 2-minute time steps. Synchronization of the gauges was aimed at through the use of electric clocks and mains power but there was also time marking using a chronometer on the daily visits to the gauges. The 16 gauges used initially were disposed over the roughly square area in 4×4 formation at about 1 km intervals. Subsequently additional gauges were put in at close spacing near the gauge at Cardington and three others added outside the area along the south-west/north-east diagonal extension, the farthest being about 10 km out. Initially the experiment was bedevilled by instrument troubles but these were largely overcome. In later years the experiment was confined to the summer half-year largely because this was the period giving by far the greatest contribution of data.

Analysis of the autographic records for the whole network was carried out only for those falls of rain which reached a peak intensity of at least 0·5 mm in 2 minutes at one or other of the gauges. On these occasions, which we shall call showers, tabulations were made in 2-minute time steps for all the gauges. These tabulation sheets form one of the ways in which this valuable body of data is available for any other use. The sheets contain data on approximately 150 showers.

Methods of analysis and results.—It is inevitable that some of the data from a field experiment such as this cannot be taken at their face value. Because of the possible effect of errors on the results and of the value of good data from this unique experiment in any other applications, it was considered worthwhile to devote considerable effort to cleaning the data. Corrections for rainfall during the siphoning interval apart, the other sources of trouble were too numerous to list here. For this correction the tabulations were subjected to rigorous checks against all available original autographic records before being mapped in 2-minute time steps. A sequence for one short shower is shown in Figure 1 (*a*) – (*f*). With the assumption that there is some space and time-wise consistency in showers of rain, such a method pointed to doubts about certain values (or allowed interpolation of missing ones). Although some smoothing is inevitably introduced, the result is that there are now more than 2000 maps in existence showing the rainfall of each of about 150 showers in 2-minute time steps and this is the second form in which the data are available for other uses. The data are also on 8-hole paper tape because machine methods were used in deriving many of the results.

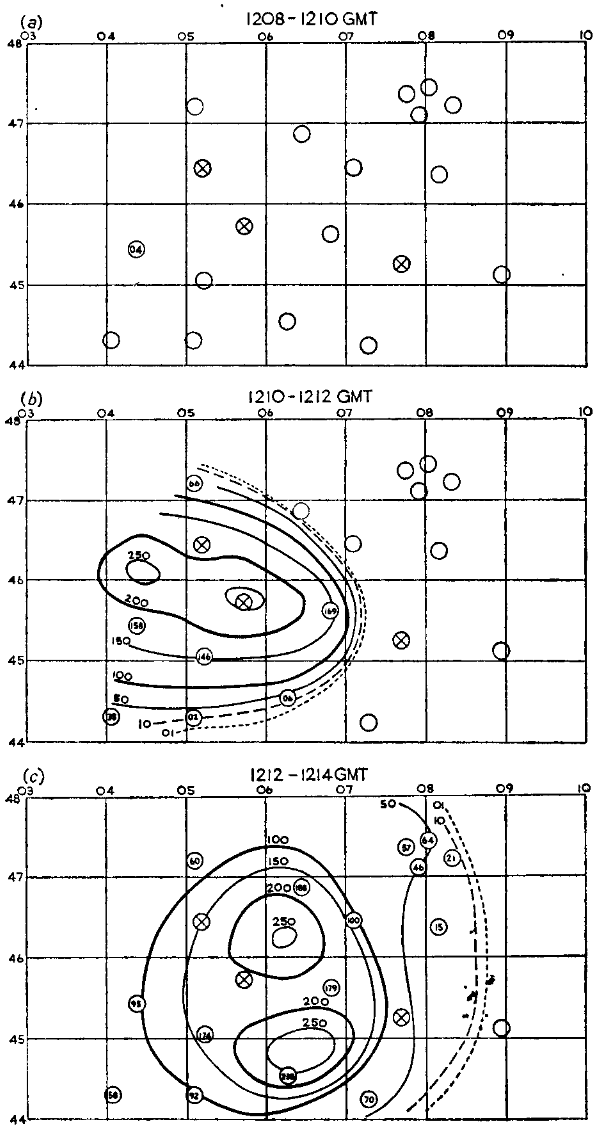

FIGURE 1—SEQUENCE OF CARDINGTON RAIN MAPS IN 2-MINUTE TIME STEPS FOR ONE SHORT SHOWER ON 22 JULY 1960

The unit is 0·1 mm. X denotes record dubious or missing. Empty circles denote definite record of no rain.

Point/areal relationships.—To illustrate the direct method used to derive point/areal relationships, Figure 2 shows the diagram obtained for 2-minute rainfall at a point (the central gauge) against 2-minute rainfall over the whole 10 sq. km area. The method used to obtain the points on the scatter diagram was as follows : Taking all the showers together the areal falls were ranked in descending order as were the point falls. Pairing

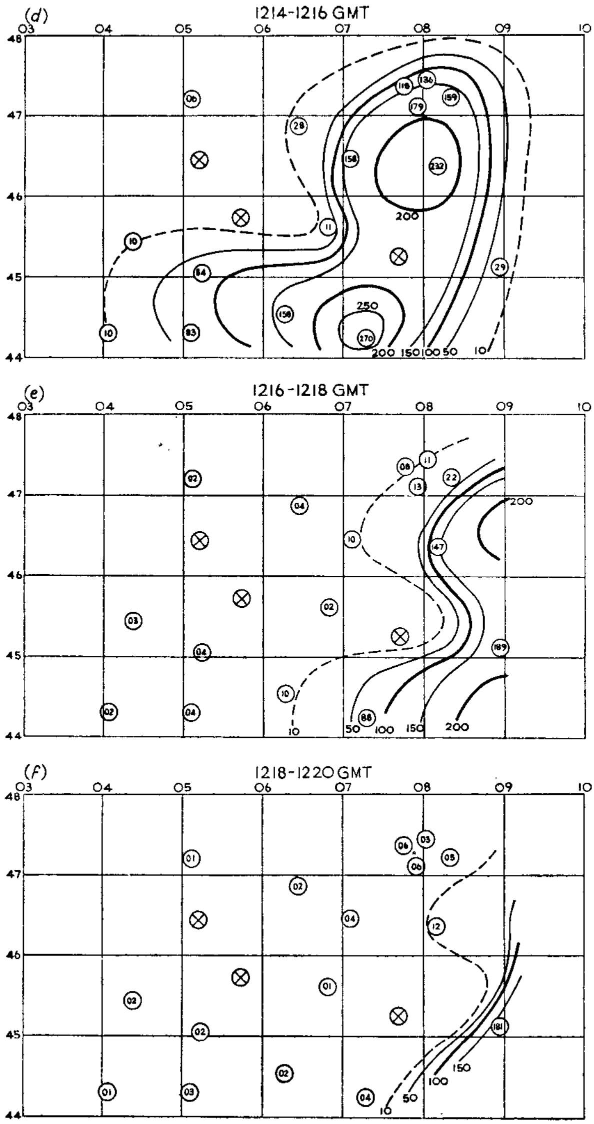

FIGURE 1—*Contd*

rank against rank produced the ordinate and abscissa for the individual points. This method was adopted because in the engineering context the need is to match frequencies or periods of return. However, in fact the slope of the line of best fit is very nearly the same as the ratio of the standard deviation of the areal values to that of the point values.

Consideration of various areas led to a simple rule that, for 2-minute rainfalls, the percentage reduction from point rainfall to areal rainfall is given by the square root of the area in hectares (or by S where $2{\cdot}5S^2$ is the area

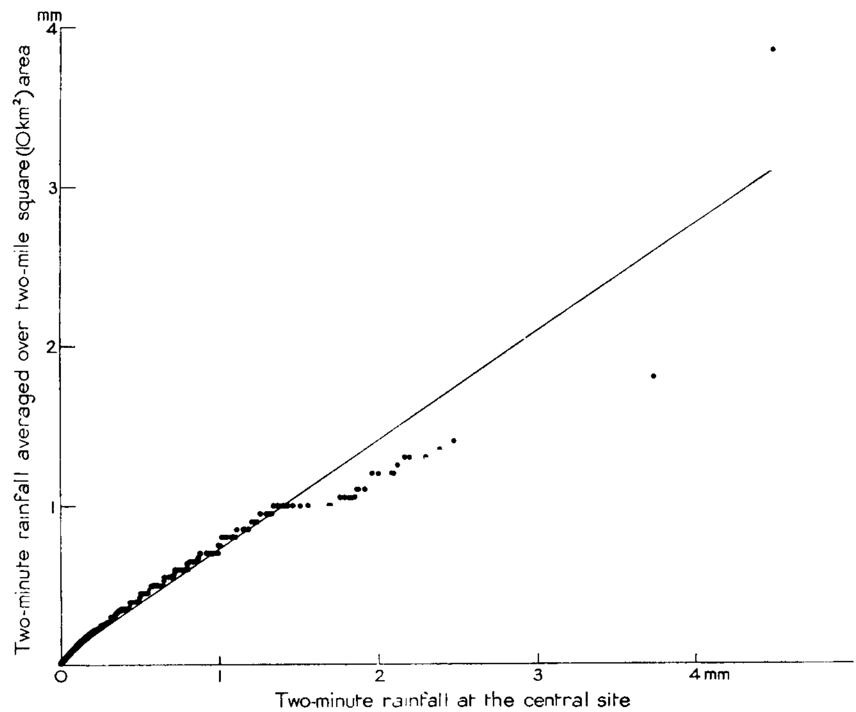

FIGURE 2—AVERAGE RAINFALL AGAINST POINT RAINFALL FOR 2-MINUTE PERIODS

in acres) to a high degree of approximation. Thus for an area of 100 hectares (about 250 acres) one can expect, on average, the 2-minute fall of rain to be 90 per cent of that near the central point. Engineers tend to welcome such rules, if not always the units which render them in their simplest form.

For time intervals longer than two minutes similar computations were carried out using COMET and it was found that the percentage shortfall from point rainfall for any time t from 2 to 120 minutes was well represented by $3S/\Gamma^{-1}(t)$ where again S^2 is the area in hectares or $2{\cdot}5S^2$ the area in acres.

Time profiles.—Turning to the time profiles of heavy showers, the design engineer requires to know the rate of build up and decay of rainfall over various areas (the sizes of the systems) smoothed time-wise over various intervals (the times of concentration of the systems). Once again the method used will be illustrated using the 10 km² area and the 2-minute time step. A selection was made from the individual showers' data such that the areal peak intensity was at least 1 mm in 2 minutes. For each shower the intensities at the 2-minute intervals before and after the peak (which might itself be sustained over successive intervals) were then expressed as percentages of the peak value. The mean profile was then obtained by meaning the ordinates (time from peak as abcissa) of the separate showers. The mean profiles for various areas and times of smoothing were computed and Table I gives the figures for the 10 km² area. The rainfall to be used as the 100 per cent value is obtained as indicated in the introduction above using the appropriate t and the return period as specified by the design engineer.

