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The use of rainfall data from radar for hydrometeorological services

By S. G. Palmer, C. A. Nicholass, M. J. Lee and M. J. Bader

(Meteorological Office, Bracknell)

Summary

Rainfall amounts measured from rain-gauges currently form the basis for answering many hydrometeorological enquiries involving rainfall and evaporation over the United Kingdom. However, rainfall information is now also available from a network of radars. Methods of combining the data from the two sources for producing more representative rainfall distributions on daily and sub-daily time scales are described and examples showing the benefits of incorporating the radar data are given.

1. Introduction

The Meteorological Office's Hydrometeorological Branch provides information on rainfall and evaporation to many users. Two very common questions are: 'How much rain has fallen over a particular area on a certain day or over a period of days, months or years?' and 'How often is a given amount of rainfall reached or exceeded for a specified period?' The first type of question is asked, for a variety of purposes, by people from many organizations, including water authorities, builders, insurance companies and farmers. The second type of question is chiefly asked by design engineers from, for example, civil engineering firms and local councils. For instance, if a new drainage system must not overflow, on average, more often than once in 10 years, the engineer will base his design on the rainfall amount that is reached or exceeded, on average, once in 10 years at the location of interest.

All these enquiries are answered using rainfall observations in the National Rainfall Archive (Shearman 1980) held at the Meteorological Office in Bracknell. The observations come from rain-gauges (i) read daily at 0900 GMT (daily rainfall totals) and (ii) which record rainfall during periods of less than a day (e.g. hourly totals).

There are currently about 3400 locations in England and Wales where the rainfall totals are read daily, which is sufficient to enable the daily rainfall distribution to be determined adequately over most regions. However, there are four aspects of daily rainfall observations to be considered:

(a) The network density varies from region to region; in some upland and rural areas where the gauge network is sparser, more detailed rainfall information is required.

(b) There is a financial requirement to reduce the number of rain-gauge stations measuring daily rainfall, so ways must be found to provide an acceptable standard of information from fewer stations.

(c) Most observers record their month's observations on cards which are sent to the Meteorological Office by collecting centres. Processing the observations requires manual intervention involving transcription to computer media, quality control, etc., and data processing would become more efficient if more automation could be incorporated.

(d) The rainfall observation cards reach the Office at the end of each month so that the rainfall distribution from all gauges for any particular day only becomes available during and sometimes after the following month; there would be a market for observations that were made available much sooner than this.

In contrast to the large number of locations where observations of daily rainfall totals are made, there are only about 150 locations in England and Wales where rainfall information from recording gauges is available at the Meteorological Office for determining rainfall totals for periods of less than a day. Sub-daily totals are particularly useful for providing information (e.g. connected with urban drainage) on local storms which can deposit very heavy rainfall for periods of up to a few hours over areas of 1000 km^2 or less. In general the short-period recording gauge network is so sparse that such storms could easily slip between gauges without being detected, particularly if they are slow moving.

A further problem with observations from all rain-gauges is that, although the measurements can be made very precisely, they only provide values of rainfall at a point. Such measurements may not be representative of the surrounding area, particularly if the rain is showery in character. Improved determinations of rainfall over areas are needed.

Alternatively, rainfall can be measured using radar (see Browning 1978). For several years now the Research and Development section of the Hydrometeorological Branch have been investigating the use of radar data to provide information on rainfall:

(i) within the gaps in the daily, and especially the sub-daily, network,

(ii) on time scales of a day or less,

(iii) over areas rather than at points,

(iv) soon after the event of interest (within one day), and

(v) automatically, to reduce the need for manual data processing.

Rainfall data from a network of radars form the basis of work being carried out by the Meteorological Office Radar Research Laboratory, Malvern in their Short Period Weather Forecasting Project and in near-real-time flood control (see Browning 1979) but there the emphasis is on having rainfall information available within a few minutes.

