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LARGE-SCALE DISTURBANCE OF THE EQUATORIAL ATMOSPHERE*

By J. S. SAWYER

Summary. Cloud distributions in the equatorial atmosphere as observed by satellites confirm the existence of long-period large-scale disturbances which can be linked with the occurrence of wet and dry spells in individual equatorial areas, e.g. East Africa and Gan, and with wind fluctuations observed in the upper atmosphere. These disturbances are also of importance in studies of the influence of one hemisphere upon the other.

Some speculations on the nature of the disturbances are put forward. In the vorticity equation, the twisting terms and the frictional terms (arising primarily from the vertical exchange of momentum by small-scale motions) may play an important part in the dynamics of large-scale motions because they provide a mechanism whereby the sign of the absolute vorticity of an airstream may change in passing from one hemisphere to the other. Further studies of large-scale motion in the equatorial belt and extending over at least 60 degrees of longitude should be undertaken as well as the effort concentrated on mesoscale and microscale observing.

Introduction. Meteorology as a science has developed principally in countries outside the tropics and important new developments, such as frontal analysis, development of aerological networks or application of numerical dynamics, have first been applied to the atmospheric problems of middle latitudes. Meteorologists, recognizing the success of these ideas in middle latitudes, have naturally tried to export them to low latitudes, but it might be argued that the development of tropical meteorology has suffered almost as much as it has gained by this. Certainly in the 1930s and 1940s there was a significant diversion of effort to the search for fronts in the equatorial belt and for a frontal theory of tropical cyclones.

It is also noteworthy that the nature of depressions, fronts and other disturbances of middle latitudes makes weather forecasting for 12 to 36 hours ahead a practical and rewarding task. This is not true of many areas of the equatorial belt. Over land masses the diurnal cycle may be so dominant that it hardly requires a meteorologist to describe it each day, and in most areas the differences from one day to the next are not generally such as to be of major importance to the weather-sensitive industries which have supported the development of weather forecasting services elsewhere — aviation, shipping, etc. The development and movement of tropical cyclones is, of course, an exception to this generalization, and provides an important justification for the maintenance of day-to-day forecasting services in the

*Paper presented at the Symposium on the Global Atmospheric Research Programme at Princeton, New Jersey, January 1969.

areas liable to their effects. However, the severe thunderstorms, etc. which are also of importance to aviation are of a local nature and are best treated on an hour-to-hour basis with radar as the main forecasting tool.

Relatively little attention has been given to disturbances of the equatorial atmosphere which have a time-scale of two or three weeks and a space-scale comparable with the major planetary waves of middle latitudes. The purpose of this article is to draw attention to the fact that such disturbances exist and to some of the dynamical problems posed by them. Since they are linked with the occurrence of wet and dry spells in many equatorial areas, they are of interest for the problems of agriculture, and the possibilities of forecasting them must have considerable economic importance. An understanding of disturbances of the tropical atmosphere on long time-scales must also be of importance in regard to extended forecasting in middle latitudes, if the influence of the opposite hemisphere is to be taken into account.

It therefore seems important that both the planned Global Atmospheric Research Programme (GARP) and any tropical observing experiments leading up to it, should make provision for the study of long-period and large-scale variations of the equatorial atmosphere.

Some illustrations of large-scale disturbances of the equatorial atmosphere. The existence of large-scale disturbances in the equatorial atmosphere has been particularly well illustrated by the cloud distributions observed by satellites, initially by the observations from the TIROS and ESSA series, but more particularly from the remarkable observations of ATS-1 and ATS-3.

Figure 1 shows an analysis of the cloud distribution over the Indian Ocean and surrounding areas from the observations of ESSA-3. This is one of a series made at Bracknell by D. H. Johnson, D. W. Dent and B. H. Preedy from the microfilm supplied by the National Weather Records Center, Asheville, U.S.A. The feature of particular interest is the belt of cloud which extends across the Indian Ocean in low latitudes. This is associated with the feature which has been known for many years as the intertropical convergence zone (ITCZ), and it is immediately apparent from these analyses that it is a very real and important feature of the equatorial atmosphere.

The analysis of the cloud systems in Figure 1 has been carried out using a slight variation of the conventional scheme which has proved particularly convenient for the purpose. Areas most heavily shaded represent systems of thick cloud which in the opinion of the analyst are associated with active weather systems. They correspond more or less with the areas of synoptic importance in the routine ESSA analyses. 'Mainly covered' areas which contain a substantial proportion of cumulonimbus clusters are cross-hatched.

The belt of cloud following the ITCZ is obvious on the satellite pictures almost every day, whatever form of analysis is adopted. However, the fact to which I wish to draw particular attention is that the ITCZ as seen from the ESSA satellite pictures is not merely a persistent climatological feature, but that it has considerable variations both in position and intensity, and that these extend over periods measured in weeks rather than days. Indeed the changes are best recognized in cloud distributions some 5 or 10 days apart rather than in the differences from day to day. Figure 2 shows the distribution

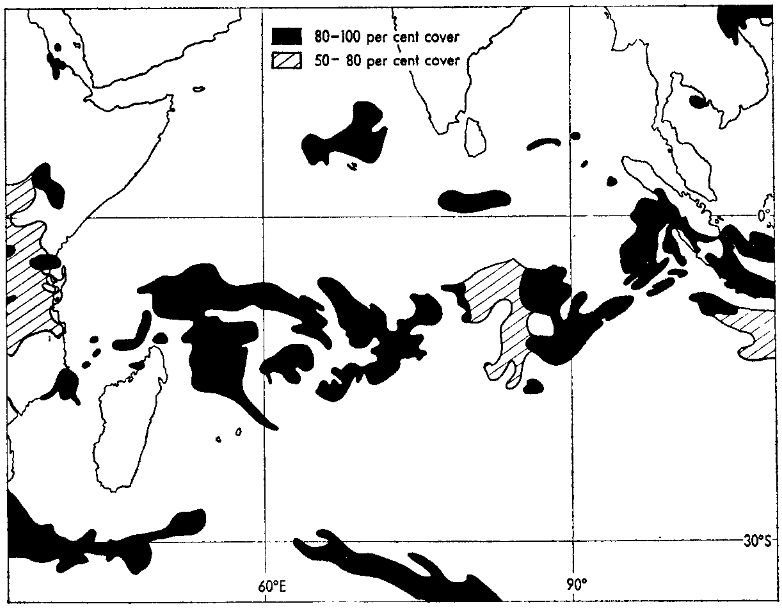

FIGURE 1—CLOUD ASSOCIATED WITH ACTIVE WEATHER SYSTEMS, INDIAN OCEAN, 8 FEBRUARY 1967

Note : Clouds not associated with active weather systems are omitted from the analysis.

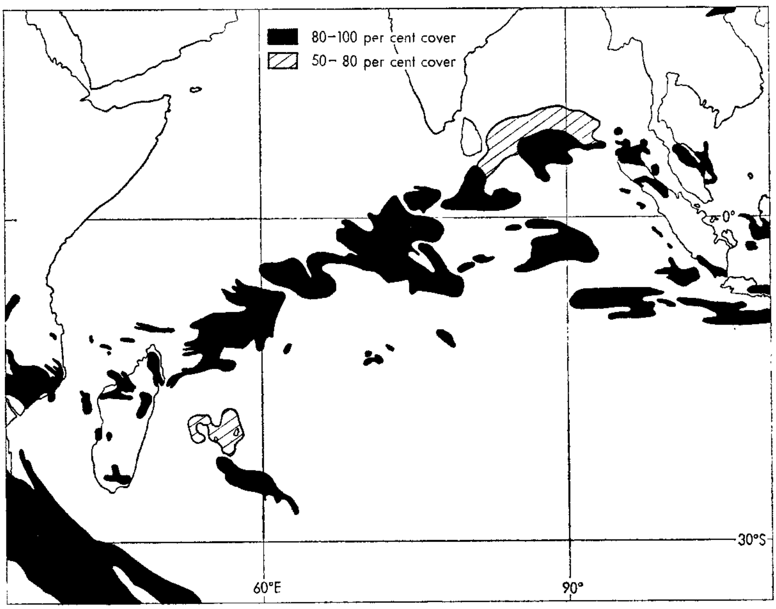

FIGURE 2—CLOUD ASSOCIATED WITH ACTIVE WEATHER SYSTEMS, INDIAN OCEAN, 19 FEBRUARY 1967

Note : Clouds not associated with active weather systems are omitted from the analysis.

of clouds as analysed fror the Indian Ocean some 11 days later than Figure 1. The change in the position of the ITCZ is apparent and also its change in orientation from an east–west line to one tilted from north-east to south-west.

The extent of the movement of the ITCZ is illustrated by Figure 3 on which lines have been drawn representing the position at 5-day intervals of the axis of the cloud belt as shown in the ESSA cloud pictures.

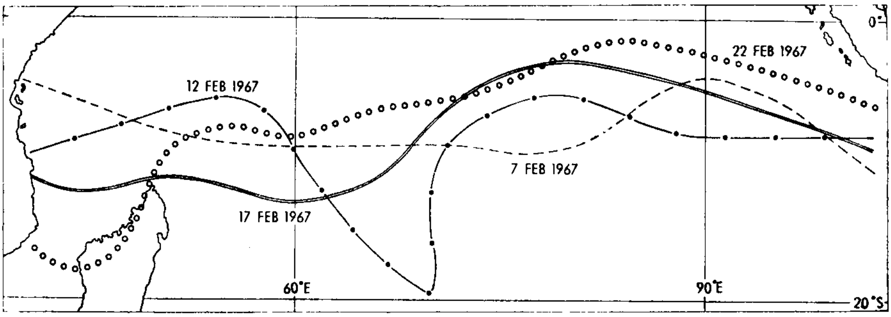

FIGURE 3—AXIS OF MAIN BELT OF CLOUD ACROSS THE TROPICAL INDIAN OCEAN AT 5-DAY INTERVALS, AS REVEALED BY ESSA-3 CLOUD PHOTOGRAPHS, 5–22 FEBRUARY 1967

The existence of disturbances of the equatorial atmosphere on the time-scale of weeks is also apparent in the upper wind observations of equatorial stations. Figure 4 shows the eastward and northward components of the wind at 200 mb day by day at the island of Gan. The existence of fluctuations with a time-scale extending beyond a few days is undeniable; these are particularly well developed in the upper troposphere.