TABLE I—MEAN PROFILES OF 10 KM² AREA INTENSITIES SMOOTHED OVER THE STATED TIME INTERVALS

Minutes from peak	Width of time-band for smoothing *minutes* 6	8	10	16	30	60	120
-50	0	0	0	0	0	0	96
-48	0	0	0	0	0	1	98
-46	0	0	0	0	0	2	99
-44	0	0	0	0	0	3	99
-42	0	0	0	0	0	6	100
-40	0	0	0	0	0	9	100
-38	0	0	0	0	0	16	100
-36	0	0	0	0	0	25	100
-34	0	0	0	0	0	37	100
-32	0	0	0	0	1	51	100
-30	0	0	0	0	1	66	100
-28	0	0	0	0	1	79	100
-26	0	0	0	0	5	86	100
-24	0	0	0	0	11	91	100
-22	0	0	1	0	22	94	100
-20	0	1	1	1	33	96	100
-18	0	1	1	1	44	97	100
-16	1	2	2	2	60	98	100
-14	2	3	3	8	74	99	100
-12	3	4	4	20	85	99	100
-10	4	6	8	41	90	100	100
-8	8	12	23	63	94	100	100
-6	22	32	49	80	97	100	100
-4	49	62	75	91	98	100	100
-2	83	88	92	97	99	100	100
0	100	100	100	100	100	100	100
2	88	90	91	96	99	100	100
4	60	65	68	87	97	100	100
6	36	41	44	68	90	100	100
8	24	25	28	48	79	100	100
10	15	17	19	31	69	100	100
12	11	13	14	21	57	99	100
14	10	11	12	15	42	98	100
16	9	9	10	12	28	96	100
18	8	8	8	10	17	93	100
20	6	7	7	7	11	91	100
22	5	5	5	6	8	83	100
24	4	3	3	4	5	73	100
26	3	2	2	3	3	63	100
28	1	1	1	2	2	50	100
30	1	1	1	2	1	33	100
32	1	1	1	1	1	21	100
34	1	1	1	1	1	14	100
36	0	0	0	0	1	9	100
38	0	0	0	0	0	5	100
40	0	0	0	0	0	3	100
42	0	0	0	0	0	1	100
44	0	0	0	0	0	1	100
46	0	0	0	0	0	1	99
48	0	0	0	0	0	1	98
50	0	0	0	0	0	0	96

These results are now being used in the Road Research Laboratory's hydrograph method for the design of urban storm water drainage systems. The method was programmed by the Road Research Laboratory for electronic computer some time ago and has been used since in a considerable number of cases. The output from the computer gives the pipe sizes to be used in various parts of the drainage scheme. The method is flexible in that it allows the engineer rapidly to be given the effect of varying some of the factors, e.g. the proportion of impermeable surface in the area, the return period of rain intensity. The Road Research Laboratory has arranged briefing courses for practising engineers, an education programme to which the Meteorological Office has contributed. The necessary computer services are now available to engineers from commercial computer laboratories. An outline of the method is given in Road Research Laboratory Road Note No. 35.[2]

Alternative method to determine the area-factor.—An alternative approach to the derivation of the area factor was made using correlations between gauge catches. At an early stage in the analysis Mr J. S. Sawyer had suggested that it might be revealing for correlation coefficients to be computed for falls of rain in various time intervals in pairs of gauges at various distances apart. It was this suggestion which led to the north-eastward extension of the network. The first step in this approach was to compute correlation coefficients between pairs of gauges aligned WSW – ENE for 2-minute rainfall amounts, plotting them against the distance between the gauges. Similarly correlation coefficients between pairs of gauges aligned NNW – SSE, i.e. at right angles to the first set, were found and plotted. The correlograms were so similar that it could be assumed that there was no directional bias. The same operation was performed on running 30-minute and 120-minute falls with the same conclusion. So correlation coefficients (R) between pairs of gauges whatever their alignment were computed and Figures 3(a) – (c) show the results. The plots on these correlograms can be well represented by straight lines of the form $R = 1 - x/M$ where x is the distance between the gauges. For x in kilometres, $M = 4$ for 2-minute falls, 5·5 for 30-minute falls and 7 for 120-minute falls.

Two workers, R. P. W. Lewis and D. J. Holland, have independently derived formulae for the variance ratio of the spatial average over an area and point values, provided the correlation between point values is independent of orientation. After the necessary integrations these both reduce, for a square area of side L, to variance ratio $= 1 - 0{\cdot}52L/M$, M being as before. The square root gives the ratio of the standard deviations between area and point values which should correspond with the figures obtained by the direct method given above. The comparison is given in Table II and the correspondence is considered gratifyingly close.

Mean storm drift.—One can imagine that the drainage engineer's nightmare would be a once in a hundred years rain storm moving across a drainage area keeping pace with the water draining in the sewers. Hence an attempt was made to assess the velocity of the peaks in the rain intensity patterns portrayed in the series of 2-minute maps drawn. This was found practicable for nearly every sequence, with only a superficial distinguishing of one synoptic situation from another, though the estimating may well have been only rough. It is interesting to note that the reduction factor for time-wise smoothing of point rainfall between $t = 2$ and $t = 6$ minutes, namely about 2/3, is much the same as the reduction factor for space smoothing for 2-minute rainfall between point and 10 km² area rainfall (square of side about 2 miles). This prompts the question whether the underlying factor is not a 20 m.p.h. mean speed of the rain intensity patterns.

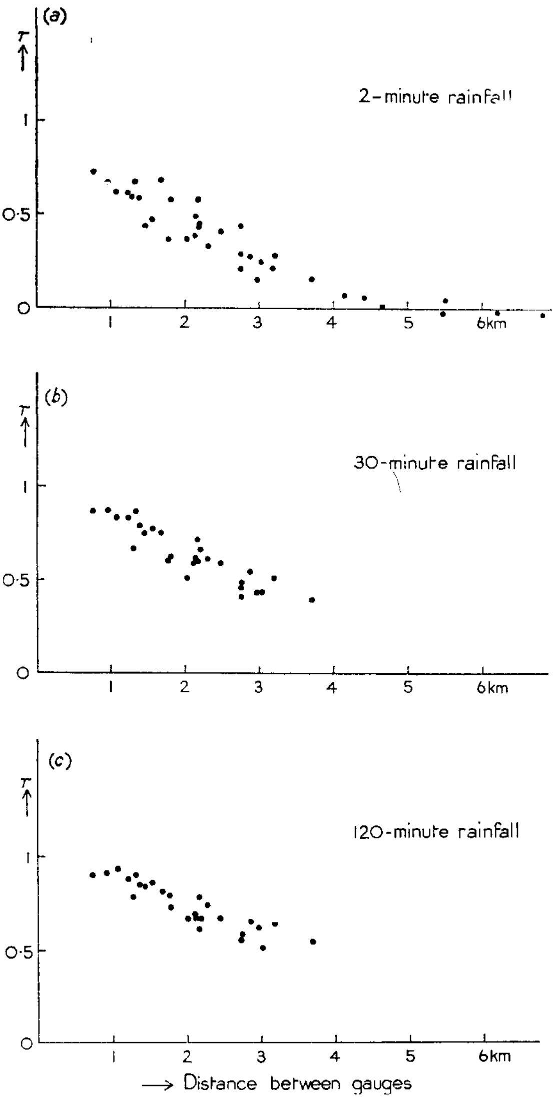

FIGURE 3—CORRELATIONS BETWEEN POINT RAINFALL AMOUNTS IN GAUGES AT VARIOUS SPACINGS, IN 2, 30 AND 120-MINUTE INTERVALS

Sequence by sequence loggings of storm drift velocity were made using the Cardington maps, then suitably averaged and compared with the corresponding 700 mb winds obtained from the *Daily Aerological Record.* The averaging was such as to give all the maps equal weight, i.e. the velocity vector was multiplied by the number of 2-minute time steps concerned thus giving displacement vectors. The scalar mean of these displacements divided by the total number of maps (2-minute time steps) yielded a mean speed

TABLE II—COMPARISON OF STANDARD DEVIATION RATIOS OF AREAL AND POINT VALUES OBTAINED BY THE TWO METHODS

Standard deviation ratio for:	Length of side of square *kilometres* 1	1·6	3·2
2-minute falls			
Alternative method	0·93	0·89	0·76
Direct method	0·91	0·84	0·71
30-minute falls			
Alternative method	0·95	0·92	0·84
Direct method	0·97	0·90	0·81
120-minute falls			
Alternative method	0·96	0·94	0·87
Direct method	0·97	0·92	0·86

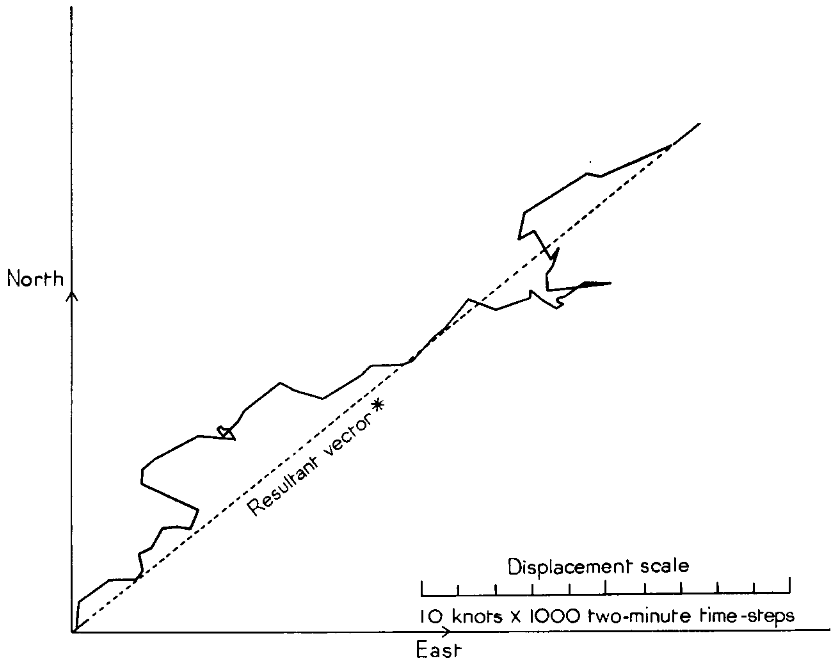

FIGURE 4—VECTOR DIAGRAM OF STORM DRIFTS AS ESTIMATED FROM 2035 RAIN MAPS

* Magnitude of resultant vector (shown by pecked line) : 2035 2-minute time steps × 10·7 knots. Scalar mean of all the speeds : 17 kt. Corresponding scalar mean 700 mb wind speed : 23 k . Corresponding vector mean 700 mb wind : 230° 16 kt.

of 17 kt (20 m.p.h.). Figure 4 gives the corresponding vector diagram, the vector mean drift velocity being 10·7 kt from the south-west. Similar treatment of the 700 mb wind vector, one for each sequence, yielded a vector mean drift velocity of 16 kt.

Future work.—Although one may hope and perhaps expect it to be the case, it cannot necessarily be assumed that the results obtained for Cardington, a flat area, apply in all parts of the country where there is, or may be, urban development. It was considered that the experiment should be repeated in a more hilly area and so a similar network over a similar area was set up near Winchcombe in the Cotswolds in rolling country with a range of altitude from about 300 to 900 feet. Sufficient data are expected to be available from this network for the experiment to be terminated during 1967. The data will be treated as in the alternative method outlined above. If the results are similar to those obtained for Cardington all will be reasonably well. If not, problems of repetition for other areas may arise. But in this event the work has shown that good results may be obtained using only a line of gauges, a field experiment easier to mount.

The limited amount of work done on storm velocities has its disquieting features. Further effort needs to be devoted to this so that the additional hazards to which some drainage systems may be subject are more definitely specified.

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THE GROWTH ENVIRONMENT OF HAILSTONES

By K. A. BROWNING

Summary.—Two models of hailstone growth environments are reviewed. One model, the 'rain storage' model, holds that hailstones grow in the presence of high concentrations of stored raindrops ; the other model, the 'no rain storage' model, holds that hailstones grow in the presence of modest concentrations of cloud droplets. It is suggested that, when large hailstones are grown in the 'rain storage' model, they are likely to be very spongy. However, in the 'no rain storage' model, large hailstones can be grown which contain relatively little unfrozen water and which may also have a lobed structure. Pronounced lobe structures may develop in large hailstones when the cloud droplets are very small. Thus the presence of a lobe structure may prove to be a valuable tool in diagnosing the nature of the hailstone growth environment.

Introduction.—It is well known that hailstones grow by colliding with and freezing onto themselves supercooled water drops within a cumulonimbus updraught at levels where the ambient temperature is somewhere between 0°C and −40°C. However, there are at present two strongly divergent views as to the nature of the cloud environment in which hailstones are grown. One view is that hail grows in the presence of large concentrations of raindrops suspended aloft; the other view is that it grows in the presence of modest concentrations of cloud droplets. We shall refer to them, respectively, as the 'rain storage' and the 'no rain storage' models. The purpose of this paper is to highlight the evidence and implications of these models and to indicate a possible new source of evidence.