2. Measurement of rainfall using radar

The use of radar for measuring rainfall has been widely documented (see Battan 1973). Briefly, the radar emits pulses of microwave radiation in a near-horizontal beam which rotates in azimuth. When a pulse intercepts precipitation the signal is scattered and a small proportion returns to the receiver. This back-scattered power is a function of the precipitation rate through the sampling volume, but the relationship varies with the type of rain (see Wilson and Brandes 1979). In practice, assumptions are made about the droplet size distribution and a single relationship between the back-scattered power and rainfall rate is used. One of the reasons for making rainfall observations by radar is to provide frequent observations and therefore only a limited time is available for the observation of rainfall at any specific location. This determines the signal-to-error ratio of the return radar signal and hence of the inferred rainfall rate. As a consequence the return signals from areas of 5 km × 5 km (or 2 km ×2 km from locations closer to the radars) are combined, leading to rainfall rate estimates averaged over the areas with acceptably small errors. This averaging over areas also reduces the otherwise vast amount of data to be handled. So, radar provides estimates of areal rainfall observed above the ground with useful accuracy while the gauges give generally more accurate measurement of point rainfalls at the surface. Also, the radar, whose beam scans continuously in time and space, can provide information automatically for large areas in real time, thus fulfilling the requirements (i) to (v) listed at the end of Section 1.

The aim of a research and development project, currently being carried out in the Meteorological Office, is to combine the precision of measurement from the rain-gauges with the areal and temporal variations observed from the radar to provide a better picture of the rainfall in time and space than either system gives alone.

3. Radar data processing methods

3.1 *Production of hourly rainfall totals*

The UK Weather Radar Network currently comprises four sites (Fig. 1): Hameldon Hill and experimental sites at Clee Hill, Upavon and Camborne. Others are planned, notably one to cover London and south-east England. The radar observations are used to produce rainfall measurements over squares of 5 km × 5 km every 5 minutes. These measurements are integrated by the Meteorological Office Radar Research Laboratory at Malvern to give hourly totals and are then sent on magnetic tape to Meteorological Office Headquarters at Bracknell.

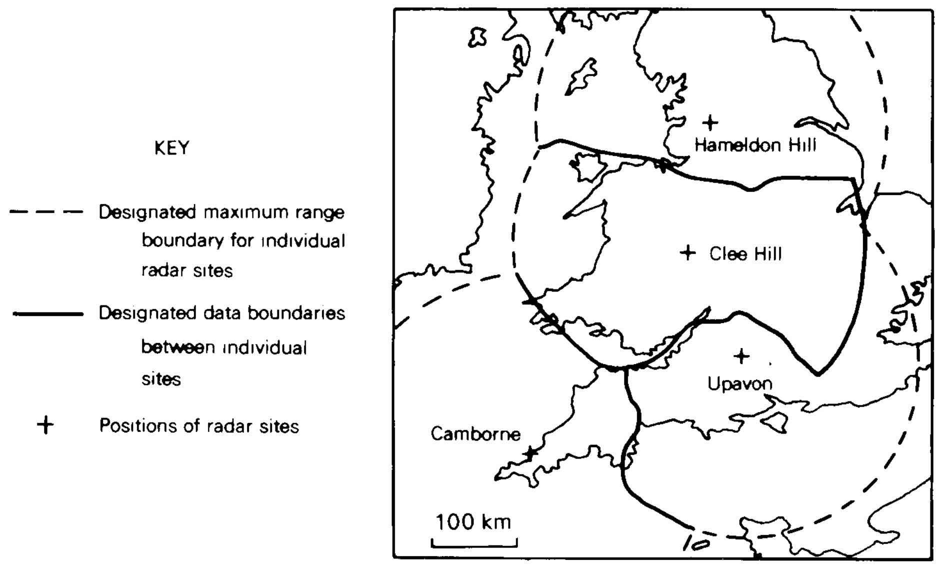


Figure 1. Locations of the four radar sets in the UK Weather Radar Network, together with data boundaries used when all four sets are working. At present, the whole of England and Wales is covered, except for parts of East Anglia and Kent.

3.1.1 *Quality control.* Quality control procedures are applied to eliminate some of the defects of the radar data. They are as follows:

(i) *Occultation.* The radar beam is partly blocked by permanent obstructions such as hills or masts, resulting in spokes of reduced power reception centred on the radar. These spokes are always blanked out.

(ii) *Permanent echo.* Certain locations give abnormally strong return signals and these are always blanked out. (This operation is in addition to the clutter cancellation previously applied by the electronics attached to the radar at each site.)