D. H. Johnson[1] in analysing the rainfall patterns over East Africa has demonstrated clearly that relatively wet and dry periods occur at intervals of two to four weeks superimposed upon the climatological cycle of seasonal rainfall. These variations are best brought out when the rainfall of a region is considered as a whole and Johnson uses the proportion of stations experiencing rain each day as an index.

The behaviour of the satellite-observed areas of extensive cloud is certainly linked with the occurrence of relatively wet and dry periods in individual areas, and is probably also linked with the observed variation of wind on the same time-scale. This is illustrated by a comparison which Johnson and Dent have made for the island of Gan (Figure 4) while testing the significance and relevance of their analyses. The upper line of the diagram shows the percentage of a 5-degree square around Gan which is cloud-covered in the satellite pictures. The groups of a few days on which cloud amounts are large clearly coincide with rainy periods as shown by the second line of the diagram.

Some speculations on the nature of long-period equatorial disturbances. So little is known about the three-dimensional structure and physical behaviour of disturbances of the tropical atmosphere that it might be regarded as inappropriate to speculate about their dynamical mechanism and causes. However, the choice of the programmes by which we investigate them is to a great extent governed by the preliminary ideas we may have as to their nature and so, at a time when observational programmes for the tropics are being prepared, some discussion of the subject is not out of place.

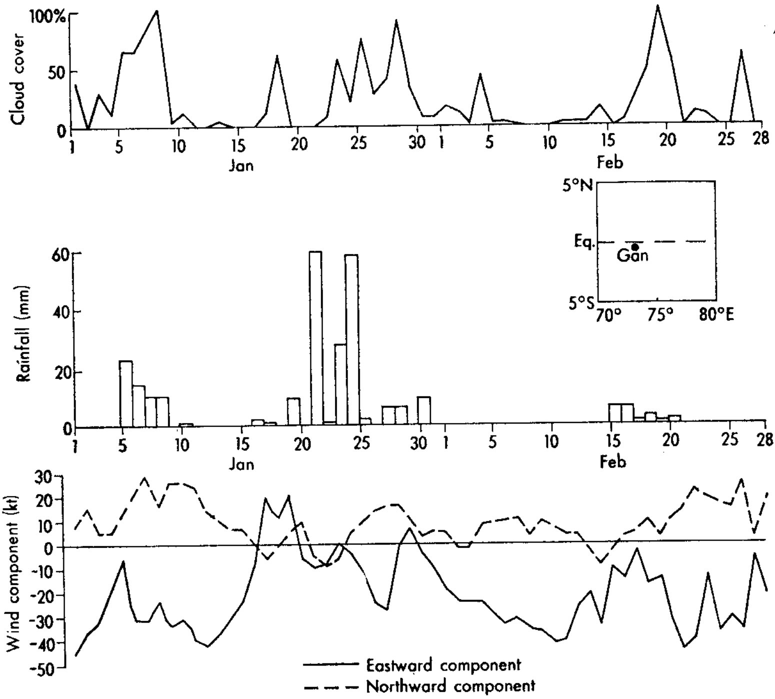

FIGURE 4—CLOUD COVER, RAINFALL AND WIND COMPONENTS AT GAN, JANUARY AND FEBRUARY 1967

Cloud cover relates to a 5° square 70–75°E by 5°S – equator.

One basic difference between the equatorial atmosphere and that of middle latitudes lies in the way in which the two regions play their part in the latitudinal transports of heat and momentum which are essential to the general circulation of the atmosphere. Transport of both heat and momentum through middle latitudes has been demonstrated to be largely dependent on disturbances of the mean circulation, the long waves, depressions, etc. Without such disturbances the transports would be quite different, and the mean state of the atmosphere could not be maintained. We must expect that disturbances should arise spontaneously in the real atmosphere and in any realistic model of it. They form an essential part of the mechanism.

The same is not true of the equatorial atmosphere. Although this is the seat of the main heating of the atmosphere, the transport of heat from equatorial to middle latitudes and the latitudinal movements of momentum can be largely explained in terms of the mean meridional circulation and the 'standing eddies'. The transient eddies play a secondary part only. In consequence there is no reason to think that the transient eddies must arise spontaneously as part of the general circulation of the atmosphere. Rather, the remarkable consistency of the major air currents in the equatorial belt and the 'reliability' of the seasonal cycle of weather in most areas leads one to think of the tropical atmosphere as a stable dynamical system responding to external influences of which the most important is the seasonal change in the declination of the sun.

Charney[2] has recently drawn attention to a type of instability — his 'conditional instability of the second kind' — which arises when latent heat is released in low latitudes in broad areas of convergence of the surface air layers. The convergence increases the vorticity, and the greater the vorticity in the Ekman layer the greater the convergence which occurs. When the convergence is linked to the energy release by latent heat an unstable development is possible. Such a mechanism must be an essential feature of the intensification of tropical cyclones. However, these are a special problem which already receives much attention, and their existence should not discourage us from looking at the remainder of the equatorial atmosphere as an essentially stable system.

Charney has also shown that the same interrelation of Ekman-layer convergence, vorticity and latent-heat release leads to the concentration of convergence along a relatively narrow band 200–300 km wide at the ITCZ. However, observations of the equatorial atmosphere are not suggestive of any unstable disturbances on a large scale, although the mechanism of Ekman-layer convergence may impose its own time-scale on the response of the equatorial atmosphere to external influences.

If one is to look for the cause of the fluctuations in the tropical atmosphere with a period of weeks, it is natural to look to the extratropical atmosphere where fluctuations on a similar time-scale undoubtedly exist as a result of the dynamical instability of the large-scale circulation. The 'index cycle' studied by Rossby and others around 1950 has this time-scale and the fluctuations also show up in the life of 'blocking systems'. A recent theoretical paper by Mak[3] has shown by numerical integration that disturbances imposed on the tropical atmosphere at latitudes 30°N and 30°S with a structure similar to those occurring in nature should result in disturbances in the equatorial belt with time-scales from 5 to 40 days rather similar to those observed.

The existence of important links between the equatorial and middle latitude atmosphere is made very clear by the analysis of winds in the upper troposphere across the equatorial belt. This can be seen clearly in some transequatorial analyses for 200 mb in a paper by Johnson.[4] Air from the easterlies near the equator enters the anticyclonic ridges on the equatorial side of the subtropical jet stream, and the dynamics of the equatorial current cannot fail to be influenced by the disturbances of the subtropical jet, itself materially affected by disturbances of middle latitude. This linkage has been dramatically illustrated recently by rapidly moving filaments of cirrus observed from the geostationary satellites as entering the subtropical jet stream from regions well within the equatorial atmosphere.

I conclude from this, that a very useful approach to the dynamics of the equatorial atmosphere might prove to be through the investigation of the disturbance initiated in the equatorial belt by distortions of the subtropical jet stream and other changes of the circulation around latitudes 25 to 30 degrees from the equator. This might well prove more rewarding than a study of disturbances arising spontaneously in the equatorial atmosphere which generally do not appear to possess the scale in time and space which is likely to be of most interest to the development of the synoptic meteorology of the equatorial belt.

Vorticity near the equator. The behaviour of the vertical component of vorticity near the equator is a specific problem of some interest which is important to the understanding of the behaviour of large-scale disturbances of the equatorial atmosphere. The problem is relevant to certain seasonal monsoon currents as well as to the behaviour of large-scale fluctuations in the seasonal currents.

It is generally recognized that in large-scale air motions of middle and high latitudes the vertical component of the absolute vorticity has the same sign as the component of the earth's rotation about the vertical. With the usual convention of sign the absolute vorticity is positive in the northern hemisphere and negative in the southern hemisphere. It is very doubtful whether quasi-geostrophic motion would be possible with absolute vorticity of the opposite sign and certainly a circular vortex or straight shearing flow and, presumably, other kinematic systems, would be dynamically unstable. There is, presumably, a region near the equator where absolute vorticity appropriate to both hemispheres can be found and Kruger[5] has endeavoured to identify areas with vorticity appropriate to the opposite hemisphere. However, this region cannot extend much beyond 10 to 15 degrees of latitude from the equator because of the observed quasi-geostrophic nature of the flow in higher latitudes. The way in which the absolute vorticity of an air-stream may be changed from the sign appropriate to one hemisphere to that appropriate to the other thus needs to be studied, particularly in regard to well-defined transequatorial currents.

That some substantial transequatorial currents exist is clearly demonstrated by Findlater[6,7] who analysed the structure of the low-level jet stream which exists over East Africa during the period of the Indian monsoon. A well-defined régime of mainly southerly winds exists from at least 10°S to near 10°N with maximum velocities of 40 kt or more at around 5000 ft. A return flow from the northern hemisphere to the southern must exist, probably in the upper troposphere, as a northerly component over a broader longitude band.

The vorticity equation (in pressure co-ordinates) expresses the rate of change of the absolute vorticity, η, as follows:

$$\underset{\text{(A)}}{\frac{\mathrm{D}\eta}{\mathrm{D}t}} + \underset{\text{(B)}}{\eta\,\mathrm{div}_{\mathrm{H}}\,\mathbf{V}} + \underset{\text{(C)}}{\left\{\frac{\partial\omega}{\partial x}\frac{\partial v}{\partial p} - \frac{\partial\omega}{\partial y}\left(\frac{\partial u}{\partial p} - \frac{2\,\Omega\cos\varphi}{g\,\rho}\right)\right\}} = \underset{\text{(D)}}{\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}}, \ldots (1)$$

where $\omega \equiv \mathrm{D}p/\mathrm{D}t$, $\mathrm{D}/\mathrm{D}t$ represents differentiation following motion, Ω is the angular velocity of the earth, and F_x and F_y represent the stresses due to friction and eddy viscosity. (A term due to the latitudinal variation of the horizontal component of the Coriolis parameter has been omitted because it is small and particularly so near the equator.)

The second term (B) in equation (1) provides the principal control on vorticity in middle and high latitudes through the action of horizontal convergence and divergence, but it cannot be responsible for a change in the sign of η because it vanishes when η is zero.

Thus in order to seek a mechanism which can change the sign of the absolute vorticity of air as it moves from one hemisphere to the other we must look either to the 'twisting terms' (C) or to the frictional terms (D) in equation (1) for the generation of appropriate absolute vorticity in air which crosses the equator and enters the quasi-geostrophic régime of the opposite hemisphere.