The 'rain storage' model.—As a parcel of moist air rises within a cumulonimbus updraught, an ever increasing proportion of the water vapour condenses into cloud droplets. Ludlam[1] has computed the resulting (adiabatic) concentration of liquid water as a function of altitude for different cloud-base temperatures on the assumption that the updraught is not diluted significantly by drier environmental air as it ascends (Figure 1). According to recent studies,[2] this is a good assumption for the updraught cores of intense hailstorms. The adiabatic cloud water content in a summertime cumulonimbus in Alberta, Canada, for example, usually turns out to be about 4g/m³, while that in a warm-base cumulonimbus in the United States mid-west often exceeds 7g/m³.

Hitschfeld and Douglas,[3] in studying Alberta hailstorms, have been impressed by the speed of growth of hailstones. They have noted occasions when the time between the first radar echo (indicative of millimetric precipitation particles) and the arrival at the ground of the first hailstones has been as small as 25 or even 15 minutes. In an effort to better explain rapid hailstone growth they have suggested that hailstones may benefit from water contents in excess of the 4g/m³ typical of adiabatic contents. They suggest that this might occur as a result of high concentrations of raindrops growing within a persistent updraught. They raise the possibility that rain storage might lead to liquid water contents as high as 30 g/m³.

A rather similar 'rain storage' model has been proposed by Sulakvelidze and his co-workers at the Alpine Research Institute of the U.S.S.R. (see the review by Battan[4]). According to Bibilashvili *et alii*[5] the updraught in a hail cloud is vertical and reaches a maximum of at least 10 m/s near or just above the 0°C level; above this the updraught velocity decreases rapidly upwards. This is thought to lead to an accumulation of supercooled raindrops just above the updraught maximum in the zone where temperatures

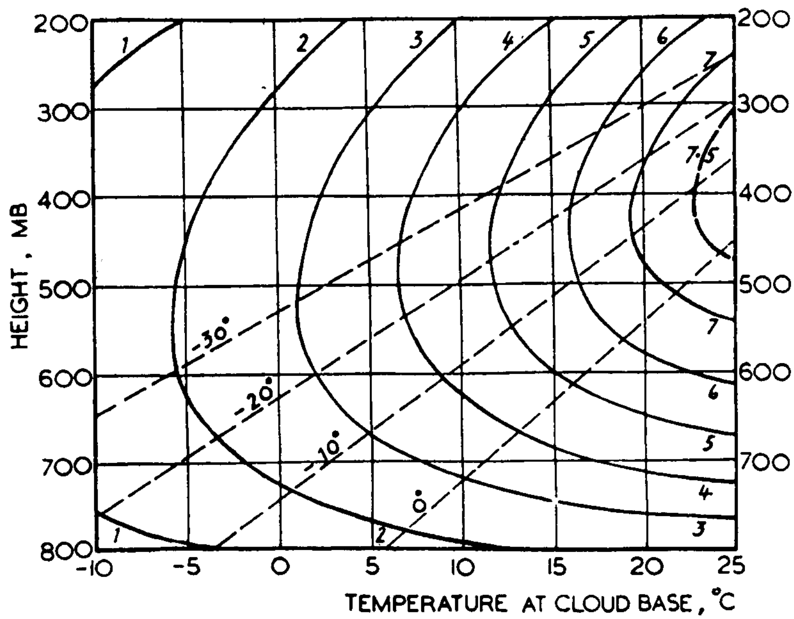


FIGURE 1—THE ADIABATIC LIQUID WATER CONTENT WITHIN CUMULIFORM CLOUDS

The values are calculated for clouds having bases at 900 mb ; saturation with respect to liquid water is assumed throughout and the isopleths show the liquid water content in g/m³. The dashed lines indicate the temperature within the cloud. Diagram after Ludlam.[1]

are between -1° and $-10^{\circ}C$. Calculations and measurements by Bartishvili *et alii*[6] suggest liquid water contents *averaging* 20 — 30 g/m^3. Measurements of even higher liquid water contents have been reported within Oklahoma hailstorms by Roys and Kessler.[7]

As a hailstone accretes supercooled water droplets the release of latent heat accompanying their freezing raises the temperature of the hailstone surface to the point where heat can be transferred to the air by conduction and convection. When a hailstone accretes rapidly its surface temperature is likely to be raised to $0^{\circ}C$ so that not all of the accreted water can be frozen immediately. It used to be thought that any excess unfrozen water would be shed, in which case the high water contents in the 'rain storage' model would not benefit hailstone growth.

However, the laboratory work of List[8] and Macklin[9] has shown that shedding usually does not occur. Rather, a hailstone is able to retain unfrozen water, amounting to as much as 70 per cent of the weight of the hailstone, to give a spongy ice-water mixture. In other words a growing hailstone can benefit from most of the supercooled water that it accretes, regardless of whether or not it may all be frozen immediately.

A feature of the Canadian and Soviet models is that a lot of the hailstone growth occurs within a rain storage region near an altitude corresponding to the $-10^{\circ}C$ isotherm. Extremely spongy hailstone growth is inevitable under these conditions, unless a large proportion of the cloud water content is already frozen at these altitudes. Figure 2, taken from Macklin,[9] shows that a 1-cm radius hailstone, for example, growing at the $-10^{\circ}C$ level can freeze immediately only 1 g/m^3 of accreted liquid water. Of course, consolidation of spongy hailstones might occur if they were subsequently lifted to higher and therefore colder altitudes by an intense updraught, but the existence of the latter appears to be inconsistent with the requirements of the rain storage mechanism. Consequently it is hard to imagine how this model can fail to give rise to rather large numbers of very spongy hailstones. Some of these would be expected to reach the ground, although spongy outer layers will be particularly susceptible to melting unless the stones happen to fall outside the cloud.

It is evident from Figure 2 that the problem of increasing the ice deposition rate on a growing hailstone could be diminished by having it grow at low ambient temperatures, say between -30° and $-40^{\circ}C$. However, it seems unlikely that large raindrops could remain unfrozen for long at such low temperatures. On the other hand, hailstone growth at these levels could proceed in the presence of supercooled small cloud droplets, provided that the hailstones themselves have no undue competition from frozen raindrops for the available cloud liquid water content.

The 'no rain storage' model.—This model stems from a study of the Wokingham Hailstorm by Browning and Ludlam[10] and from subsequent studies of severe hailstorms in Oklahoma by the present writer.[11] As such, the model is biased towards giant travelling hailstorms with tops penetrating into the stratosphere.

Radar has been one of the chief tools used in these studies, since it is capable of providing a crude but almost instantaneous description of the three-dimensional distribution of precipitation particles. A feature of the radar

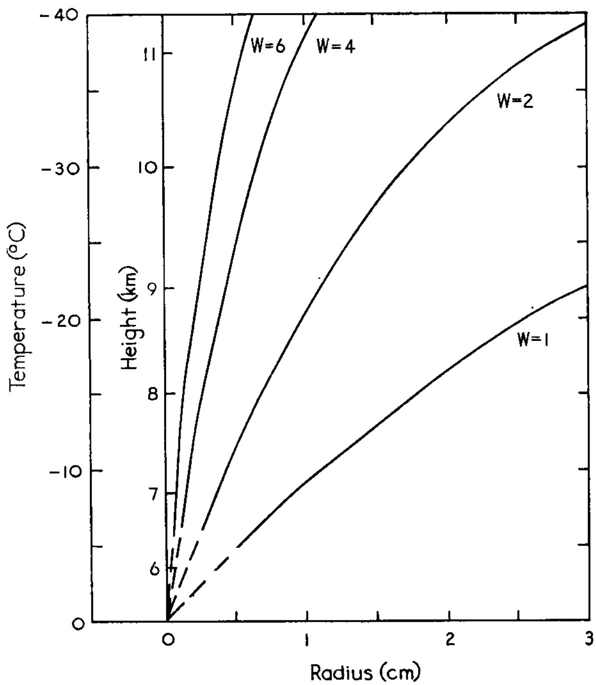


FIGURE 2—THE CONDITION FOR ENTRY OF HAILSTONES INTO THE WET-GROWTH PHASE

The maximum liquid water content that will permit a hailstone to freeze immediately all of the accreted water, assuming a collection efficiency of unity. If the position of a hailstone on the diagram, as determined by its size and the cloud temperature, is to the right of the appropriate isopleth of liquid water content (w), then it will be unable to freeze immediately all of the accreted water, and spongy ice will be produced. Diagram after Macklin.[9]

structure of some severe travelling hailstorms which has particular relevance in the present context is a region of very weak echo in the heart of the storm, called the echo-free vault. Vaults are difficult to resolve from the intense echo within which they are embedded, but those which have been detected so far have been located directly beneath the storm's highest top and have extended from the ground upwards into the middle or even upper troposphere (e.g. Figure 3). Convincing evidence has been obtained to show that the vault is located within an intense and tilted updraught[11] and indeed it is believed to be the updraught itself that is largely responsible for the existence of the vault. The updraught is thought to be strong enough to prevent rain and hail from falling into the vault. Moreover, cloud droplets formed within the vault near cloud base are thought to be carried upwards towards the ceiling of the vault within a period of several minutes which is too short to allow them to grow by condensation to anything near radar detectable sizes. The hailstorms with vaults that have been observed so far have been associated with a large horizontal extent of intense echo penetrating the tropopause and also a large horizontal extent of hail at the ground. This has led to the view that the updraught within the vault was only part of a more extensive updraught many kilometres in diameter, i.e. large enough for mixing with

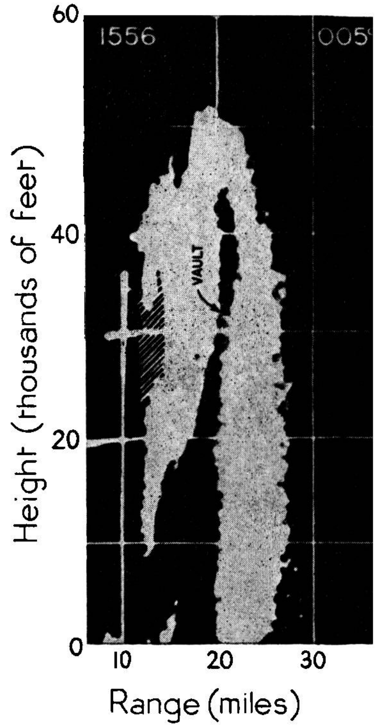


FIGURE 3—A VERTICAL SECTION THROUGH THE RADAR ECHO FROM A SEVERE OKLAHOMA HAILSTORM

This is a photograph of an RHI scope and it has a greatly exaggerated vertical scale. Notice the echo-free vault extending from the ground upwards directly beneath the storm's highest top. It is thought that the vault marks the location of an intense updraught containing adiabatic concentrations of small cloud droplets. Diagram after Browning.[11]

environmental air to be neglected, particularly if there is smooth flow in the updraught core. Therefore it appears likely (*a*) that the vault contains only small cloud droplets and (*b*) that the droplets are present in adiabatic concentrations.

Detailed observations of surface weather by the writer both in England and in Oklahoma have made it clear that the largest hail generally reaches the ground quite close to the periphery of the vault. A consideration of the hailstone trajectories, and also the high intensity of the radar echo surrounding the vault at higher levels, suggests that the hailstones have in fact descended close to the edge of the vault (Figure 4). Bearing in mind that the same intense updraught that exists within the vault is probably also present around its periphery where the hail is growing, it is reasonable to assume that this hail does grow for much of the time within an environment containing an adiabatic concentration of small cloud droplets but no stored rain. Hailstones growing in such an environment would be expected to grow somewhat more slowly than in the 'rain storage' model but with a much smaller amount of unfrozen water. The 'no rain storage' model would make it easier to account for hailstones, especially large ones, that arrive at the ground containing only small amounts of spongy ice.