(iii) *Anomalous propagation (ANAPROP).* Under certain atmospheric conditions the radar beam may be refracted more than usual and may strike the ground, giving high return signals. These often occur over preferred areas. A method of detecting ANAPROP, relying on the difference in signal between those preferred areas and adjacent unaffected areas, is under development. For the time being, those areas subject to severe ANAPROP are being blanked out.

3.1.2 *Compositing of the hourly data.* The data from the individual sites are composited to form a data set of radar-derived totals for the region covered by all the radars. The boundaries between the coverage of each radar are chosen according to the radar sets that were operating during each hour. Fig. 1 shows the boundaries when all four radars are operating. At present all England and Wales is covered, except for parts of East Anglia and Kent. These areas should be covered by the forthcoming London radar.

The composite data are stored in the 'Hourly Radar Archive Dataset' in blocks corresponding to 100 km × 100 km National Grid squares; each block contains values for four hundred 5 km × 5 km squares. The data sets are constructed using a package of computer routines designed for direct-access storage and retrieval of meteorological data (Shearman 1980), which means that data from any area covered by radar may be retrieved quickly and output in map form.

3.2 *Production of daily rainfall totals*

Once the hourly radar archive has been constructed, the next step is to sum the hourly totals into rainfall-day totals (0900–0900 GMT) to correspond with the nominal time of reading the rain-gauges. The problem with the summation is that, with the present experimental radar network, few days have 24 hours of data from all four sites, but typically one or more sites will have a few missing hours. If these hours are wet a daily total cannot be calculated. However, if, using information from the existing data set of hourly rainfall from gauges which is held in the Hydrometeorological Branch, it is likely that these hours were dry, a daily total is computed (though it is flagged in the data set). The problem should become less severe as more radar sets are added to the network, giving a greater degree of redundancy. For example, the forthcoming London radar will allow for triple redundancy over most of England south of Nottingham. The radar-derived daily totals are stored in a direct-access archive, in a similar way to the hourly totals.

4. Combination of radar and rain-gauge data

4.1 *Method*

The radar rainfall observations are now ready to be combined with the gauge-derived observations in order to compute the most representative distribution of rainfall at the ground, within the region covered by the radars.

It is often observed that over extensive areas the radar consistently overestimates or underestimates surface rainfall; for instance at large ranges from a radar the beam can be above the bulk of the precipitating cloud, so the radar registers a relatively small rainfall. The radar rainfalls need to be adjusted by a spatially varying calibration factor to bring them into agreement with the general level of rainfall as measured by gauges, while at the same time allowing them to contribute to the definition of the rainfall distribution between gauges.

The two kinds of observations for a specific day are combined in the following way:

(i) A calibration factor $c = g/r$ is computed for each 5 km × 5 km square that contains at least one gauge, where r is the radar rainfall and g is the gauge-derived areal rainfall over the same square, computed using the methods of Shearman and Salter (1975).

(ii) Interpolation is carried out between these calibration factors to form a continuous calibration field, using a local fitting least-squares technique. The most reliable calibration factors are in the vicinity of gauges.

(iii) The calibration field and the radar rainfall field are multiplied together to form the combined radar and gauge-derived rainfall field, but only where the calibration factor is within reasonable limits. Naturally this method constrains the combined rainfalls to be weighted strongly towards the gauge-derived rainfalls in the neighbourhood of gauges.

(iv) Areas not covered by the calibrated radar data (owing, for instance, to occultation, permanent echo or ANAPROP) are filled with interpolated rain-gauge data in order to complete the combined rainfall field.

Further details are given by Nicholass *et al.* (1981).

4.2 *Removal of bright band*

The 'bright band' is a region of strong echo that is produced when the radar beam intersects the melting layer (Battan 1973) and is caused by the large reflectivity of wet snowflakes. The bright band appears on a map of radar-derived rainfall as an annulus located about the position of the radar: the lower the melting layer, the closer is the bright band to the radar position. The boundaries of the bright band are not sharp because of the depth of the melting layer and the vertical depth of the radar beam.