The possible magnitude of the 'twisting terms' (C) depends on the horizontal gradients of ω and is clearly greater for smaller-scale features (i.e. a narrower current). Examination of the possible magnitude of the terms in the light of the winds observed near the equator shows that only with relatively narrow currents of, say, 1000-km width or less could these terms produce a vorticity change comparable with the Coriolis parameter in latitude 10 degrees, and then only in particularly well-suited distributions of wind and vertical velocity.

It is interesting to note that some positive vorticity could be generated in a northward-moving current in which wind decreases with height if there were descent to the left (west) of the current and ascent to the right (east). The very dry and subsided nature of air over Somalia and parts of Kenya when the low-level East African jet is present in July–August suggests that appropriate vertical movements may be present. A careful evaluation of the magnitude of the twisting terms from synoptic charts of the area would be needed to assess the possible significance of the effect.

Whatever the role of the twisting terms in the rather special East African current, they cannot be large enough to play the primary role in vorticity changes in the broader currents which are more characteristic of trans-equatorial air movements at least in the upper troposphere.

We are therefore led to look at the 'frictional terms' (D) the effect of which arises primarily from the vertical exchange of momentum by small-scale motions.

Charnock, Francis and Sheppard[8] measured the surface wind stress in the Caribbean and the average value which they observed, 0·041 N/m^2 (0·41 $dynes/cm^2$), would have removed half the momentum of the atmosphere up to 800 mb in about 3 days. A similar time-scale would arise in the exchange of momentum between the upper and lower troposphere if the eddy viscosity K were about 50 m^2/s (5×10^5 cm^2/s), a value comparable with that given by Riehl *et alii*[9] and about half of that deduced by Tucker[10] when including the effect of vertical motions on all horizontal scales.

The time-scale for the exchange of vorticity will, of course, be similar to that for the exchange of momentum, and it appears probable that the vertical transfer of momentum by vertical motions in relatively small-scale systems may play an important part in the dynamics of the large-scale motions of the equatorial atmosphere. The vertical motions in convective cloud systems, by their magnitude and vertical penetration, are likely to be the most effective factors.

It may be significant in this connection that when the mean air motion across the equator is analysed (Tucker,[11] Wright and Ebdon[12]) it is usually found that a current with a southerly component in the upper troposphere overlies a current with a northerly component in the lower troposphere and vice versa. Such a distribution of currents gives an opportunity for the vorticity of transequatorial currents in the upper troposphere to be brought to an appropriate sign for the hemisphere into which they move by the vertical eddy transport of momentum. A recent paper by Fujita *et alii*[13] has demonstrated that vertical momentum transfer mainly to the ground is effective in changing the sign of absolute vorticity in transequatorial currents in the lower troposphere.

Desirable characteristics of tropical observing experiments. The aim of the present note is to bring out some of the significance of large-scale air motions in the equatorial belt and of fluctuations in them. It is desirable that tropical research programmes should put some emphasis on these features, and that special observing programmes mounted as sub-programmes of GARP, or otherwise, should be designed so that the large-scale motions can be studied.

It is true, as I have indicated, that small-scale convective systems play an important part in the dynamics of the larger systems by the transfer of momentum, heat and water vapour which they bring about. Such convective systems deserve our study, but I think that we should be unduly optimistic and perhaps misguided, if we were to assume that the quantitative aspects of the transfer processes can be inferred from studies of mesoscale and microscale systems alone. The motions in the large-scale systems are themselves likely to prove an important control on the fluxes, particularly on that of momentum, and realistic assessment of the fluxes may, in fact, only prove possible through the study of the dynamics of large-scale systems.

I therefore regard it as particularly important that the tropical observing experiments should endeavour to document the large-scale air motion over the whole equatorial belt from one hemisphere to the other and extending over at least 60 degrees of longitude. Effort should not be solely concentrated on mesoscale and microscale observing which is, perhaps, somewhat easier to organize, and which, perhaps, provides objectives more readily achieved with the resources of an individual experimenter or a small group.

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SOME FACTORS AFFECTING THE CATCH OF RAIN-GAUGES

By M. J. GREEN

Water Research Association*

Summary. Meteorological Office Mk 2 gauges were installed at various heights above ground and their catch compared with that of a 9-hole gauge mounted close to the ground. An experiment was devised to examine the effect of rim height on catch and also the effect of the size of an anti-splash grid surround. Various values of wind speed and rain inclination were considered.

Introduction. It is desirable to design and site a rain-gauge so that the funnel collects the same amount of precipitation as that which would have fallen on the ground surface had the gauge not been present. If the gauge has the rim of its collecting funnel above ground level it deflects the local airflow so as to cause a wind eddy effect and a consequent loss of catch, whilst if the rim is installed flush with the ground surface the funnel becomes subject to in-splash from the surrounding ground. A critical review of precipitation measurements compiled by Kurtyka[1] describes these errors. The present paper describes the performance of a 9-hole gauge mounted close to ground level with an anti-splash surround and compares its catch with that of different rain-gauge installations for various values of wind speed and rain inclinations. The effect of rim height on catch is examined and also the effect of the size of an anti-splash grid surround.

Location. The site at Turville Hill, in the Chiltern Hills, was selected for its relatively level hilltop site and its open aspect to the south and south-west winds. As the hill is used solely for sheep grazing, a 1-metre high wire sheep-netting fence with a 5-cm hexagonal mesh was erected to enclose an area of 8 × 15 metres. Figures 1 and 2 show the plan of the site and the position of each gauge within the enclosure before and after 1 October 1966. Plate I is a photograph of the earlier enclosure.

Instrumentation. Within the enclosure was sited the 9-hole gauge described by Bleasdale,[2] which comprised a 3 × 3 group of square funnels mounted close to ground level each with a collecting area of 250 cm^2 and each with its own collecting bottle. To prevent in-splash the gauge was surrounded by an aluminium frame into which were slotted, at angles of 45°, green-painted aluminium venetian-blind slats, 5 cm in width (Plate II). The complete frame with slatting, measuring 228·5 × 228·5 cm, was laid on the grass so that the top edges of the slats were level with the gauge rim at a height of 4 cm above ground. The slatting was angled in the frame in such a way that raindrops which could have splashed into the funnels were deflected away from the gauge. This arrangement also served to prevent in-splashing from the ground surface.

Gauges A and B were 5-inch Mk 2 gauges, installed without any shielding, with their rims at 30·5 cm above ground level. Gauge C, also a 5-inch Mk 2 gauge with its rim at 30·5 cm, was shielded by a 'turf wall' which had been constructed from a framework of eight sections with tongued and grooved

*Ferry Lane, Medmenham, Marlow, Bucks.

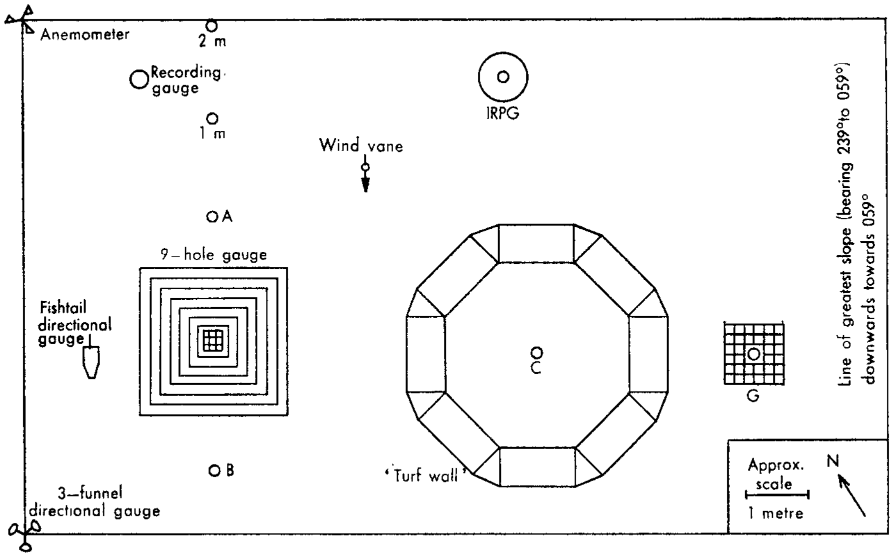

FIGURE 1—PLAN OF HILLTOP ENCLOSURE, BEFORE 1 OCTOBER 1966

A and B	Mk 2, 5-inch gauges (rim at 30·5 cm above ground)
C	Mk 2, 5-inch gauge (rim at 30.5 cm above ground) with 'turf wall'
1 m	Mk 2, 5-inch funnel with rim at 1 m above ground
2 m	Mk 2, 5-inch funnel with rim at 2 m above ground
IRPG	Mk 2, 5-inch funnel with an Alter shield and rim at 1 m above ground
9-hole gauge	3×3 group of square funnels each with collecting area of 250 cm^2 and mounted with rim 4 cm above ground
G	5-inch gauge with rim at ground level and flush with a 90×90 cm polystyrene grid.

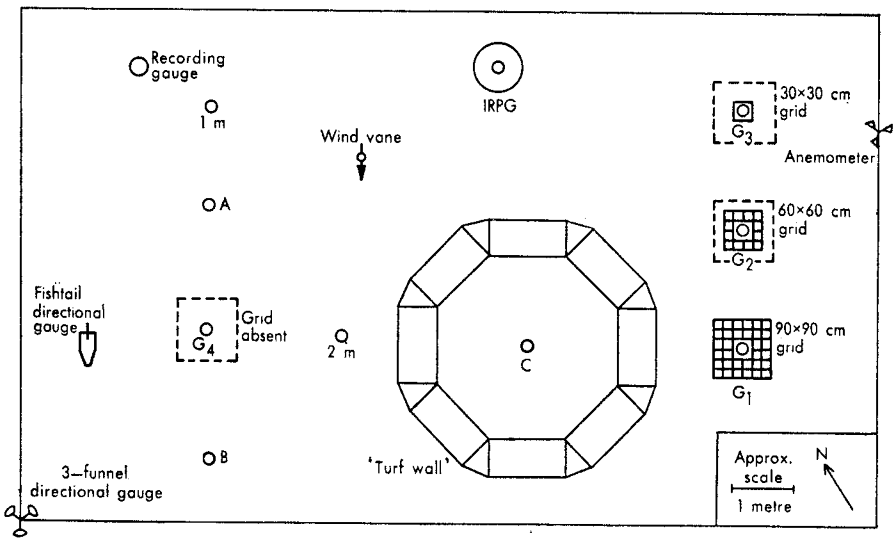

FIGURE 2—PLAN OF HILLTOP ENCLOSURE, AFTER 1 OCTOBER 1966

G_1 to G_4 5-inch gauges with polystyrene grid surrounds of different areas but flush with the ground; rim heights above ground were varied from 0 to 22 cm

Details of the Turville gauges are given beneath Figure 1.

board for the inside retaining walls. Initially, fine chicken-wire was stretched over the frame to represent the sloping outside walls, but this was replaced later by an earth slope.