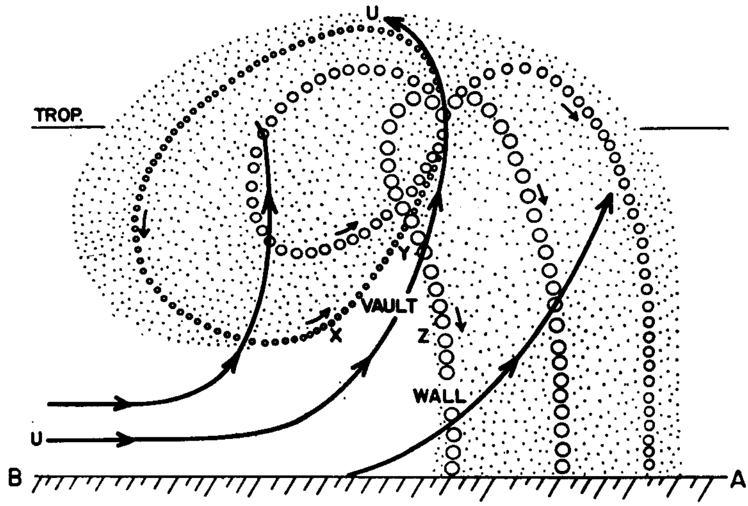
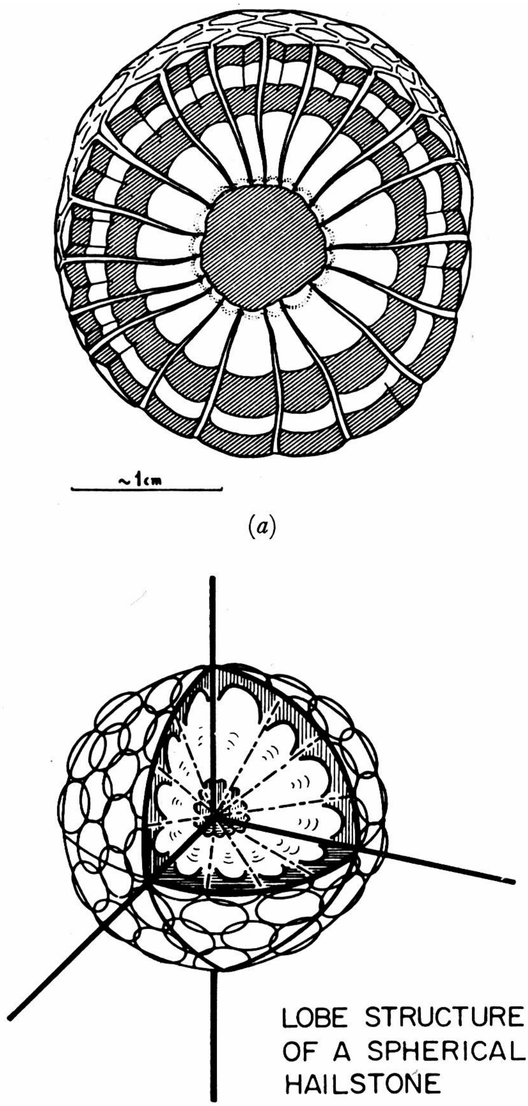


FIGURE 4—A VERTICAL SECTION SHOWING SCHEMATICALLY HOW A VAULT MIGHT BE PRODUCED

Solid lines are streamlines of airflow within the updraught, the updraught axis being along UU. Circles represent hailstone trajectories, the size of the circles denoting whether the stones are small, medium or large. The stippled area denotes the extent of moderately intense radar echo. Diagram after Browning.[11]

The growth environment as determined from the hailstone structure.—After Ludlam[12] had framed the concept that hailstone growth would be 'wet' or 'dry' according to whether the mean surface temperature was at or below 0°C, and after Macklin[13] had shown that the opacity of the accreted ice depended upon the surface temperature, optimism ran high that at least some aspects of the growth of a hailstone might be deduced from its layered structure. Since then optimism has been tempered by the discovery that spongy ice formed at 0°C may sometimes be confused with ice accreted at lower surface temperatures. After presenting a long list of parameters affecting hailstone structure, List[14] concludes that 'the feasibility of relating specific icing conditions to given hailstone shells still has to be rated as poor'. Recently, however, a different line of study has suggested a possible new way in which the hailstone can tell us something about its growth environment and, in particular, about the size of the cloud droplets.

Most of us are familiar with the layered or onion-like structure of hailstones, in which growth variations in a radial direction have led to alternate shells of clear and opaque ice. However, we are less familiar with growth variations that in spherical polar co-ordinates have an angular dependence and lead to lobe structures. Although mentioned from time to time in the literature, it is only lately that any great importance has been attached to the lobe structure. Almost identical descriptions have been published independently by Sarrica[15] and by the present writer.[16] Apparently some hailstones grow as three-dimensional arrays of more or less totally frozen lobes, sometimes but not always separated by regions of spongy ice characterized by radial lines of large air bubbles (Figure 5). The growing surface of individual lobes is sometimes strongly convex outward and this causes successive growth layers to become convoluted or scalloped, giving rise to knobs on the hailstone surface (Plate I). Lobe structures are generally most pronounced in large hailstones (Plates II and III); however, they can often be distinguished in smaller hailstones too (Plate IV).



(*a*)

(*b*)

FIGURE 5 (*a*) AND (*b*)—SCHEMATIC DIAGRAMS ILLUSTRATING HOW SOME HAILSTONES ARE COMPRISED OF ASSEMBLIES OF RADIALLY DISPOSED LOBES SEPARATED BY RADIAL CHANNELS

The strongly convex-outward surface of the lobes leads to scalloped growth layers and to surface knobs ((*a*) : after Sarrica,[15] (*b*) : after Browning[16]).

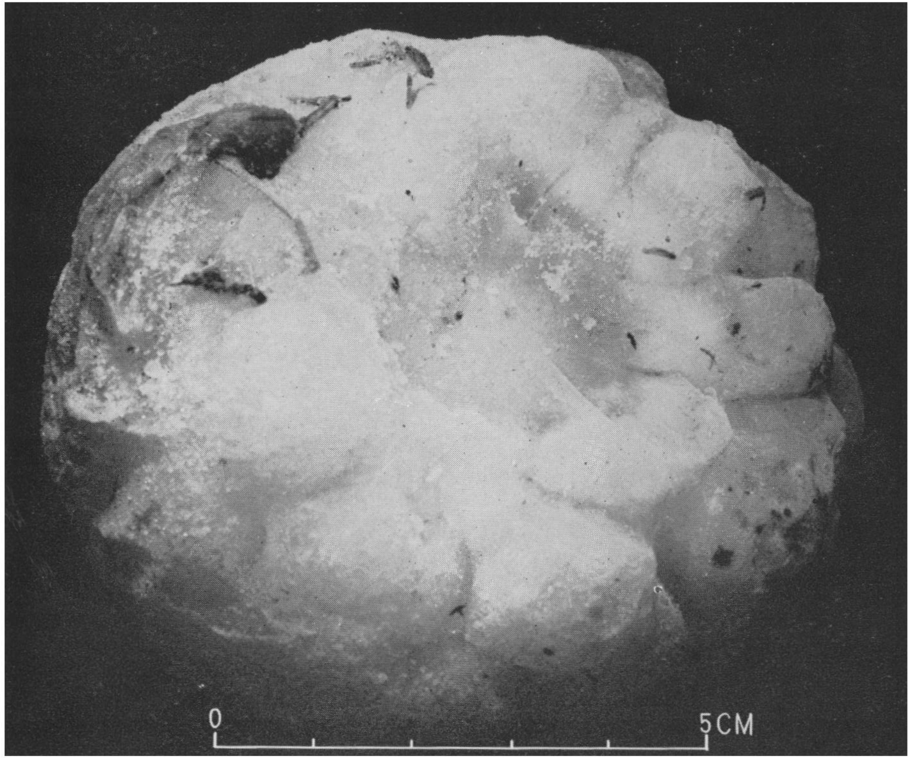


PLATE I—PHOTOGRAPH OF A KNOBBLY HAILSTONE 8 CM IN DIAMETER

The dark circular indentation about 2 cm in diameter, which can be seen in the centre of the hailstone surface, is probably due to melting.

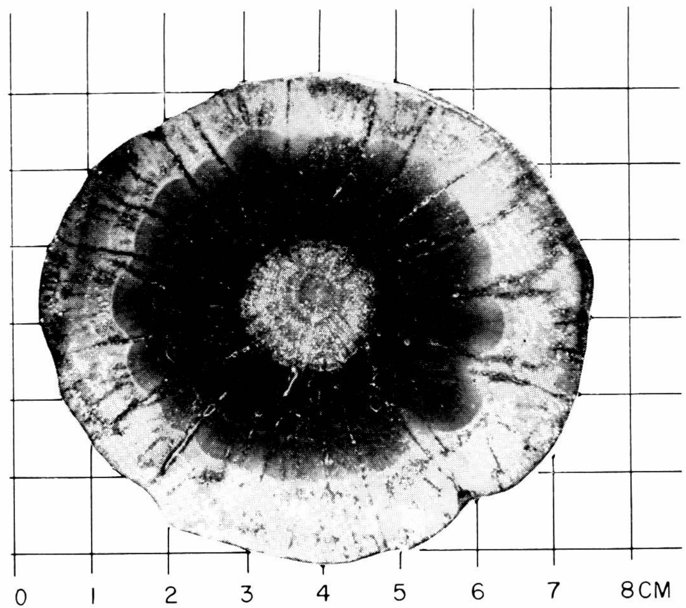


PLATE II—PHOTOGRAPH[16] OF A THIN SECTION PASSING THROUGH THE GROWTH CENTRE OF A GIANT LOBED HAILSTONE

Regions of transparent ice appear black, while opaque ice containing many air bubbles appears white. Notice the well-defined radial channels separating some of the lobes. The smooth outer surface of the hailstone is due to melting.

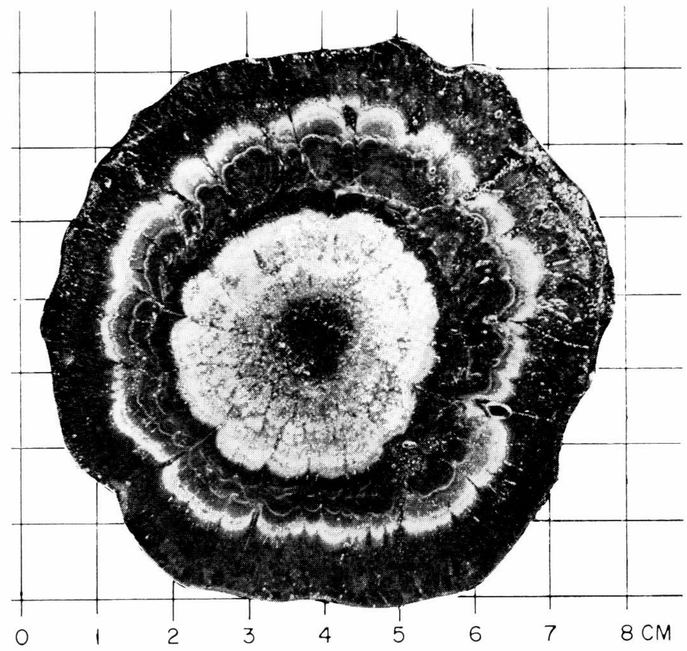


PLATE III—PHOTOGRAPH OF A THIN SECTION PASSING CLOSE TO THE GROWTH CENTRE OF A GIANT LOBED HAILSTONE COLLECTED BY THE AUTHOR AFTER THE 26 MAY 1963 HAILSTORM NEAR OKLAHOMA CITY

Regions of transparent ice appear black, while opaque ice appears white.