Calibration using data from gauges with a spacing smaller than the horizontal extent of the annulus can remove the undesirable effect of the bright band. With a sparser gauge network the bright band would have to be identified by other means and removed at least partially before combining the radar and gauge observations.

5. Examples of combining rainfall observations from radar and rain-gauges

5.1 *Daily rainfall*

To illustrate the combination of observations of daily rainfall by radar and gauges results are shown for two days, 11 October 1981 and 2 June 1982. The first day was one of fairly uniform rainfall while the rainfall on the second day was localized and heavier.

5.1.1 *Rainfall on 11 October 1981.* Fig. 2(a) shows the distribution of rainfall during the period 0900 GMT on 11 October to 0900 GMT on 12 October 1981, over North Wales and north-west England using observations from the full gauge network (mean gauge spacing about 6 km). Rainfall amounts were between 10 mm and 15 mm over the Pennines, the Snowdon area and Liverpool, between 5 mm and 10 mm over a large area to the west of the Pennines and over west Wales and between 0 mm and 5 mm over east Wales, the Midlands and south-east of Preston.

The radar-derived distribution, Fig. 2(b), shows clearly the tendency for radar to overestimate rainfall close to the radar over the Pennines and Liverpool, and to underestimate rainfall at large ranges, over the north Midlands and west Wales. The radar rainfall distribution nevertheless shows many of the features of the detailed distribution given by the full gauge network. Fig. 2(b) also shows an area of occultation extending north-west from the radar at Hameldon Hill and areas of permanent echo.

The rainfall distribution as observed by a reduced gauge network consisting of one-tenth of the original number of gauges (mean spacing 19 km) is shown in Fig. 2(c). As would be expected in these widespread rainfall conditions the main features of the rainfall field are preserved but smoothed and some significant detail is lost. For instance, the curved elongated area of 10–15 mm rainfall over the Pennines reduces from three separated areas to one smaller area, the 0–5 mm rainfall area extending south-east from Blackpool degenerates into small isolated areas, an area of 10–15 mm rain between Liverpool and Manchester disappears altogether and the 0–5 mm rainfall area no longer extends to the coast of North Wales.

All these rainfall features are restored to a great extent by the addition of the radar data to these sparse gauge network observations (Fig. 2(d)). Even though the rainfall distribution in areas of occultation, permanent echo and rainfall less than 1 mm are derived from gauges only, the retrieval of detail of rain over and to the west of the Pennines is particularly encouraging. This example demonstrates both the purpose of calibration by gauges, to adjust the general level of the calibrated radar rainfalls to surface values, and the contribution of radar observations in inserting detail between gauge observations. These results suggest that in widespread daily rain the radar observations can compensate greatly for a loss of observations from a large proportion of the total number of rain-gauges. Obviously the contribution that radar data can make to observations from a full gauge network is less. (The combined rainfall distribution from radar and the full gauge network is not shown for this day as it is almost identical to that from the gauges above.)

5.1.2 *Rainfall on 2 June 1982.* Fig. 3(a) shows the distribution of rainfall for the period 0900 GMT on 2 June to 0900 GMT on 3 June 1982, over north-eastern England. The gauges indicated isolated areas of rain between 10 mm and 20 mm north-east of Hexham, near Newcastle, west of York and south of Leeds, and a larger area with a peak rainfall between 30 mm and 40 mm to the west of Darlington, all superimposed on an extensive area of rainfall of less than 10 mm.

The radar observations, Fig. 3(b), also registered those areas of rainfall but indicated larger extents and greater amounts, especially for the rain to the north-west of Hexham. Radar observations through the day showed that these localized heavy rainfalls occurred during the period 1600 to 2100 GMT on 2 June, moving northwards.

Fig. 3(c) shows the radar observations combined with the observations from the full gauge network, the positions of the gauges in the vicinity of the heavy rainfall also being shown. It is to be noted that the radar improves the detail and reveals the extended coverage of the heavier rainfall into areas which are lacking surface observations. Radar observations indicate that there are central areas of rainfall greater than 60 mm (peak value 61.8 mm) south-west of York and greater than 50 mm (peak value 56.6 mm) west of Darlington, larger than those observed by gauges alone, but also that gauges have been effective in reducing the large radar rainfalls observed near Hexham and Newcastle to more plausible values. All peak values occur within 10 km of adjacent calibrating gauges, so errors in the combined rainfalls caused by error in the interpolation of calibration factors are thought to be small.