The elevated gauges included an interim reference precipitation gauge (IRPG) (Mk 2 funnel mounted at 1 metre with an Alter shield), and two 5-inch Mk 2 funnels without any shielding, one mounted at 2 metres and the other at 1 metre.

Gauge G was pit-mounted with its rim set at ground level and flush with a 90×90 cm polystyrene grid composed of cells 5 cm square by 4·5 cm deep (Plate III). Other gauges included a recording rain-gauge designed by Barsby,[3] which, with the records from a recording anemometer and wind vane, made it possible to determine wind speed and direction during rainfall. Two directional gauges furnished data on rain inclination and wind direction during rain. One was the stationary '3-funnel type' similar to that described by Rose and Farbrother[4] and the other, called the 'Fishtail' gauge, was one that can rotate with the wind through 360° and in which rainfall can be deposited in 8 bottles representing 45° sectors of wind direction during rain.

The 9-hole gauge. The area of each compartment of the 9-hole gauge was checked by planimetry and linear measurement and the difference between compartments was found to be less than 1 per cent. A check on splash from the slatting surround was made by pasting the slats with a viscous solution of gum arabic and sodium chloride. The catch within each funnel was analysed after each rain event, but no increase in sodium chloride was detected.

The coefficient of variation (the ratio of standard deviation to mean) in catch was examined for 1962 and found to be 0·026; this was thought to be the result of wind eddies within the square funnels, and for the following years each compartment was subdivided by diagonal inserts which were 12·5 cm deep. The effect was to reduce the coefficient of variation to 0·009, 0·011, 0·012 and 0·011 respectively for the individual years 1963 to 1966. For the 1963–66 period the ratios, where available, of the catch of other gauges within the enclosure to the mean of the 9-hole gauge did not vary appreciably (see Table II). All results exclude snow.

Bleasdale[2] states that under windy conditions it is preferable to analyse the compartments in groups of three, at right angles to the rain direction. The results for rain from the south-west are given in Table I. The variance between groups was not significant at the 1 per cent level with the inserts.

TABLE I—ANALYSIS OF COMPARTMENTS IN GROUPS OF THREE AT RIGHT ANGLES TO RAIN FROM THE SOUTH-WEST

Reference number of compartments	Catch ratio with reference to (i) Overall mean of the 9 compartments	(ii) Mean of the 3 centre compartments
(*a*) Without inserts (1962)		
1 2 3	0·986	0·961
4 5 6	1·026	1·000
7 8 9	0·988	0·963
(*b*) With inserts (1963–66)		
1 2 3	0·992	0·987
4 5 6	1·005	1·000
7 8 9	1·003	0·998

Note : The compartment rows 1 4 7, 2 5 8, 3 6 9 are aligned 239° to 059°.

From these results the 9-hole gauge appears to be a suitable standard of reference when the diagonal inserts are installed.

Annual catch of gauges compared with that of the 9-hole gauge. A preliminary experiment was carried out to test the homogeneity of rainfall over a rectangular area of 120×45 metres, which included the enclosure. The results showed that over the 120-metre distance the range of catch at a given rim height was within ±6 per cent of the mean, while the 45-metre distance gave a ±3 per cent range. It was therefore assumed that the catch across the enclosure area of 8×15 metres was adequately homogeneous and that the gauges within the enclosure were directly comparable. Gauge B is excluded for reason of its proximity to the perimeter mesh fence.

The annual results are shown in Table II. The catch of each gauge is compared with the mean of the 9-hole gauge with inserts, and expressed as a catch ratio. The overall result shows that gauges A and B had catch deficiencies of 3 per cent and 7·5 per cent respectively; gauge C (turf wall) was within 1 per cent of the ground-level gauge; gauges IRPG, 1 metre and 2 metres had deficiencies of 4 per cent, 6 per cent and 10 per cent respectively, and gauge G had an excess of 2·5 per cent. At a less exposed site Rodda[5] found that during a 5-year period a ground-level gauge caught 6·6 per cent more rain than a standard gauge at 30·5 cm (occasions of snow were disregarded).

TABLE II—CATCH OF GAUGES REFERRED TO MEAN CATCH OF 9-HOLE GAUGE FOR THE YEARS 1962–66

Gauge	1962		1963		1964		1965		1966		1962–66	
	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.
9-hole (mean)	1·000	18	1·000	37	1·000	34	1·000	50	1.000	26	1·000	165
A	0·975	18	0·971	37	0·966	34	0·967	50	0·966	26	0·968	165
B					0·919	24	0·928	50	0·923	26	0.925	100
C					0·989	19	1.005	50	0·987	26	0·997	95
IRPG			0·957	17	0·952	33	0·973	50	0·959	26	0·962	126
G							1·023	45	1·029	15	1·025	60
2 m							0·868	8	0·910	26	0·900	34
1 m							0·911	7	0·952	18	0·941	25

N.R. = number of readings.
For positions and descriptions of gauges see Figures 1 and 2.

In Figure 3 the mean catch ratio has been plotted against rim height together with data from de Zeeuw,[6] Symons (after Kurtyka[1]) and Law (Fylde Water Board — private communication). It must be pointed out that the reference gauge height for Symons was 5 cm, for de Zeeuw and Turville it was 4 cm, and for Law 0 cm. All gauges except IRPG and C are unshielded. The results for gauge A indicate that it may be somewhat sheltered at this site.

Dependence of catch ratio on wind speed and on rain inclination and direction. According to Poncelet[7] and Reynolds[8] the long-term catch ratios may be misleading, and they suggest classifying data into climatic seasons. The Turville results go further in that they have been classified by wind speed during rain, by rain direction and by rain inclination, for periods of up to 2 weeks.

When the catch ratios were plotted against wind speed recorded at a height of 2 metres during rain, the relationships exhibited a large amount of scatter. Rain amounts, inclinations measured from the horizontal, and directions were calculated from the 3-funnel gauge[4] at a height of 2 metres, but when such data were introduced into the plot of wind speed against catch ratio there was no visible improvement in the relationship.

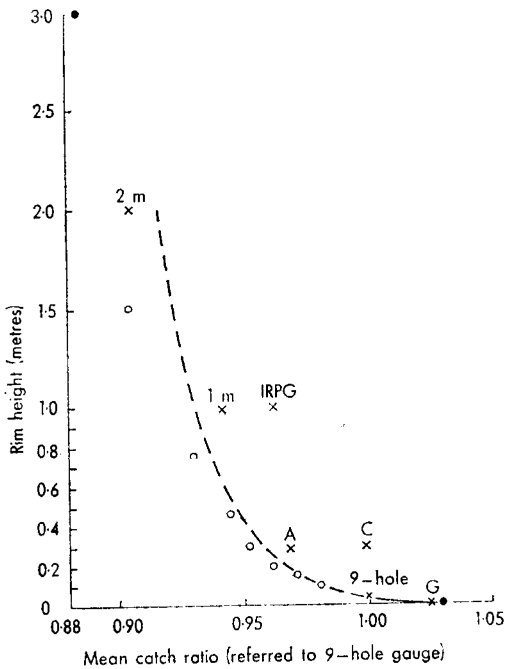

FIGURE 3—COMPARISON OF CATCH AT TURVILLE HILLTOP GAUGES WITH OTHER DATA FOR UNSHIELDED GAUGES

x Turville o Symons after Kurtyka[1] . Law

— — — De Zeeuw[6] regression

Details of the Turville gauges are given beneath Figure 1. Reference gauge was the 9-hole at Turville. All gauges were unshielded except IRPG and C.

Another approach is seen in Table III where rain inclination is grouped into four classes for a given rain direction. The predominant south-west

TABLE III—CATCH RATIOS* FOR VARIOUS GAUGES ACCORDING TO SPECIFIED RAIN INCLINATION GROUPS

Gauge	Rain inclination to horizontal							
	<50°		50° – 60°		60° – 70°		>70°	
	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.	Ratio	N.R.
9-hole								
1	0·994	49	0·974	17	1·000	10	0·980	19
2	0·994	49	1·000	17	0·990	10	1·000	19
3	0·985	49	0·988	17	0·991	10	1·002	19
4	0·992	49	1·002	17	1·011	10	1·001	19
5	1·010	49	1·027	17	1·007	10	1·021	19
6	1·023	49	1·024	17	1·015	10	1·010	19
7	0·997	49	0·989	17	0·989	10	0·993	19
8	1·014	49	1·008	17	1·009	10	1·001	19
9	0·990	49	0·987	17	0·987	10	0·992	19
Mean	1·000	49	1·000	17	1·000	10	1·000	19
A	0·962	49	0·974	17	0·977	10	0·985	19
C	0·987	30	1·009	8	1·013	6	1·010	12
IRPG	0·960	31	0·974	11	0·987	8	0·992	18
G	1·029	18	1·027	5	1·009	4	1·040	10
2 m	0·888	17	0·906	4	0·943	2	—	—
1 m	0·924	12	0·935	4	0·962	3	—	—

N.R. = number of readings.

*Catch ratios obtained for gauges in hilltop enclosure for rain direction from the south-west (between 194° and 284°) and referred to the mean catch of the 9-hole gauge.

For positions and descriptions of gauges see Figures 1 and 2.