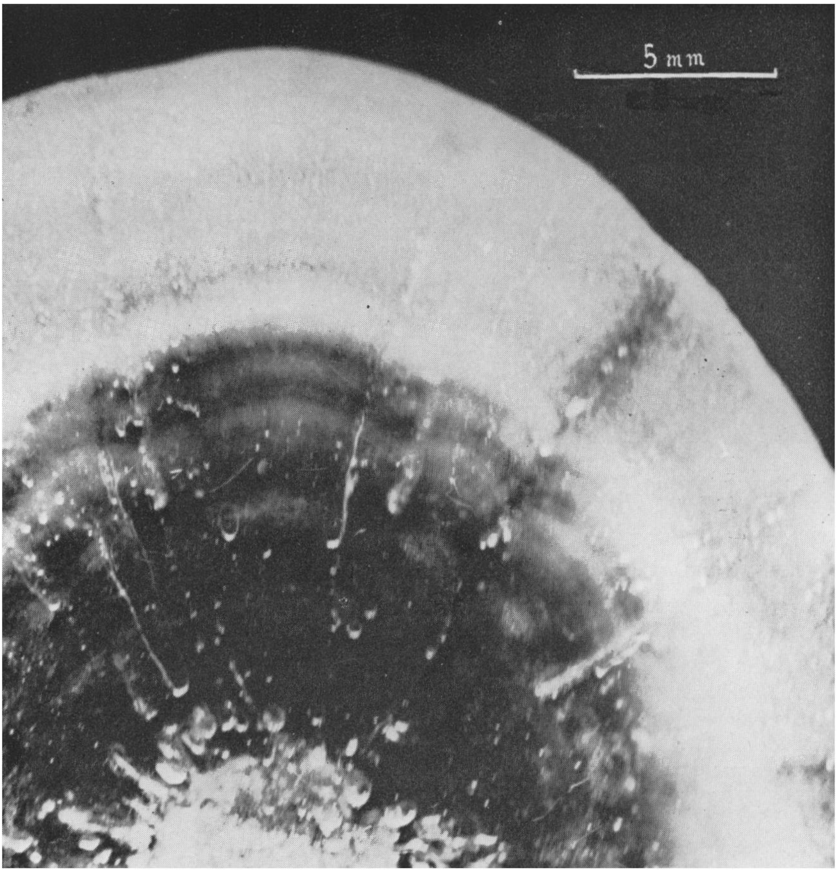


PLATE IV—PHOTOGRAPH[15] OF PART OF A THIN SECTION PASSING THROUGH THE GROWTH CENTRE OF A RELATIVELY SMALL LOBED HAILSTONE

Regions of transparent ice appear black, while opaque ice appears white.

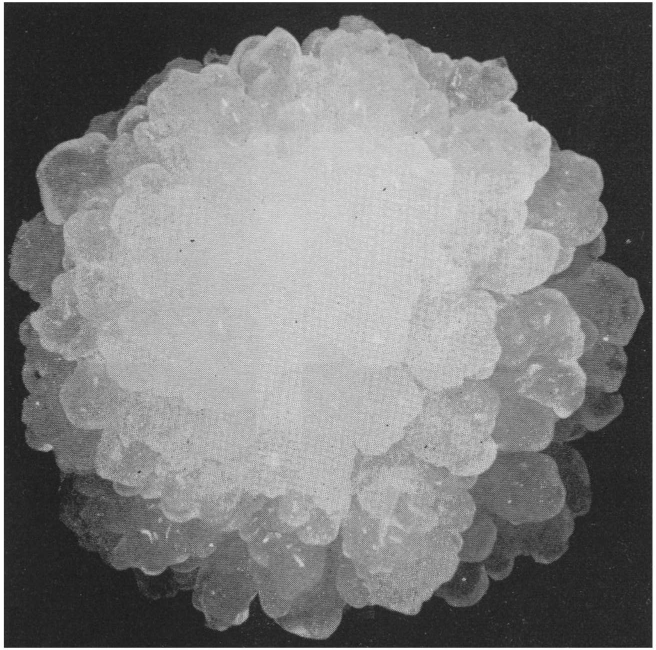


PLATE V—PHOTOGRAPH[20] OF A LOBED HAILSTONE 10 CM IN DIAMETER GROWN FREELY SUSPENDED IN A VERTICAL WIND-TUNNEL

The scale is as in Plate VI. This stone was grown near the wet-growth limit but not spongily. The ambient temperature was between −12°C and −7°C, the effective cloud liquid water content was about 1·7 g/m^3, and the median volume radius of the droplets was 15μm. In the presence of larger droplets, or when the growth was appreciably spongy, lobe structures were not produced.

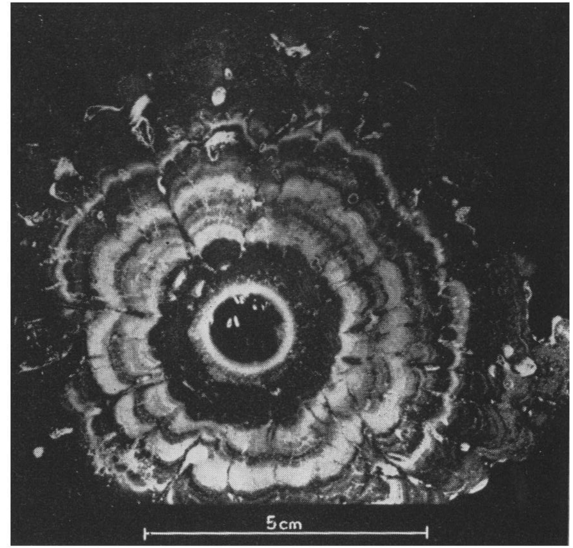


PLATE VI—PHOTOGRAPH[20] OF A THIN SECTION THROUGH AN ARTIFICIAL HAILSTONE RATHER SIMILAR TO THE ONE SHOWN IN PLATE V

This stone was grown freely suspended at ambient temperatures between −22 and −19°C, the effective cloud liquid water content being close to 4·3 g/m^3, and the median volume droplet radius being 15μm. Bailey and Macklin suggest that the sharp changes in bubble structure probably coincide with the periodic removal of the hailstone from the hail tunnel. Notice the remarkably similarity between the lobe structure of this artificially grown hailstone and that of the natural stone in Plate III.

Several authors have suggested that the development of surface knobs is favoured by the presence of very spongy ice.[9,14,17,18] My own analysis,[16] on the other hand, suggested that lobe structures and the resultant surface knobs occur in the absence of very spongy growth. It was suggested that the absence of very spongy growth might be due in part to an enhancement of the rate of heat transfer compared with that for a smooth sphere. The implication was strong that lobes developed spontaneously as a result of circumstances in which minor protuberances on the hailstone surface acquired a collection efficiency greater than that of the hailstone as a whole. Computations by Macklin and Bailey[19] of the collection efficiency of large hailstones with respect to cloud droplets supported this view. Their curves, shown in Figure 6, demonstrated that in the presence of small droplets there may be a large decrease in collection efficiency as a smooth hailstone grows large. This means that small irregularities are likely to grow into knobs, because they will have enhanced collection efficiencies compared with the stone as a whole. The effect appears to be very small for 50μm or larger droplets but becomes pronounced for 10μm droplets. If these curves are valid, therefore, it means that wherever a hailstone is found to have a lobe structure it is likely to have grown mainly in the presence of small cloud droplets and not in

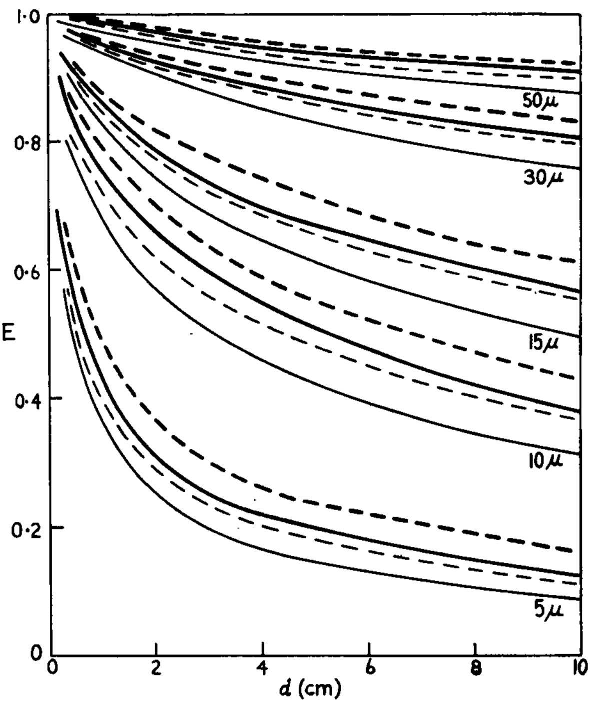


FIGURE 6—THE COLLECTION EFFICIENCY, E, OF SMOOTH SPHERICAL HAILSTONES FOR CLOUD DROPLETS OF VARIOUS RADII COMPUTED AS A FUNCTION OF HAILSTONE DIAMETER, d

The full curves are appropriate to the –20°C level and the broken curves to the –40°C level. The heavy and light curves have been computed assuming hailstone drag coefficients of 0·55 and 1·1 respectively. Diagram after Macklin and Bailey.[19]

the presence of the large droplets of the 'rain storage' model. The pronounced lobe structure leading to large surface projections that is occasionally encountered in severe hailstorms (see Figures 8(*a*) and 9 in Browning,[16] and Figure 5(*i*) in Carte and Kidder[17]) appears to require growth in the presence of unusually small cloud droplets.

It is clearly desirable that these ideas should be checked on the basis of laboratory experiments with artificially grown hailstones. Unfortunately until recently none of the experiments with artificial hailstones had properly reproduced the growth conditions that would lead to lobe structures. First of all, no experiments had been made using large concentrations of very small droplets. Secondly, most experiments had been conducted with rigidly suspended or rotated hailstone models, whereas my analysis[16] of natural hailstones had suggested that a three-dimensional radial lobe structure would only develop if a hailstone were tumbling freely as it grew. These shortcomings have been made good in a study by Bailey and Macklin.[20] They have grown large artificial hailstones freely supported within a vertical wind tunnel. By using a battery of sprays they obtained realistically high concentrations of droplets with median volume radii sometimes as small as 15μm. They were thus able to verify the applicability of the curves in Figure 6, at least in a qualitative sense. Radial lobe structures strikingly similar to those found in some natural hailstones were reproduced when the median volume droplet radius was as small as 15μm (Plates V and VI). However, the lobes became less pronounced as the droplet size was increased. The lobes also became less pronounced when the growth was very spongy, even when the droplets were fairly small.

The lobed hailstones, described in my article[16] and subsequently discussed by Macklin and Bailey,[17] fell in an Oklahoma hailstorm close to a well-developed echo-free vault. The structure of the hailstones and of the parent hailstorm have been discussed in detail in a monograph by Browning and Fujita.[21] The point to be emphasized here is that the lobe structure of the hailstones, and also the fact that they grew on the edge of a vault, are both consistent with the 'no rain storage' model. However, in order to draw any general conclusions about severe hailstorms it will be necessary to find out how frequently lobed hailstones occur in relation to spongy stones. It is possible that we shall find that in some parts of the world most storms fit the 'rain storage' model while in others most fit the 'no rain storage' model.

Conclusion.—The environment in which hailstones are grown is difficult and hazardous to study by means of direct probing techniques, and we are often forced to make the best use we can of indirect radar techniques and of the structure of the hailstones themselves. The structure of hailstones is, however, very complicated and there is an almost bewildering array of microphysical factors that can influence their structure. Indeed one is justified in wondering whether there can be any unambiguous interpretation of the hail growth from an analysis of the structure of the hailstones alone. However, if independent evidence is obtained concerning the structure of the cloud from which the hail has fallen it is then sometimes possible to make a more reasonable interpretation of the hailstone structure.