This example demonstrates that radar can add information to observations from even the full daily gauge network in localized heavy rainfall conditions, in contrast with its performance in uniform rainfall. It is possible that some very localized rainfalls would not be observed at all with the one-tenth gauge network but could be detected by radar with its uniform 5 km (or 2 km) resolution.

5.2 *Sub-daily rainfall*

Short-period rainfalls are very important, for instance in the design of storm-water drainage systems which is determined by the frequency and coverage of high-intensity rainfall lasting for up to a few hours. Storms responsible for such rainfall often have dimensions of only a few kilometres or tens of kilometres and could easily slip through the sparse network of recording gauges from which sub-daily rainfall is available. For instance, the detailed time-variation of the localized heavy rain on 2 June 1982 simply was not observed by the available recording gauges which are shown plotted in Fig. 3(a).

Hourly radar and gauge rainfalls cannot be effectively combined directly by the method described in Section 4.1 because of the large distances between the gauges leading to large errors in the calibration factors. Instead a procedure is used in which the daily rainfall in each 5 km × 5 km square from the combined rainfall field (radar plus full-gauge network) is multiplied by the ratio of the radar-measured hourly and daily totals for the same square. This procedure ensures that the sum of the hourly totals over the day is equal to the daily total. Also the combined hourly field is not constrained to be in close agreement with the observations from nearby independent recording gauges.

An example of the use of this procedure to prepare maps of hourly rainfall from radar observations is given for an outbreak of heavy rain over southern England on 20 September 1980. Figs 4(a) to (d) are maps of the rainfall for each hour between 1800 and 2200 GMT on which the positions of short-period recording rain-gauges are also shown. The heavy rain began around Worthing between 1800 and 1900 GMT (Fig. 4(a)), extended north-westwards during the next 3 hours (Figs 4(b) to (d)) but a maximum in the isohyetal pattern persisted over Worthing throughout the 4-hour period. The wettest clock hour was between 2000 and 2100 GMT when more than 40 mm fell over a 50 km^2 area a few kilometres to the north-east of Worthing.

A recording rain-gauge was situated at Worthing very close to the area of interest. In Fig. 5 the hourly rain-gauge totals from this gauge are compared with those incorporating radar data in the 5 km × 5 km square covering Worthing. Clearly, precise agreement would not be expected because the gauge measures point rainfall and radar measures areal rainfall. However, Fig. 5 shows that:

(a) the maximum values are recorded between 2000 and 2100 GMT by both methods and are similar in magnitude, and

(b) during the 4-hour period 1800–2200 GMT the totals are in good agreement; the gauge measured 68 mm while the other method gave 77 mm.

This measure of agreement shows that the radar-derived totals in Figs 4(a) to (d) are realistic and enables confidence to be placed in using the radar data for obtaining storm profiles over areas where the recording gauge network is very sparse. For those areas close to recording gauges a method is being devised for incorporating the recording gauge data into the final answer: the closer the area of interest to a gauge, the more influence the gauge reading will have.

Provided the information from the radar can be calibrated accurately, it can also be used to enhance existing knowledge of the characteristics of storms and to revise rainfall depth-area-frequency statistics for short durations. A discussion of how radar data have been used to determine the detailed characteristics of a storm over Manchester in 1981 and how the derived areal rainfall totals compare with advice given in the *Flood Studies Report* (NERC 1975) is given by Bader *et al.* (1983).

6. Operational use of radar and sparse gauge network observations

The foregoing examples show that radar data should be able to fulfil a useful role when supplementing gauge observations, particularly from sparse networks. One interesting operational application is in *The Meteorological Office Rainfall and Evaporation Calculation System MORECS* (Thompson *et al.* 1981) in which estimates of average evaporation and soil moisture in 40 km × 40 km squares are made weekly and sent to a variety of subscribers for near-real-time use. In order to produce the estimates each week using the latest information, the weekly rainfall totals (comprised of seven daily totals added together) are needed promptly, and certainly before observers send in their data to the