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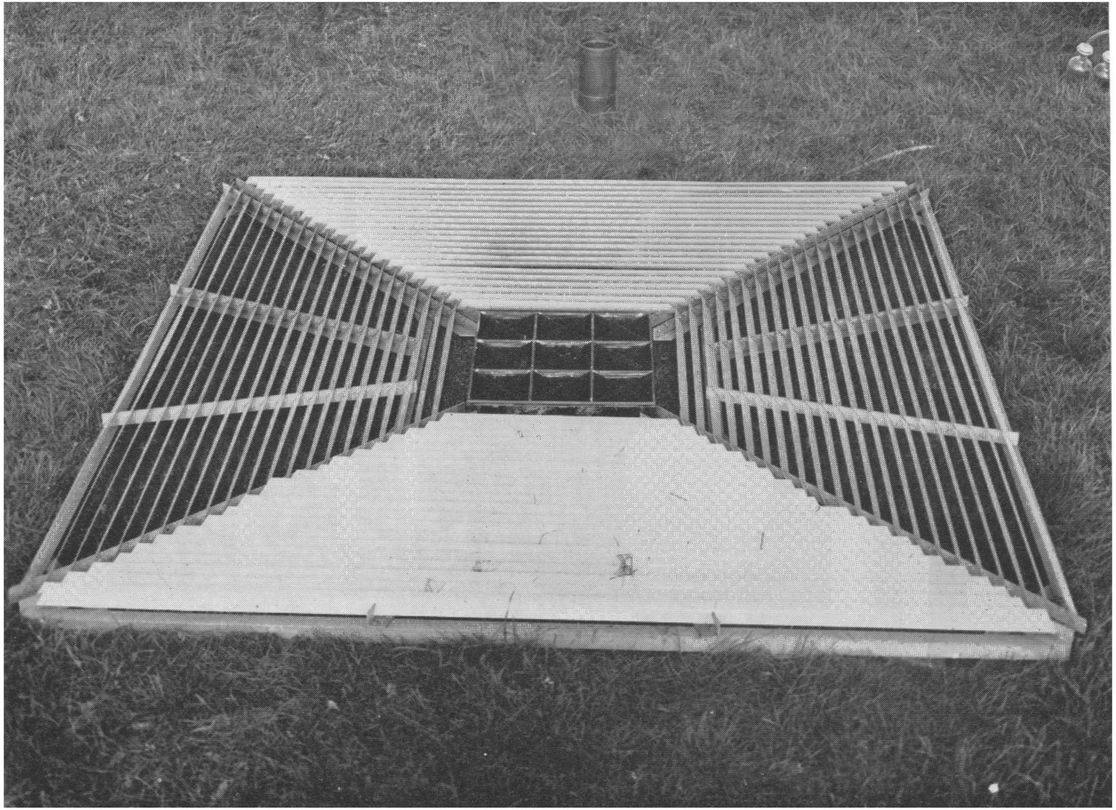
PLATE I—VIEW OF HILLTOP ENCLOSURE, LOOKING NORTH, BEFORE 1 OCTOBER 1966



By courtesy of Water Research Association

PLATE II—9-HOLE GAUGE WITH INSERTS AND SLATTING SURROUND

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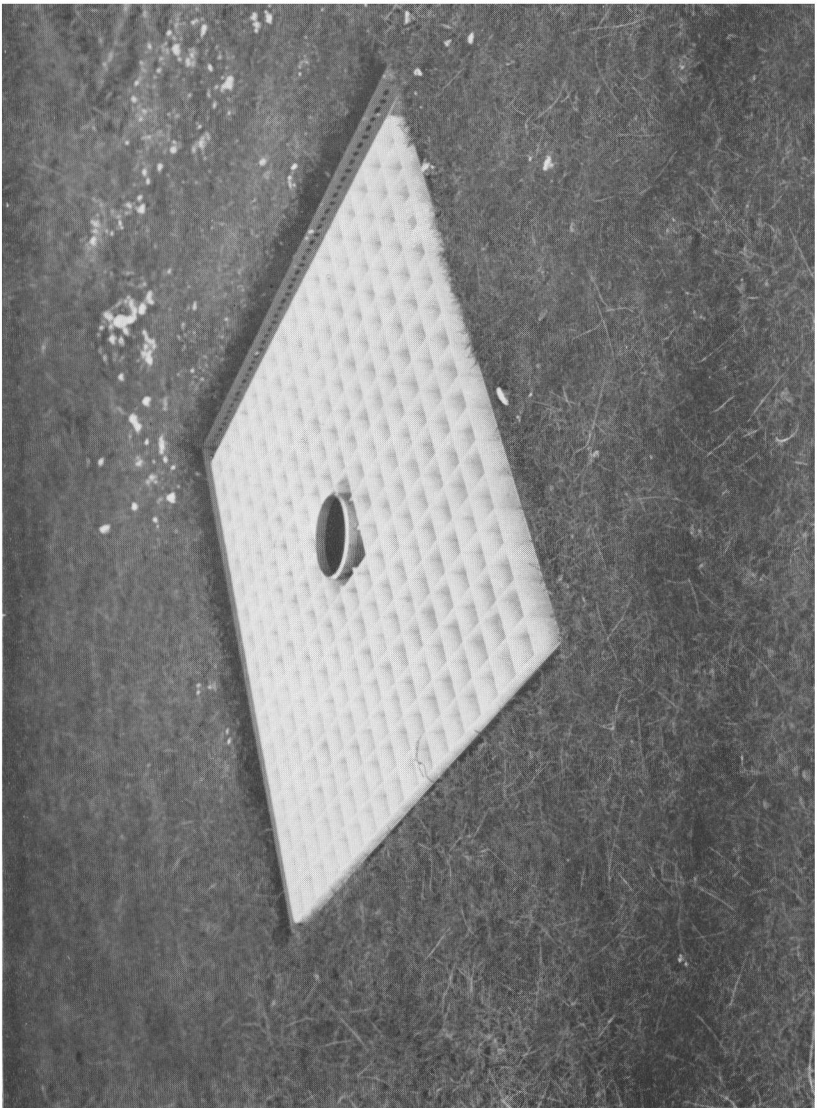

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PLATE III—PIT GAUGE WITH POLYSTYRENE GRID SURROUND direction was examined. The groups were selected according to the limitations of the 3-funnel gauge which was only able to measure rain inclination from 45° to 90° from 1962 to 13 September 1965 and from 35° to 90° after a modification to the funnels on the 13th. From examination of Table III it is seen that, excepting gauge G and individual compartments of the 9-hole gauge, catch ratios decrease with decreasing rain inclination to the horizontal.

A better estimation of catch ratio is given when wind speed at gauge height is combined with rain inclination. Initially wind speed at gauge height had to be correlated with wind speed at 2 metres, and five surveys were carried out with sensitive cup anemometers installed adjacent to and at the rim height of each gauge. Each survey comprised a 25-minute wind run for a given wind direction. From these results the wind speed at gauge heights was normalized with respect to that at 2 metres. This was undertaken by calculating a linear regression of wind speed at gauge heights with that at 2 metres. The regression coefficients have been incorporated in Figure 4 which shows the relationship between catch ratio, wind speed and rain inclination. The wind speed at the 9-hole gauge (height 4 cm) was extrapolated from a relationship of wind speed with height.

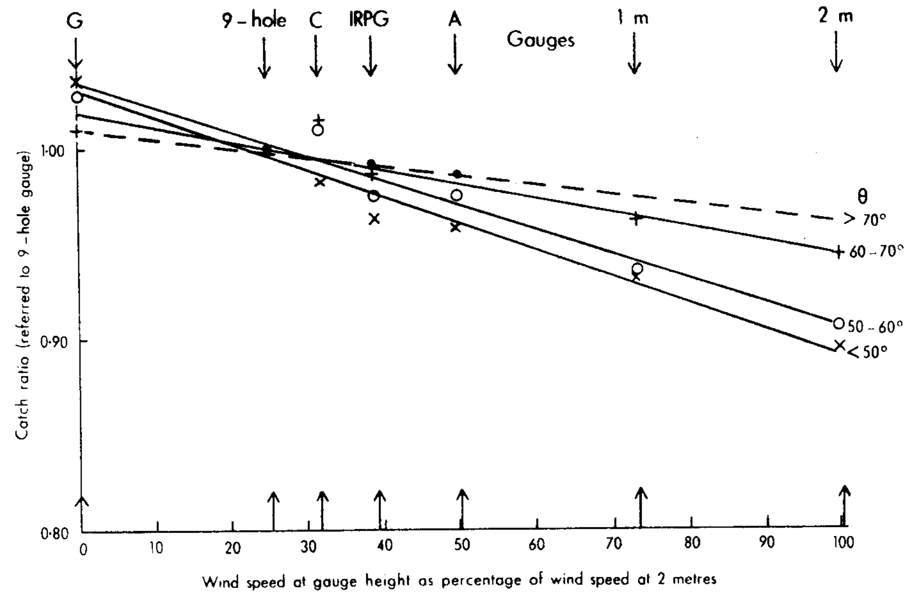

FIGURE 4—RELATIONSHIP BETWEEN CATCH RATIO, WIND SPEED AND RAIN INCLINATION

θ = rain inclination from the horizontal.

. Catch ratio for θ>70° + Catch ratio for θ 60–70°

o Catch ratio for θ 50–60° x Catch ratio for θ<50°

The pecked line was estimated because data for θ>70° were limited.

For three groups of rain inclination, linear regressions were calculated as seen in Table IV.

TABLE IV—REGRESSION DATA FOR RANGES OF RAIN INCLINATION

Rain inclination, θ	Regression	Correlation coefficient	Standard error of y
$\theta<50°$	$y = 1{\cdot}029 - 0{\cdot}14x$	0·85	0·03
$50°<\theta<60°$	$y = 1{\cdot}032 - 0{\cdot}13x$	0·96	0·01
$60°<\theta<70°$	$y = 1{\cdot}017 - 0{\cdot}07x$	0·86	0·01

y is catch ratio,
x is wind speed at gauge rim height expressed as per cent of that at 2 m.

The limited data available for rain inclination (θ) greater than 70° did not warrant a regression and the dashed line in Figure 4 represents an estimate. Gauge B results were omitted from the analysis because of the proximity of this gauge to the fence (Figure 1).

From Figure 4 it is seen that the regressions tend to converge to a point where the catch ratio is 1·00, and for catch ratios between 1·01 and 0·99 the regressions give wind speeds of between 20 per cent and 30 per cent of that at 2 metres. The maximum wind speed experienced during the wind surveys was 13·6 m/s at 2 metres which, if the wind at the lower rim height is assumed to be 25 per cent of that at 2 metres, gives 3·4 m/s. This satisfies the requirements of Gold[9] who recommended that the wind speed at rim height should not exceed 10–15 miles/h (4·4 to 6·7 m/s).

Effect of area of grid and rim height on the catch of a gauge.