This paper has stressed the possible importance of hailstone lobe structures. It has not been claimed that all hailstones possess a lobe structure ; rather it has been suggested that those stones that do have such a structure are likely to have grown in the absence of high concentrations of raindrops. If this notion stands up to further experimental verification it will provide an important diagnostic tool in the difficult study of hail-growth.

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THE FORECASTING OF RAIN IN SOUTHERLY AIRSTREAMS OVER SOUTH-EAST ENGLAND IN SUMMERTIME

By C. A. S. LOWNDES

Summary.—The predictors used in previous studies of shower activity (in north-westerly airstreams), were applied to forecasting non-frontal summer rain or thunder in south-east England in southerly airstreams, but they could not be used to give good forecasting rules. Some limited success in forecasting thunder was obtained from the modified Jefferson index. Observations of atmospherics and 700 mb winds were more useful predictors for rain or thunder, and led to some success in forecasting days with small amounts of rain.

Introduction.—It is well known that the development of a surface depression or trough to the west or south-west of the British Isles or over Biscay, with southerly upper winds over France and England, is sometimes followed by outbreaks of rain over England in summertime. The forecasting of the rain is especially important when it involves the possible ending of a dry spell. This investigation is an attempt to formulate rules for forecasting such outbreaks, not associated with fronts, over south-east England. The investigation was restricted to airstreams which approached the British Isles from the southerly quarter. This was achieved by including only those days when the 500 mb wind direction at Crawley at midday was between south-east and south-west (135° to 225° inclusive). Occasions when a front was situated over south-east England during the day were not included. There were 96 frontal days, leaving 110 days as the basis of the investigation. The rainfall was based on nine stations in south-east England in the months May to September during the seven-year period from 1960 to 1966. From 1962 the stations were Kew, Heathrow, Gatwick, Thorney Island, Hurn, Wattisham, Gorleston, Mildenhall and Cardington. For 1960 and 1961, Felixstowe was used instead of Wattisham. The total and average rainfall for the nine stations during the period 0900 to 2100 GMT was obtained for each day and a note was made of thunder reported at any of the stations. The surface reports of thunder were supplemented by observations of atmospherics. The work was restricted to the years 1960–1966 because of the doubtful accuracy of observations of atmospherics previous to 1960.

Bradbury[1] gave an example of the development of a rain area ahead of a 300 mb trough which moved eastwards across the British Isles on 7 April 1961. The associated 1000–500 mb thickness trough was of small amplitude and very broad and no front was involved. However, a study of four years data showed that this type of development occurred on average only about once per year. Further investigation on these lines was therefore not pursued.

Association with temperature and thickness anomalies and with instability indices.—In an earlier paper[2] a study was made of shower activity in airstreams from the north-west quarter over south-east England in summertime and the relative usefulness of seven predictors for indicating shower activity, rainfall amount, thunder and hail was evaluated. In the present investigation the same predictors were obtained in exactly the same way and used to indicate average rainfall at the nine stations of 0·5 mm or more, or less than 0·5 mm, and thunder or no thunder. For each predictor a skill score S was evaluated[3] where

$$S=\frac{\text{number of correct forecasts} - \text{number correct by chance}}{\text{total number of forecasts} - \text{number correct by chance}}$$

It ranges from 0 for no success to 1 for complete accuracy. It became clear that the indicators were of limited use as predictors of rainfall or thunder. Table I shows the skill scores obtained by the seven predictors for the southerly airstreams compared with those for airstreams from the north-west quarter. For the north-westerly airstreams the highest skill score for indicating rainfall (0·64) was obtained by the Rackliff index and the modified Jefferson index and for the southerly airstreams (0·49) by the 700 mb temperature predictor. For the north-westerly airstreams the highest skill score for indicating thunder (0·67) was obtained by the Boyden index and for the southerly airstreams (0·56) by the modified Jefferson index. It is interesting to note that the critical values of the indices which give the highest skill scores are all higher for the southerly airstreams than for the airstreams from the north-westerly quarter. In considering the usefulness of the predictors it should be borne in mind that this will depend on the success with which they can be forecast.

Table I shows the skill scores obtained by the atmospherics and 700 mb wind indicator compared with those obtained by the other seven predictors.

TABLE I—A COMPARISON OF SKILL SCORES

	Southerly airstreams		North-westerly airstreams	
	Rainfall (limit 0·5 mm)	Thunder	Rainfall (limit 0·5 mm)	Thunder
700 mb temperature anomaly and surface pressure	0·49	0·39	0·58	0·62
1000–500 mb thickness anomaly and surface pressure	0·41	0·32	0·53	0·56
1000–700 mb thickness anomaly and surface pressure	0·43	0·26	0·47	0·48
Boyden instability index	0·31	0·44	0·56	0·67
(critical values)	(94/95)	(94/95)	(93/94)	(93/94)
Rackliff instability index	0·31	0·42	0·64	0·62
(critical values)	(31/32)	(30/31)	(30/31)	(29/30)
Jefferson instability index	0·33	0·42	0·59	0·59
(critical values)	(26/27)	(26/27)	(25/26)	(25/26)
Modified Jefferson index	0·40	0·56	0·64	0·61
(critical values)	(26/27)	(26/27)	(22/23)	(24/25)
Atmospherics and 700 mb winds	0·66	0·54		

Association with observations of atmospherics and 700 mb winds.—A study of observations of atmospherics to the south of the British Isles showed that on a few occasions a group of atmospherics apparently moved with the upper winds from Biscay or France to south-east England. On many other occasions, rain or thunderstorms over south-east England were preceded by reports of atmospherics over Biscay or France on the previous day. This suggested that observations of atmospherics and upper winds might be useful predictors.

The area to the south of the British Isles was divided into 12 areas A to L as shown in Figure 1. If the day for which the forecast was required was day '*d*' then the areas in which atmospherics were reported on day '*d*–1' were noted for the six-hour periods 1200–1700 GMT and 1800–2300 GMT. The most useful upper wind indicator was found to be the 700 mb wind speed and direction at Trappes which were extracted for 1200 GMT (*d*–1) and 2359 GMT (*d*–1). From an alanysis of these data the following forecasting rules were obtained : an average rainfall of 0·5 mm or more over the period 0900–2100 GMT based on nine stations in south-east England is likely on day '*d*' if :

(i) The 700 mb wind direction at 2359 GMT (*d*–1) at Trappes is between 150° and 250° (inclusive) and the speed 10 knots or more.

(ii) The difference between the Trappes 700 mb wind direction at 1200 GMT (*d*–1) and 2359 (*d*–1) GMT is not more than 50°.

(iii) The 700 mb wind speed at Trappes at 1200 GMT (*d*–1) is not less than 5 kt.

(iv) The Trappes 700 mb wind direction at 2359 GMT (*d*–1) is between 150° and 180° (inclusive) and atmospherics are reported in both of the areas C and F between 1200 GMT (*d*–1) and 2300 GMT (*d*–1); or, the Trappes 700 mb wind direction at 2359 GMT (*d*–1) is between 190° and 250° (inclusive) and atmospherics are reported in one or more of the areas B, D or E between 1200 GMT (*d*–1) and 2300 GMT (*d*–1).

Of the 27 occasions when the criteria were satisfied, 85 per cent were associated with 0.5 mm or more, representing 68 per cent of all occasions of 0·5 mm or more. Of the 83 occasions when the criteria were not satisfied, 87 per cent were associated with less than 0·5 mm, representing 95 per cent of all occasions of less than 0·5 mm. If the rules were used to indicate either 0·5 mm or more, or less than 0·5 mm, a skill score of 0·66 would be obtained.

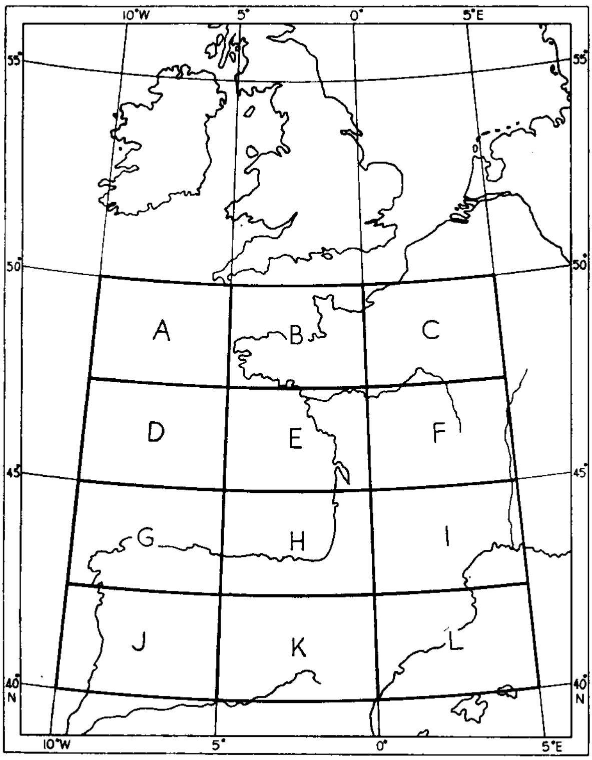

FIGURE 1—AREAS USED FOR NOTING THE POSITION OF OBSERVATIONS OF ATMOSPHERICS

Of the 23 occasions of 0·5 mm or more indicated by the rules, all but two were associated with thunder. Of the 72 occasions of less than 0·5 mm indicated by the rules, 13 were associated with thunder.

If the rules were used to indicate thunder, of the 27 occasions when the criteria were satisfied, 85 per cent were associated with thunder, representing 56 per cent of all occasions of thunder. Of the 83 occasions when the criteria were not satisfied, 78 per cent were associated with 'no thunder', representing 94 per cent of all occasions of 'no thunder'. If the rules were used to indicate either thunder or 'no thunder', a skill score of 0·54 would be obtained.

Other factors considered.—Among other factors considered were the surface dry bulb, wet bulb and dew-point temperatures at Paris, at 1200 GMT (*d*–1) and 2359 GMT (*d*–1). These proved to be of little use as predictors. It is interesting to note that Carlson and Ludlam[4] in an investigation of severe local thunderstorms found that in the two cases considered, θ_w at screen level over northern France reached values of 21–23°C by 1500 GMT and on the same afternoon severe local storms developed over southern England. In a single case, when other conditions were right but storms failed to develop, θ_w over northern France reached only 20°C or less. From the data used in the present investigation, a study was made of occasions when the 700 mb wind direction at Trappes at 2359 GMT (*d*–1) was between 150° and 250° and the speed 10 kt or more, for the years 1960–62. On days when the average rainfall was 0·5 mm or more, the screen wet-bulb temperature at Paris at 1200 GMT (*d*) varied between 12°C and 21°C. For days when the rainfall was less than 0·5 mm, it varied between 12°C and 20°C. It became clear that there was no useful critical value of the wet-bulb temperature.

Conclusions.—This investigation was concerned with southerly air-streams affecting south-east England in summertime and was restricted to days when no fronts were situated over south-east England. A good indication of an average rainfall for nine stations in south-east England of 0·5 mm or more, or less than 0·5 mm, can be obtained by a forecasting rule based on observations of atmospherics and 700 mb winds during the second half of the preceding day to the south of the British Isles. The success in forecasting days with small amounts of rain may be of particular use in determining whether or not to forecast the end of a dry spell in south-east England. The rule also gave some limited success in forecasting thunder in south-east England. Other predictors, including the Boyden, Rackliff and Jefferson instability indices were in general of little use in forecasting rainfall or thunder. Some limited success in forecasting thunder was obtained by the modified Jefferson instability index, but the usefulness of this predictor depends on how successfully it can be forecast.