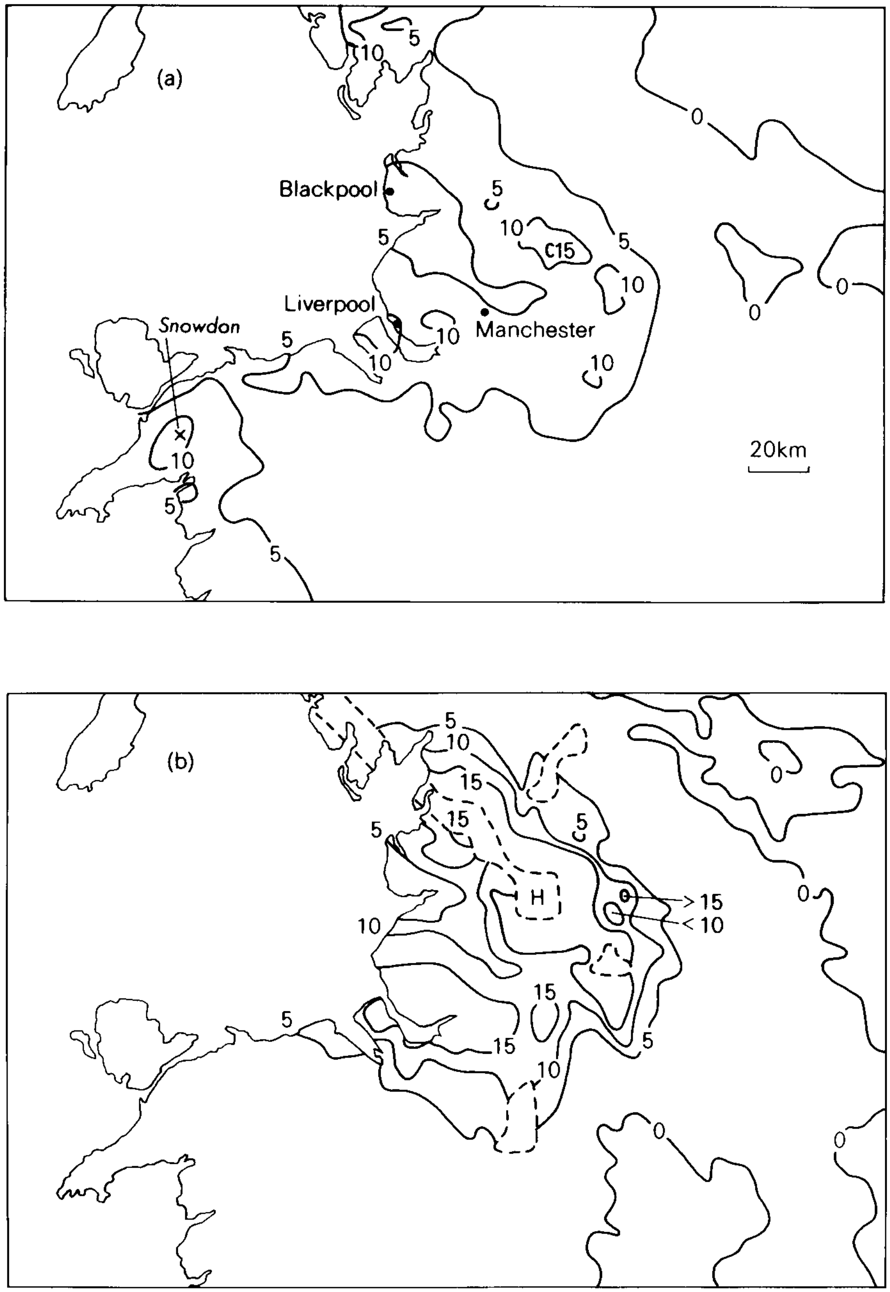
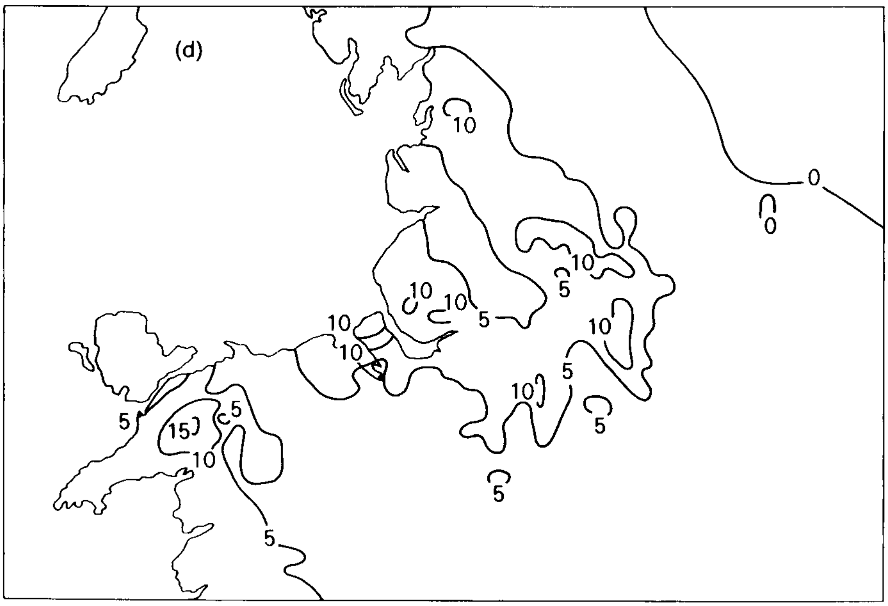