Chemical tests of in-splash. Although appreciable amounts of splash had never been detected in the early trials of the 9-hole gauge, a further investigation was undertaken with gauge G. To provide evidence of in-splash a semicircular metal tray with three annular compartments of width 30·5 cm and depth 1·5 cm was placed on the ground surface on the south-west of the gauge with its diameter passing through the rain-gauge (Figure 5). The central semicircular portion was cut away and the nearest tray was 50 cm from the centre of the gauge. The 90 × 90 cm grid surround occupied the space between

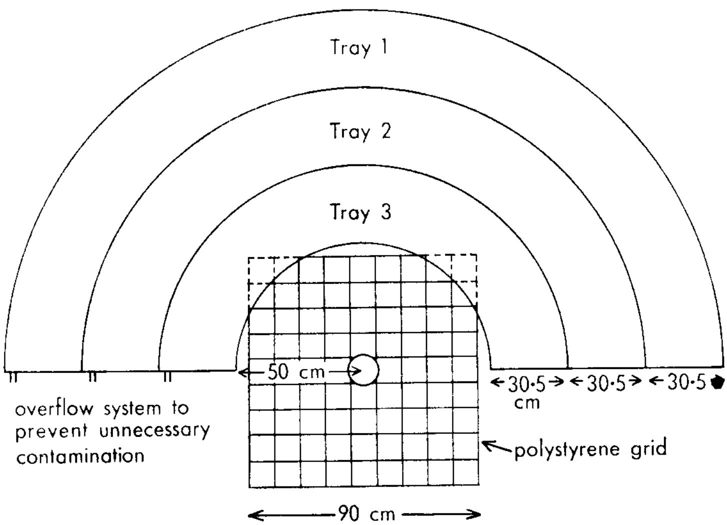

FIGURE 5—SKETCH PLAN OF SEMICIRCULAR TRAY ARRANGEMENT
A 5-inch rain-gauge is at the centre of the grid.

the tray and the gauge. Each tray was filled to a depth of 0·5 cm with a chemical solution; sodium chloride in the tray furthest from the gauge (No. 1), ammonium sulphate in the middle tray (No. 2) and potassium chloride in the nearest (No. 3).

The aim was to detect the chemicals in the rain catch. The mean catch ratio of gauge G with the trays was 1·079 against the long-term mean without trays of 1·029. Probably more splash was generated from the wet metal surface than would have been the case with grass.

The mean concentration in each tray was determined and it was assumed that rainfall causes a proportionate dilution of the chemical solutions. For each rain event the in-splash from the tray zone was found from the analyses of the catch in the gauge. The results are set out in Table V.

TABLE V—ANALYSIS OF CATCH SHOWING IN-SPLASH FROM TRAYS OF CHEMICAL SOLUTIONS

Apparent proportion of catch ratio derived from in-splash from trays				Catch ratio of G to the mean of 9-hole gauge	Corrected catch ratio	θ
Tray 1	Tray 2	Tray 3	All trays 1+2+3			
0·033	0·004	0·020	0·057	1·127	1·070	36°
0·020	0·028	0·030	0·078	1·120	1·042	52°
0·007	0·023	0·025	0·055	1·067	1·012	40°
0·004	0·004	0·007	0·015	1·020	1·005	47°
0·008	0·015	0·013	0·036	1·059	1·023	<35°
				Mean 1·079	Mean 1·030	

θ = rain inclination to horizontal.

From these results the catch ratios, less the apparent proportion due to splash from the trays, were greater than unity on each occasion, varying from 1·005 to 1·070 with a mean value of 1·030. This latter figure is essentially identical with the long-term catch ratio of 1·029 for gauge G without chemical trays (see Table III), when compared to the mean of the 9-hole gauge for rain inclinations of less than 50° to the horizontal. The subtraction of chemical in-splash from the tray zone is equivalent to inserting a splash-free zone there. Consequently the near equality of these figures, 1·030 and 1·029, implies that the grass beyond the 90×90 cm grid of gauge G contributes negligible in-splash.

Variation of grid area and rim height. Following the chemical in-splash investigation a more detailed study was undertaken at four sites within the enclosure. The size of grid surround and rim height of gauge above the surround were varied. The positions of the gauges are seen in Figure 2 (G_1 to G_4).

The polystyrene grid surrounds, installed flush with the ground surface, were 90×90 cm, 60×60 cm and 30×30 cm and the fourth site was left without a grid. The rim heights above the ground were 0 cm, 7·5 cm, 15 cm and 22·5 cm. When the rim height was flush with the ground surface and the grid surround was absent, an annular space of 1 cm was left between the gauge wall and the soil. The levelled rim of the gauge was left slightly above the ground surface to prevent any surface run-off entering the funnel. Table VI sets out the mean of four catch ratios, and rain inclinations and directions for each grid area and rim height. As the 9-hole gauge was not available all catch ratios are with reference to gauge C (rim 30·5 cm above ground, set within a turf wall).

TABLE VI—CATCH RATIOS,* AND RAIN INCLINATION (θ) AND DIRECTION WITH DIFFERENT RIM HEIGHTS AND GRID SIZES

	Gauge G_1 (Grid 90×90 cm)			Gauge G_2 (Grid 60×60 cm)			Gauge G_3 (Grid 30×30 cm)			Gauge G_4 Grid absent			Mean catch ratio
Rim height	Catch ratio	θ	Rain direction E of N	Catch ratio	θ	Rain direction E of N	Catch ratio	θ	Rain direction E of N	Catch ratio	θ	Rain direction E of N	
cm													
0	1·054	34°	159°	1·041	47°	194°	1·054	37°	148°	1·127	41°	167°	1·050 (excluding 1·127 result)
7·5	1·027	41°	167°	1·036	34°	159°	1·012	47°	194°	1·033	37°	148°	1·027
15·0	0·951	37°	148°	1·010	41°	167°	1·006	34°	159°	0·993	47°	194°	0·990
22·5	0·987	47°	194°	0·948	37°	148°	0·969	41°	167°	0·979	34°	159°	0·971

*Mean of 4 readings compared with gauge C (rim at 30·5 cm).
θ = rain inclination to horizontal.

The effect of grid area was not critical except when rim heights were 0 and 7·5 cm. The ranges of mean ratios for these rim heights, excluding occasions when the grid was absent, were 1·041 to 1·054 and 1·012 to 1·036 respectively. Anomalies did occur; for example, the mean catch ratio with the 60×60 cm grid was less than that with the 90×90 cm grid at a rim height 0 cm, and with the 30×30 cm grid the mean ratio was less than that with the 60×60 cm or the 90×90 cm grid at a rim height of 7·5 cm.

At rim heights 15 and 22·5 cm the mean catch ratio ranges were 0·951 to 1·010 and 0·948 to 0·987 respectively, while the ratio of gauge A (30·5 cm) to that of gauge C for the corresponding period was 0·971. Analysis of variance shows that the effect of grid area on catch ratio is not statistically significant at the 1 per cent level using an *F*-test.

The effect of rim height is seen in Table VI and the analysis of variance shows that the effect is highly significant at the 1 per cent level using an *F*-test. The decrease in catch ratio with rim height is seen in Figure 6. The solid curve represents the catch ratio when in-splash is avoided and the dashed curve the ratio when the grid surround is absent and when splash is probable. The area between these curves estimates the amount of in-splash, which at a height of 7·5 cm and above is less than 1 per cent. Gold[10] gives the theoretical maximum height reached by splash in still air of raindrops 2 mm in diameter or over as 0·73 to 0·43 metres, depending on the number of splash droplets produced. The spectrum of raindrop size as given by Meinzer,[11] indicates that raindrops are usually smaller than 2 mm diameter.

Conclusions. There was no evidence to suggest in-splash into the 9-hole gauge from the angled venetian-blind slatting, whereas the inter-compartment variation was attributed to wind eddying within the square compartments. Diagonal inserts within each funnel diminished the wind eddying and the variation.

For the 5 years of record a Mk 2 gauge with rim at 30·5 cm caught 3·2 per cent less than the mean catch of the 9-hole gauge, and when a Mk 2 with rim at 30·5 cm was surrounded by a turf wall the catch was within 1 per cent of the mean catch of the 9-hole gauge. An IRPG and Mk 2 funnels at 1 metre and 2 metres caught 4, 6 and 10 per cent, respectively, less than the mean catch of a 9-hole gauge. A 5-inch gauge set in a pit with its rim flush with the ground surface and surrounded by a 90×90 cm polystyrene grid caught 2·5 per cent more than the mean catch of the 9-hole gauge.

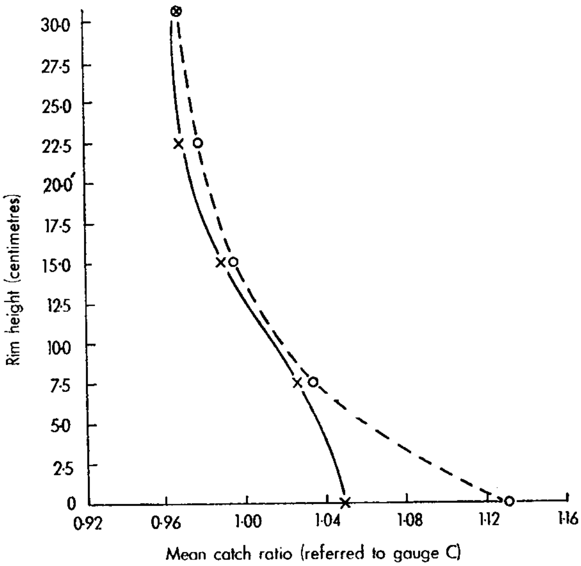

FIGURE 6—RELATIONSHIP BETWEEN CATCH RATIO (REFERRED TO GAUGE C) AND RIM HEIGHT

x Mean catch ratio for each rim height with gauges in positions G_1 to G_4 as shown in Figure 2 (rim heights of 0 and 7·5 cm with grid absent are excluded)

o Mean catch ratio for each rim height with grid absent

Catch ratio for gauge A shown at 30·5 cm.

When the area of the grid was varied between 30×30 cm and 90×90 cm around a pit gauge the range in catch ratios was from 1·041 to 1·054. From measurements of induced chemical in-splash it was found that the grass area beyond the 90×90 cm grid was producing negligible in-splash.

The effect of rim height on loss of catch was highly significant but in-splash was not significant above a rim height of 7·5 cm.

It was shown that a gauge would catch within 1 per cent of the mean of the 9-hole gauge if the wind speed at rim height was between 20 to 30 per cent of that at 2 metres.