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SOME FURTHER EVIDENCE OF CROSS-EQUATORIAL JET STREAMS AT LOW LEVEL OVER KENYA

By J. FINDLATER

Introduction.—It has been demonstrated in a recent analysis[1] that low-level jet streams from a southerly point occurred with considerable regularity over the equatorial station at Garissa, Kenya, during the period of the south monsoon which usually extends from about April to October. A table of the occurrence of high speeds, related to the heights at which they were recorded, was given in Table I of that paper and it showed that southerly winds of 40–100 kt occurred at heights of only 4000–7000 ft above MSL over the flat

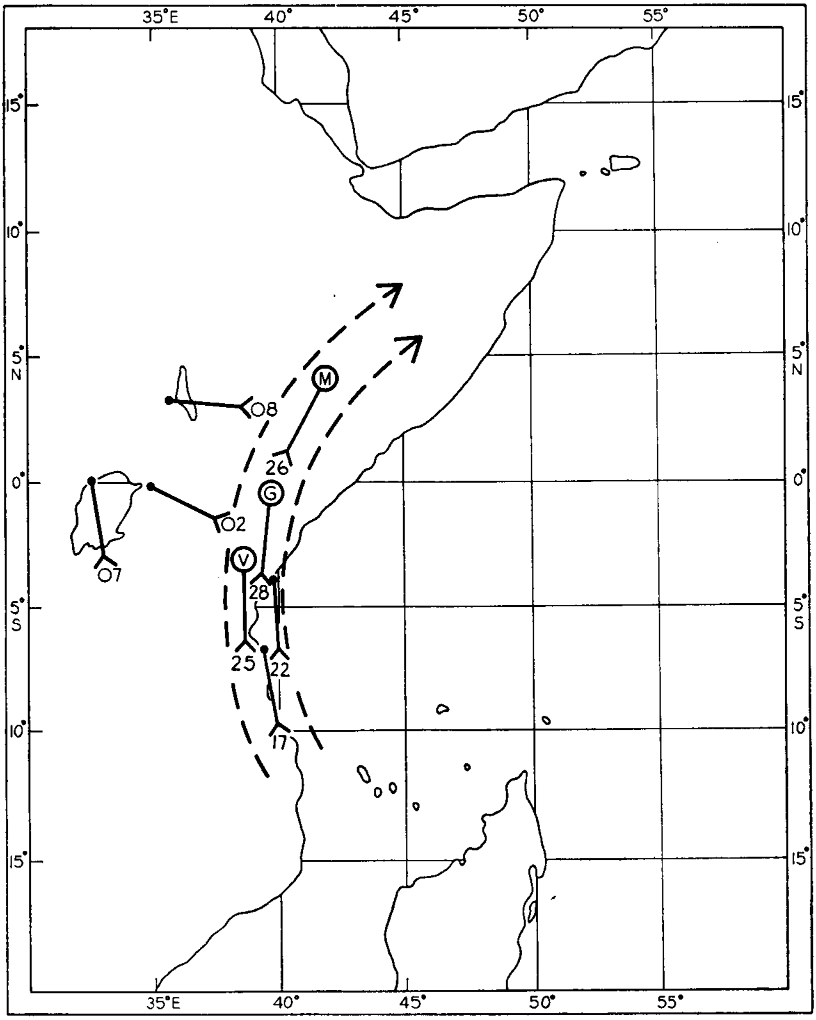

FIGURE I—MEAN WINDS AT 5000 FT IN JULY
The positions of Garissa (G), Mandera (M), and Voi (V) are shown.
The mean speed at each station is given in knots.

eastern areas of Kenya in the vicinity of the equator. High speed flow at low level has now been confirmed at two other stations in the area during the south monsoon and some further evidence for the existence of similar-type flow in the north-east monsoon has been noticed also.

South monsoon.—A study has been made of high wind speeds at low level reported by two other stations, one to the north of Garissa and the other to the south. These stations are Mandera (03°57′N 41°52′E, height 1085 ft) and Voi (03°24′S 38°34′E, height 1837 ft) both of which lie in Kenya and whose locations are shown in Figure 1. The mean monthly direction and speed of the winds at 5000 ft, for a number of stations at the height of the south monsoon season in July, are also included in Figure 1. The mean winds emphasize the very definite western edge of the south monsoon over Kenya. Because the direction of the monsoon stream varies little during the season, even during periods of extreme acceleration, the major streamlines shown are also representative of the direction of high-speed flow when it is present.

Tables I and II give the number of occasions on which wind speeds of 40 kt or more were recorded at heights of 10,000 ft or less at Mandera and Voi respectively during the five-year period from 1959 to 1963 inclusive.

TABLE I—OCCURRENCES OF CORE SPEEDS RELATED TO HEIGHT OF CORE AT MANDERA

(Based on 81 cases during the south monsoon in the years 1959-63 inclusive, where core speed ⩾40 kt.)

Height of core of maximum wind above MSL *feet*	Speed of core of maximum wind (kt) 40–49	50–59	60–69	70–79	80–89	90–99	⩾100	All speeds
	number of occasions							
10,000	2	1						3
9000			winds not computed for this level					
8000	6	4	2					12
7000	3	1						4
6000	13	1	1					15
5000	14	5	1	3				23
4000	16	2	1	1				20
3000	1		1					2
2000	2							2
1000								0
All heights	57	13	7	4	0	0	0	81

TABLE II—OCCURRENCES OF CORE SPEEDS RELATED TO HEIGHT OF CORE AT VOI

(Based on 54 cases during the south monsoon in the years 1959–63 inclusive, where core speed ⩾40 kt.)

Height of core of maximum wind above MSL *feet*	Speed of core of maximum wind (kt) 40–49	50–59	60–69	70–79	80–89	90–99	⩾100	All speeds
	number of occasions							
10,000	1							1
9000			winds not computed for this level					
8000	8	1	1					10
7000	1	2	1					4
6000	11	1		2				14
5000	14	3						17
4000	4		1					5
3000	3							3
2000								0
1000								0
All heights	42	7	3	2	0	0	0	54

These tables are additional to Table I of the earlier paper and they serve to confirm the existence of high-speed flow at low level at two other stations which lie under the monsoon stream. The tables should not be compared directly with the analysis for Garissa, however, because the periods are not the same and the stations have quite different low-cloud characteristics which lead to variations in the frequencies with which pilot balloon ascents are made. Also, it is of interest to note that although no winds of more than 79 kt at low level have been intercepted during the south monsoons of the 1959–63 period at either Mandera or Voi, both stations recorded winds of between 95 and 100 kt at or below 8000 ft during the 1965 and 1966 south monsoon seasons. These extreme winds will be discussed in a more extensive analysis which is currently being prepared for this area of eastern Africa.

The south monsoon blows over eastern Kenya from about April until October and high-speed flow can occur at any time during the season although most cases are noted in the middle months of June–August. Figure 2 shows

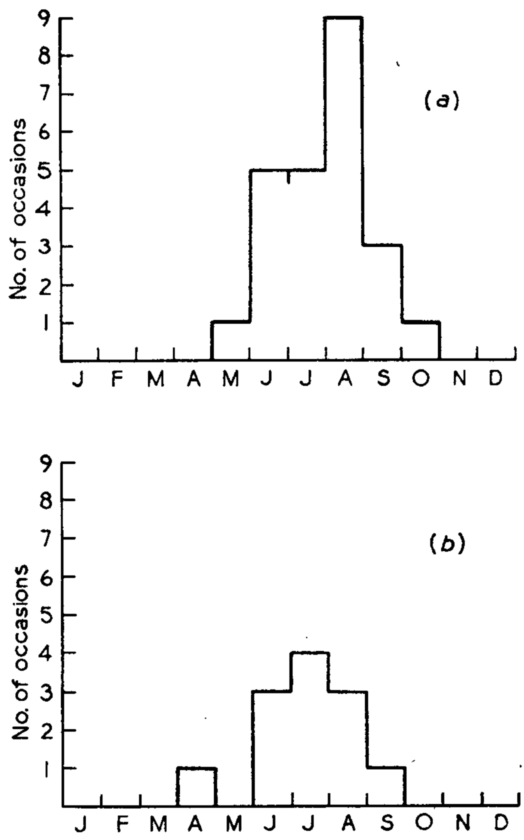

FIGURE 2—NUMBER OF OCCASIONS ON WHICH SPEEDS ⩾50 KT WERE RECORDED BELOW 10,000 FT DURING THE SOUTH MONSOON IN THE YEARS 1959–63 INCLUSIVE IN KENYA

(*a*) Mandera (*b*) Voi

the total number of occasions by months on which speeds of 50 kt or more were recorded at or below 10,000 ft at Mandera and Voi during the years 1959–63 inclusive. Both stations show a maximum number of occasions in the middle months. Although Mandera recorded twice the number of high speeds which were noted at Voi this again may be only a result of the frequency with which pilot-balloon ascents were made. Nevertheless the data presented here confirm the existence of the low-level jet streams recorded previously at Garissa.

North-east monsoon.—In the earlier analysis it was noted that only one case of high-speed flow was known to have occurred at Garissa in three seasons of the north-east monsoon, which blows mainly from December to February each year. The present analysis of data for five years from Mandera and Voi has revealed three cases of winds over 50 kt at Mandera and a further three cases at Voi, all of them at heights of 8000 ft or less. Directions were mainly from between 010 and 060°. However, there are as yet insufficient data to attempt a detailed analysis of high-speed flow in the period of the north-east monsoon and these cases have been omitted from the present analysis, but the isolated case of a jet stream at low level in the north-east monsoon at Garissa which was reported in the previous paper may now be viewed with much less suspicion than hitherto.

Acknowledgement.—The writer is grateful to the Director of the East African Meteorological Department for kindly supplying the pilot-balloon data from Mandera and Voi.

REFERENCE

1. FINDLATER, J.; Cross-equatorial jet streams at low level over Kenya. *Met. Mag., London*, **95**, 1966, p. 353.

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SYMPOSIUM ON AGRICULTURAL METEOROLOGY, ABERYSTWYTH, 8 MARCH 1967

In his address of welcome to the many participants in this, the tenth annual symposium on agricultural meteorology to be held at Aberystwyth under the auspices of The Department of Geography and Anthropology, University College of Wales, Professor P. T. Thomas did say that perhaps Aberystwyth was not the best place to chose for a symposium on frost, since, even in the hardest of winters, this favoured spot generally managed to escape the rigorous conditions that fall to the lot of most other parts of Britain. Conditions on 8 March 1967 certainly lent a great deal of support to this view — the blue skies and balmy airs, and the temperature inside the lecture hall of the Welsh Plant Breeding station in which the symposium was held appeared more appropriate to a symposium on tropical meteorology than on frost.

Inappropriate though the environment may have been, however, a redress, albeit perhaps only psychological, was soon achieved by the opening paper presented by Mr. J. A. Taylor (University College of Wales), convener and chairman of the symposium. He set out the factors involved in the incidence of frost and its biological, economic and technical implications and underlined the need for more meteorological data related to predetermined biological thresholds, and for cost–benefit analysis studies of protection and production in frost-sensitive areas.

There followed an extremely interesting contribution by Dr E. A. Fitzpatrick (Aberdeen University) on the occurrence, form, and mechanics of formation of ice in soils, amply illustrated by a number of splendid colour slides which left one in no doubt of the importance and effect of frost in the soil. One could not fail to be impressed by the dramatic colour illustrations of frost at work in the tundra regions of North America. Following on Dr Fitzpatrick's theme, Dr Barnes (University of Nottingham) discussed the important effects of frost upon pedological and geomorphological process and its implications in fields ranging from paleography to highway and water engineering. A good deal of data on the penetration of frost into the soil is available for lowland Britain, but little is known about the problems in the uplands, and Dr Barnes's review of the available data at high altitudes, both in this country and abroad, represents a useful source of information to those interested in the problems of upland farming.

After coffee Mr W. H. Hogg (Meteorological Office, Bristol) neatly tied up the loose ends to be found in the terminology applied to frost, and ensured that the participants at least were talking the same language. His advice on the practical application of frost data to the utilization of land for horticultural and agricultural activities in particular will be of great assistance to many in this field.