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WINTER PRECIPITATION OVER EAST ANGLIA

By M. F. SMITH

Summary. Occasions of snow in East Anglia during a period of five winters were found to be associated with 1000–850-mb thickness of 1310 gpm or less. Nearly all occasions of sleet occurred in this thickness range also, and there were many occasions of rain. A scatter diagram was prepared in which the 850-mb temperature and the height of the freezing-level above sea level were used as axes and the type of precipitation (snow, sleet or rain) appeared in the diagram in symbolic form. The diagram was then divided, by eye, into sectors containing the main concentrations of snow, sleet or rain. The percentage of each type in each sector was calculated and used to represent the probability of the type within that sector. The occasions were then classified further, mainly into 10-gpm bands of 1000–850-mb thickness, and again scatter diagrams were drawn.

The diagrams were used as prediction diagrams over a set of independent data for winter 1967/68 and tables are given showing the success obtained at Mildenhall and Marham. Comparison is made with the success obtained with the two predictors recommended by Boyden for a snow probability of 50 per cent and above.

Introduction. Murray[1] investigated the use of 1000–700-mb and 1000–500-mb thickness and height of freezing-level as predictors of winter precipitation. Mineeva,[2] following the work of Popova, used the surface temperature and 1000–850-mb thickness with the air temperature at 850 mb in certain cases over Russia. Boyden[3] compared several predictors, though the air temperature at 850 mb was not among them. He came to the conclusion that surface temperature is an unreliable predictor and he decided that, of those he examined, the height of the freezing-level and the 1000–850-mb thickness with some allowance for sea-level pressure and station height, were the two best predictors of winter precipitation over the British Isles.

In the present paper it is assumed (as it was in the other investigations mentioned above) that some entirely different techniques have been used to decide that precipitation is going to fall, and once this has been decided, the question which then has to be answered is what kind of precipitation will fall. The method presented in this paper combines the 1000–850-mb thickness and the height of the freezing-level with a third predictor, the 850-mb temperature. It also distinguishes between rain and snow mixed, and snow or rain separately. An attempt is also made to give the probability of a forecast being correct.

Data used. The upper air ascents for Hemsby, Crawley and Aughton reported daily in the *Daily Aerological Record* for the months November to April for the five winters 1962/63 to 1966/67 were examined and an estimate was made of the following items appropriate to East Anglia for 0000 and 1200 GMT each day :

(i) 1000–850-mb thickness in geopotential metres.
(ii) 850-mb temperature in degrees Celsius.
(iii) Height of freezing-level expressed in millibars above sea level. The lowest value was taken, surface inversions being excluded.

The surface observations as given in the *Daily Weather Report* for Wittering (66 m above MSL), West Raynham (76 m), Gorleston (2 m), Cardington (28 m), Mildenhall (5 m) and Wattisham (89 m) were examined for the same months and years. All cases of snow and of sleet* were recorded. There were 370 cases with the 1000–850-mb thickness ⩽1310 gpm and only 9 extra cases of sleet occurred with the thickness value in the range 1311–1320 gpm. The observations were then re-examined and 224 cases of rain and/or drizzle which occurred with the 1000–850-mb thickness value of ⩽1310 gpm were also recorded and classified as rain. For precipitation in the period 0000–1200 GMT, upper air data were taken from the 00 GMT ascents and for the period 1200–0000 GMT from the 12 GMT ascents.

A total of 594 cases with thickness ⩽1310 gpm were recorded, classified as snow, sleet or rain. If more than one type of precipitation was reported by the stations in the same 12-hour period, the type was classified as snow if snow was reported at any of the stations, otherwise it was classified as sleet.

At Mildenhall only, the dew-point at the time of commencement of the precipitation was noted by reference to the register of observations.

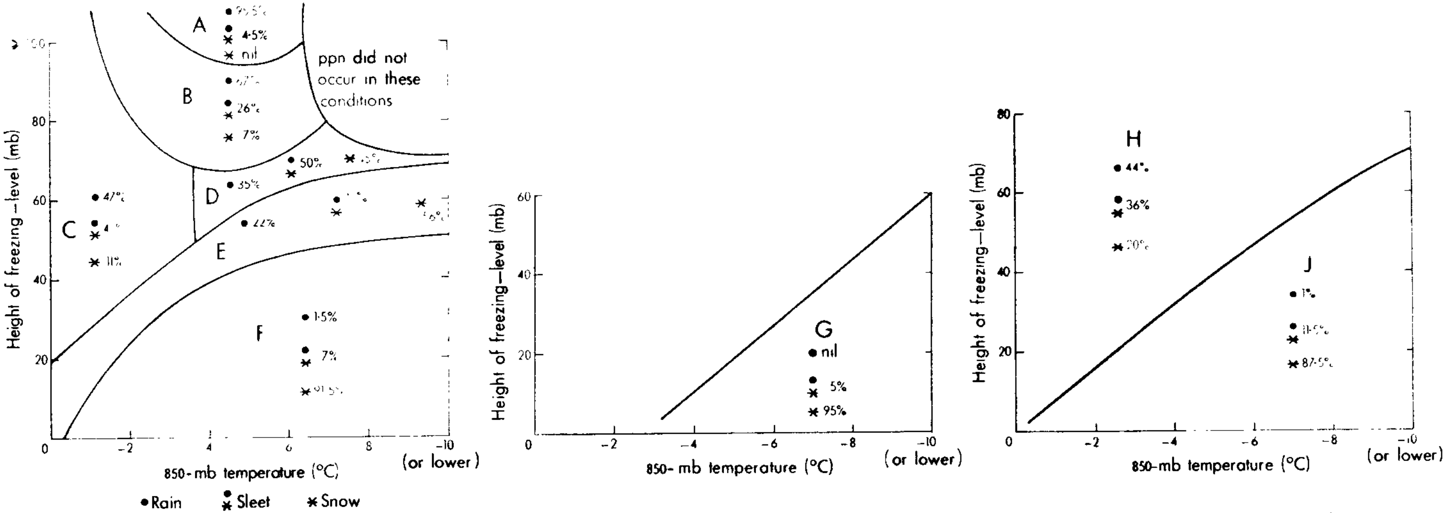
Preparation of the prediction diagram. A scatter diagram of 850-mb temperature against height of freezing-level was plotted for the 594 cases with geopotential thickness ⩽1310 gpm, and the 9 cases of sleet with thickness 1311–1320 gpm were included. Different symbols were used for snow, sleet and rain. The diagram was divided into sectors containing significantly different proportions of snow, sleet or rain by drawing lines to avoid as many rogue plots as possible. The percentage of each type of precipitation in each sector was calculated by counting the number of plots of each type of precipitation, multiplying by 100 and dividing by the total number of plots in that sector. The boundary lines are given in Figure 1(*a*) and each sector is identified by a letter. The number of observations and percentage frequencies are given in Table I.

TABLE I—NUMBER OF OBSERVATIONS AND PERCENTAGES IN THE SECTORS IN FIGURES 1(*a*) – (*f*)

Figure	Sector	Number of observations				Percentages		
		Rain	Sleet	Snow	Total	Rain	Sleet	Snow
(*a*)	A	64	3	Nil	67	95·5	4·5	Nil
	B	84	32	9	125	67	26	7
	C	29	26	7	62	47	42	11
	D	14	20	6	40	35	50	15
	E	11	11	28	50	22	22	56
	F	4	18	237	259	1·5	7	91·5
	A to F				603†			
(*b*)	G	Nil	4	72	76	Nil	5	95
(*c*)	H	11	9	5	25	44	36	20
	J	1	11	84	96	1	11·5	87·5
(*d*)	K	27	5	1	33	82	15	3
	L	9	21	4	34	26	62	12
	M	9	10	56	75	12	13	75
(*e*)	N	66	4	Nil	70	94	6	Nil
	P	52	24	7	83	63	29	8
	Q	15	13	9	37	40	35	25
(*f*)	R	16	2	Nil	18	89	11	Nil
	S	6	9	Nil	15	40	60	Nil

†Including the 41 cases of snow with thickness < 1270 gpm.

*Sleet is here defined as snow and rain (or drizzle) together or snow melting as it falls.

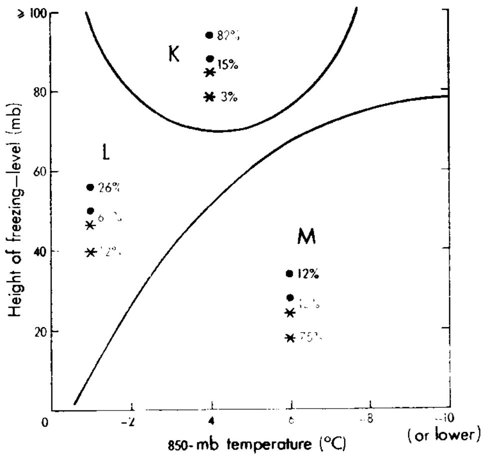


(a) With 1000–850-mb thickness ≤ 1310 gpm, including 9 occurrences of sleet with thickness 1311–1320 gpm.

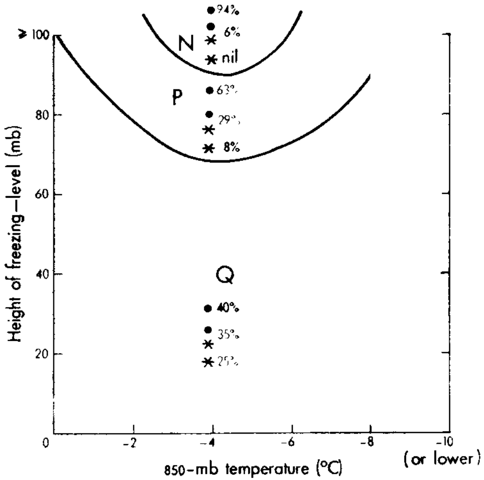
(b) With 1000–850-mb thickness 1270–1279 gpm.

(c) With 1000–850-mb thickness 1280–1289 gpm.

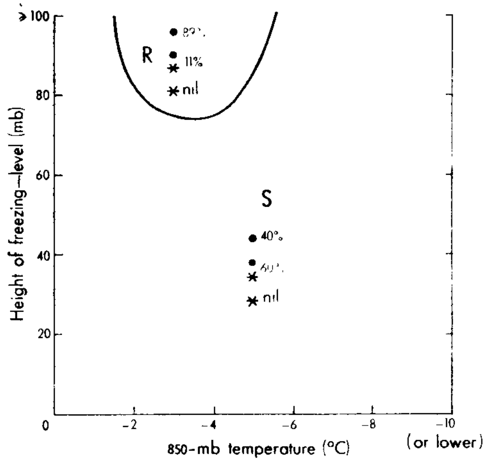
FIGURE 1—PERCENTAGE PROBABILITY OF OCCURRENCE OF WINTRY PRECIPITATION



(*d*) With 1000–850-mb thickness 1290–1299 gpm.



(*e*) With 1000–850-mb thickness 1300–1309 gpm.



(*f*) With 1000–850-mb thickness 1310 gpm, including 9 occurrences of sleet with thickness 1311–1320 gpm.

FIGURE 1—PERCENTAGE PROBABILITY OF OCCURRENCE OF WINTRY PRECIPITATION
—*continued*

Secondly, all cases were grouped according to the 1000–850-mb thickness in the ranges *(a)* <1270 gpm, *(b)* 1270–1279 gpm, *(c)* 1280–1289 gpm, *(d)* 1290–1299 gpm, *(e)* 1300–1309 gpm, and *(f)* 1310 gpm (which included the 9 extra cases of sleet with thickness 1311–1320 gpm), and scatter diagrams were also prepared of 850-mb temperature against freezing-level for the groups *(b)* to *(f)* separately. Figures 1*(b)*–*(f)* show the boundary lines and lettered sectors for these groups and Table I gives the number of observations and percentage frequencies. All 41 cases of precipitation in group *(a)* — thickness <1270 gpm — were of snow, and these are included in Figure 1*(a)* only.

No physical explanation is offered for the shapes of the sectors in the various diagrams. They were derived empirically and their usefulness depends on how well they behave in practice. This is discussed later in the paper.

Use of diagrams. A forecast of the type of precipitation for the periods 0000–1200 GMT and 1200–0000 GMT can be made using the diagrams and the appropriate ascent, if it is assumed that the diagrams are representative. Figure 1*(a)* contains all cases with thickness ⩽1310 gpm and therefore by use of this figure an answer can be obtained quickly from a single diagram. Note that the boundary limit for snow is of probability 56 per cent, i.e. higher than that used by Boyden, and in most sectors the relevant probability is much more than 50 per cent. Figures 1*(b)* – *(f)* classify the cases according to thickness and therefore selection of a diagram from amongst these figures, by taking in an extra predictor, should increase the reliability of the result.

From the latest available upper air ascents at Hemsby, Crawley or Aughton, estimate the values of the 1000–850-mb thickness, the 850-mb temperature and the height of the freezing-level for the forecast area (East Anglia). Plot the point given by these estimates in Figure 1*(a)* or one of the Figures 1*(b)* – *(f)*. Forecast snow, sleet or rain according to the type of precipitation with maximum percentage probability. For example, if Figure 1*(a)* were used and the values of the 850-mb temperature and the height of the freezing-level were −3°C and 40 mb respectively, the forecast would be snow with a probability of 56 per cent (say 60 per cent).

However, if the forecaster thought that the advection of colder air either near the surface or at 850 mb would cause the freezing-level, the 850-mb temperature and/or the 1000–850-mb thickness to fall so that the plot would fall in area F, then the probability of snow could be raised to 91 per cent.

Test of the method. The method was tested on independent data at Mildenhall and Marham during the winter months November 1967 to April 1968 inclusive. As the primary purpose of this method is to help the forecaster to decide in doubtful cases what kind of wintry precipitation will occur, the diagrams were used only on those occasions when the 1000–850-mb thickness was ⩽1310 gpm. It was found from the preliminary examination of the data that no precipitation other than rain occurred with the 1000–850-mb thickness in excess of 1320 gpm, and only 9 cases of sleet (less than 3 per cent of 370) occurred in the range 1311–1320 gpm; therefore the results of the test are not weighted with a large number of successful forecasts of rain on occasions when a forecaster would not even have considered any other possibility. On the other hand, no occasion of sleet or snow has been omitted from the analysis. Occasions when no precipitation occurred have been ignored.

TABLE II—NUMBER OF FORECASTS OF SNOW, SLEET AND RAIN AT MILDENHALL AND MARHAM COMPARED WITH THE TYPE OF PRECIPITATION THAT ACTUALLY OCCURRED DURING THE PERIOD NOVEMBER 1967–APRIL 1968 WITH 1000–850-mb THICKNESS $\leqslant$ 1310 gpm

Forecast of:	MILDENHALL				MARHAM			
	Snow occurred	Sleet occurred	Rain occurred	Total	Snow occurred	Sleet occurred	Rain occurred	Total
Snow	20	4	3	27	12	1	0	13
Sleet	2	7	4	13	1	1	2	4
Rain	0	0	11	11	1	0	6	7
Total	22	11	18	51	14	2	8	24

Table II gives the 3×3 contingency tables of the results of the method at Mildenhall and Marham. There were fewer cases at Marham as observations there are made only from 0000 GMT on Mondays to about 1800 GMT on Fridays.

The chi-square test showed that the results were significant at the 0·1 per cent level for Mildenhall but there were too few cases at Marham for the test to be properly applied.

At Mildenhall, on the three occasions when snow was forecast from the diagrams but rain occurred, the percentage probability of occurrence of snow was over 80 per cent; in each case only slight rain fell. On the two occasions when snow occurred and on the four occasions when rain occurred, after a sleet forecast, the figures gave a probability of sleet of about 30 per cent.

Comparison with other methods.

(i) Murray's criterion[1] for snow is that the 1000–500-mb thickness is <5224 gpm. In the test only 4 out of 22 cases of snow at Mildenhall occurred with the 1000–500-mb thickness <5224 gpm, so that 18 out of 22 did not satisfy Murray's criterion.

(ii) Boyden[3] found that a 1000–500-mb thickness of 5258 gpm gave a 50 per cent probability of snow occurring. In the test winter at Mildenhall only 4 cases out of 22 cases of snow occurred with the 1000–500-mb thickness <5258 gpm.

(iii) Boyden[3] found that the two most suitable snow predictors over the British Isles during four winters were *(a)* the height of the freezing-level above ground and *(b)* the 1000–850-mb thickness adjusted for sea-level pressure and for height above sea level. He found that the 50 per cent probability of snow occurred when the freezing-level was 35 mb above ground or when the adjusted 1000–850-mb thickness was 1293 gpm. Boyden forecast two categories only, snow or rain, and used the 50 per cent probability of snow as the boundary limit. If sleet actually occurred the forecast was counted half right and half wrong. For this comparison, occurrences of sleet were counted for the present method in the same way and, in addition, forecasts of sleet were counted as half snow forecasts and half rain forecasts. A comparison with the present method is given in Table III.

Table III gives the 2×2 contingency tables comparing forecasts of rain or snow with the actual occurrences of rain or snow for the present (reduced) method and for Boyden's two recommended predictors for probabilities of

TABLE III—NUMBER OF FORECASTS OF SNOW OR RAIN AT MILDENHALL AND MARHAM COMPARED WITH THE TYPE OF PRECIPITATION THAT ACTUALLY OCCURRED, USING THREE METHODS OF FORECASTING

Method	Forecast of:	MILDENHALL Snow occurred	MILDENHALL Rain occurred	MILDENHALL Total	χ^2	MARHAM Snow occurred	MARHAM Rain occurred	MARHAM Total
a	Snow	24¾	8¾	33½	13·4	13¼	1¾	15
	Rain	2¾	14¾	17½		1¾	7¼	9
b	Snow	18½	4½	23	10·0	11	4	15
	Rain	9	19	28		4	5	9
c	Snow	16	3	19	8·6	9½	½	10
	Rain	11½	20½	32		5½	8½	14

Method *a* As described in this paper
b Boyden, 1000–850-mb thickness
c Boyden, freezing-level height

Note : the fractions ¼ and ¾ occur when the 3 × 3 contingency table is reduced to a 2 × 2 table.

snow of 50 per cent and above. The chi-square value (with Yates's corrections) is also given. The 0·1 per cent significance value is 6·63. However, the value of the present method is considerably reduced by the counting of sleet forecasts as half snow forecasts and half rain forecasts.

The 13 forecasts of sleet at Mildenhall (see Table II) occurred with 1000–850-mb thickness 1290–1309 gpm and were re-examined and re-forecast as either rain or snow with the help of Figures 1*(d)* and *(e)*. Table IV gives the 2 × 2 contingency table including the sleet forecasts reassessed either as a rain forecast or as a snow forecast. The value of chi-square for the table is 19·8.

TABLE IV—NUMBER OF FORECASTS OF SNOW OR RAIN AT MILDENHALL COMPARED WITH THE TYPE OF PRECIPITATION THAT ACTUALLY OCCURRED, USING PRESENT REDUCED METHOD

Forecast of:	Snow occurred	Rain occurred	Total
Snow	24½	5½	30
Rain	3	18	21
Total	27½	23½	51

From Tables III and IV it is shown that the present reduced method gave 24½ correct snow forecasts out of 30 snow forecasts, and only 3 occasions of snow occurred after a rain forecast, whereas Boyden's freezing-level method gave 16 correct snow forecasts out of 19 but 11½ occasions of snow occurred after a rain forecast. Boyden's adjusted 1000–850-mb thickness method gave 18½ correct snow forecasts out of 23 snow forecasts and 9 occasions of snow occurred after a rain forecast. In Table II a point of interest is the fact that the present method did not give a rain forecast for any occasion on which snow or sleet occurred at Mildenhall.

Dew-point at time of commencement of precipitation. At Mildenhall the dew-point at the time of commencement of the precipitation was noted. Out of the 139 cases of snow, 134 occurred with a dew-point of 0·0°C or below, 4 occurred with a dew-point of + 0·1 to + 0·5°C and only one occurred with the dew-point above 0·5°C. Out of seven cases of rain occurring with a negative dew-point, five were pre-warm-frontal, and in fact the dew-point soon increased to zero or above. For sleet, dew-points were in most cases less than + 1·0°C. If a definite increase or decrease of the surface dew-point through advection could be foreseen, some modification of the probabilities for snow or rain given by the diagrams could be made.

Conclusions. This paper provides the forecaster who is dealing with winter precipitation with a method of deciding in doubtful cases whether to forecast rain, sleet or snow.

During the period of the test, as Table II shows, no snow or sleet occurred after a forecast of rain at Mildenhall and the only forecast which failed to satisfy this criterion at Marham was ahead of a warm front. This method is therefore recommended when the forecasting problem is to ensure that no occasion when snow occurs is forecast as rain. Alternatively, the predictors for 90 per cent probability of snow suggested by Boyden may be used.

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