Turning to frost formation in plant tissues and the nature of the frost resistance of plants, Dr Idle (University of Birmingham) confined himself to the events surrounding ice formation in the tissues of typical herbaceous perennials such as the primrose and biennials such as the common cabbage. His very able and interesting exposition of the freezing process, the effect of inter-cellular ice, the thawing process, and the micrometeorological factors involved must certainly have given much food for thought on how such damage can be avoided.

Dr J. Grainger (West of Scotland College of Agriculture) discussed frost and wind damage to plants and described work done by Dr D. F. Booth and himself in Ayrshire on frost and the economics of its control. This was followed by Dr G. Jenkins (Plant Breeding Institute, Cambridge) who showed how some control of frost resistance of winter cereals can be obtained by selective breeding.

Agricultural meteorology does, of course, embrace forestry, and Mr G. W. Hurst (Meteorological Office, Bracknell) described an investigation into the variation of frost in Forestry Commission plantations at Thetford Chase, and convincingly demonstrated the need to consider several factors, such as surface vegetation, in the reduction of frost in plantations of young trees. Mr J. M. B. Brown (Forestry Commission) enlarged on the theme introduced by Mr Hurst, and by means of some excellent colour slides was able to show very vividly the effect of frost on seedlings and on more mature forest trees.

After a paper by Dr D. L. Jennings (Scottish Horticultural Research Station, Dundee) describing work carried out in association with a colleague, Dr M. R. Cormack, on the cultural and varietal factors affecting the hardiness of raspberry canes, came a contribution, read on behalf of the author Mr D.

Benzie (Rowett Institute), on frostbite as a probable cause of the early shedding of permanent incisor teeth in sheep — surprisingly enough the sole contribution specifically devoted to the relationship between frost and the animal world.

To end the session, Mr K. E. Hunt (Agricultural Economics Research Institute, Oxford) dealt very comprehensively with the economics of frost and frost control, and underlined the difficulty of forecasting the incidence of frost and defining the relationship between frost conditions and economic loss.

In the lively discussion which followed the presentation of papers, a number of points raised by the papers, notably those of Dr Idle and Mr Hunt, were debated, and when the participants finally emerged into the warm evening sunshine there was a general feeling that, thanks to the initiative and hard work of Mr Taylor and his associates and the excellent facilities afforded by the University College of Wales, substantial progress had been made towards a better understanding of the physical, biological and economic significance of frost. The author, at least, left reasonably convinced that the sturdy smallholders of Co. Wicklow might have had a point when they got up in the early hours of the morning over 150 years ago to remove the hoar frost from the haulms of their early potatoes lest they be damaged by the thawing effect of the morning sun.

W. MCKAY

LETTER TO THE EDITOR

Freezing drizzle

The synoptic conditions which led to widespread freezing rain and drizzle in the Home Counties on 20 January 1966[1] closely resembled a similar occurrence on 3–4 January 1963. The effects of this latter outbreak on communications were masked by the general inclement conditions that had prevailed since the end of December 1962. Many of the areas affected had considerable snow cover which had disrupted public services before the onset of the freezing rain.

On 3 January 1963 a depression moved north-west from central France to central southern England accompanied by two occlusions. Ahead of the first occlusion a belt of snow was followed by freezing rain and drizzle over a wide area of south-east England and East Anglia. Subsequently this precipitation moved slowly north-westward and affected the Midlands before dying out. Figure 1 shows the slow progression of the glazed frost conditions. The first occlusion represented the boundary between cold continental air and rather warmer air, with temperatures slightly above freezing, that had originated in more southerly parts of Europe. As the front moved north-west it weakened and became indistinct and temperatures remained close to freezing over a wide area of the Midlands and southern England with the result that further freezing rain and drizzle occurred during the night.

Brooks and Douglas[2] have shown that glazed frost of a few hours duration is comparatively common, particularly in the Midlands and eastern England,

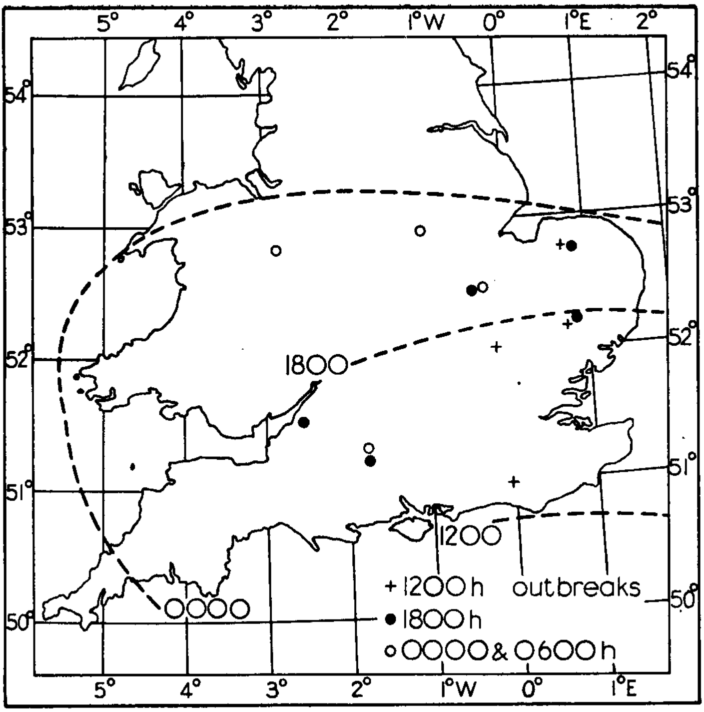


FIGURE 1—OUTBREAKS OF FROZEN PRECIPITATION ON 3 JANUARY 1963 AND THE POSITION OF THE ASSOCIATED OCCLUDED FRONT

ahead of warm fronts or warm occlusions, but it would seem that these two recent occurrences were more protracted and severe than for many years. It would seem from the evidence of the 1940 outbreak and the two recent occurrences that southern England and the Midlands are particularly prone to glazed frost.

University of Southampton. A. PERRY

NOTES AND NEWS

Retirement of Dr A. G. Forsdyke

Dr A. G. Forsdyke retired from the Meteorological Office on 3 July after more than 38 years service.

Dr Forsdyke joined the Office in 1929 following 3 years research in fluid dynamics which had gained him his Ph.D. His early appointments were to forecasting duties at Headquarters and at Renfrew. In 1936 he was sent as an instructor to the Naval Meteorological Branch (later the Naval Weather Service) and many weather forecasters in the following years have valued the very practical handbook which he then wrote anonymously under the title of the Admiralty Weather Manual.

After two years as one of the senior forecasters at the Central Forecasting Office, Dunstable, during the critical war years, Dr Forsdyke was mobilized in

1943 and sent to East Africa as deputy to the Chief Meteorological Officer. Here he reached the rank of Wing Commander and developed an expertise in problems of tropical meteorology which was of considerable value to the Office in later years. His report on 'Weather Forecasting in Tropical Regions' published as a *Geophysical Memoirs* is a valuable survey of tropical meteorology in the formative years after World War II.

Apart from a further short period of forecasting work, Dr Forsdyke's subsequent career was spent mainly as leader of research teams first on extended range forecasting when forecasts were tentatively being extended to 4 or 5 days by synoptic methods and later, from 1954 onwards as an Assistant Director of the Office, in climatology when the mapping of the upper winds of the world and the study of world-wide climatic anomalies expanded under his guidance.

At Dunstable, Harrow and Bracknell Dr Forsdyke has taken a very active interest in the development of the social life of the Office and its activities in sport. He has been Chairman of the Bracknell Meteorological Office Sports and Social Club since the headquarters moved to Bracknell in 1961. His many friends throughout the Office wish Dr Forsdyke a long and happy retirement.

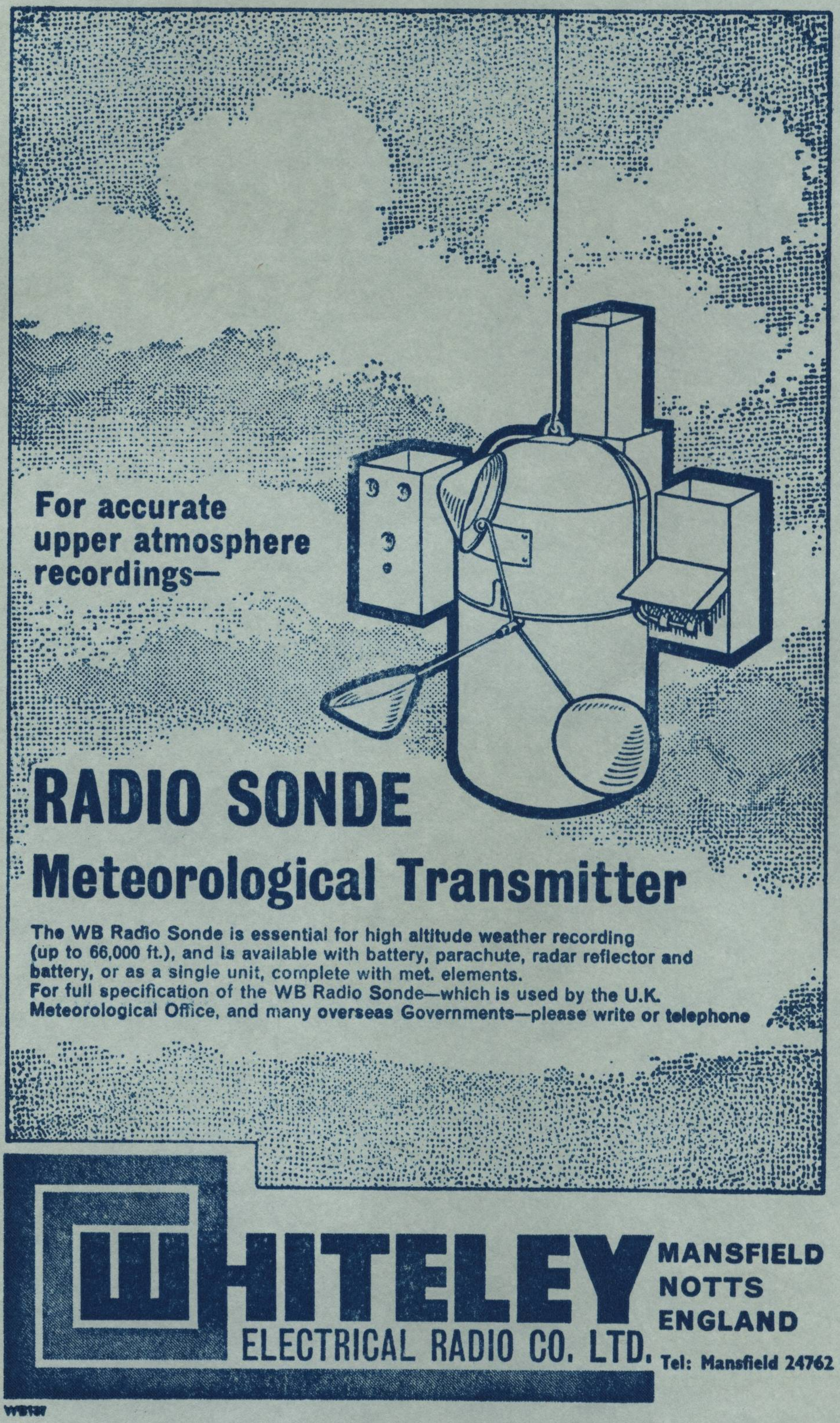
J. S. SAWYER

HONOUR

The following award was announced in the Birthday Honours List in June 1967 :

I.S.O.

Dr A. G. Forsdyke, Senior Principal Scientific Officer, Bracknell.



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THE METEOROLOGICAL MAGAZINE

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NOTICES

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

The responsibility for facts and opinions expressed in the signed articles and letter published in this magazine rests with their respective authors.

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