Figure 2. Rainfall distribution (mm) for the period 0900 GMT on 11 October to 0900 GMT on 12 October 1981 using (a) the full daily gauge network, (b) radar only (dashed lines denote regions subject to occultation or permanent echo, H denotes position of radar at Hameldon Hill), (c) one-tenth of the gauges of the permanent network, chosen randomly, and (d) the combination of (b) and (c). Isohyets are at 5 mm intervals.


(c)
5
5
10
5
5
0
10
5
10


(d)
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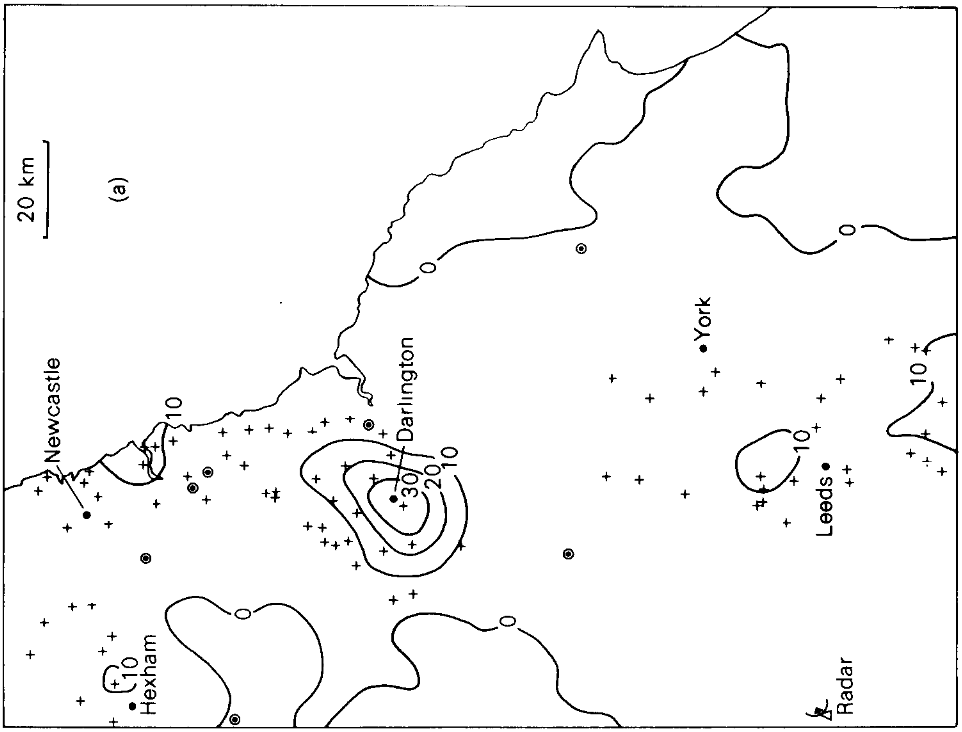
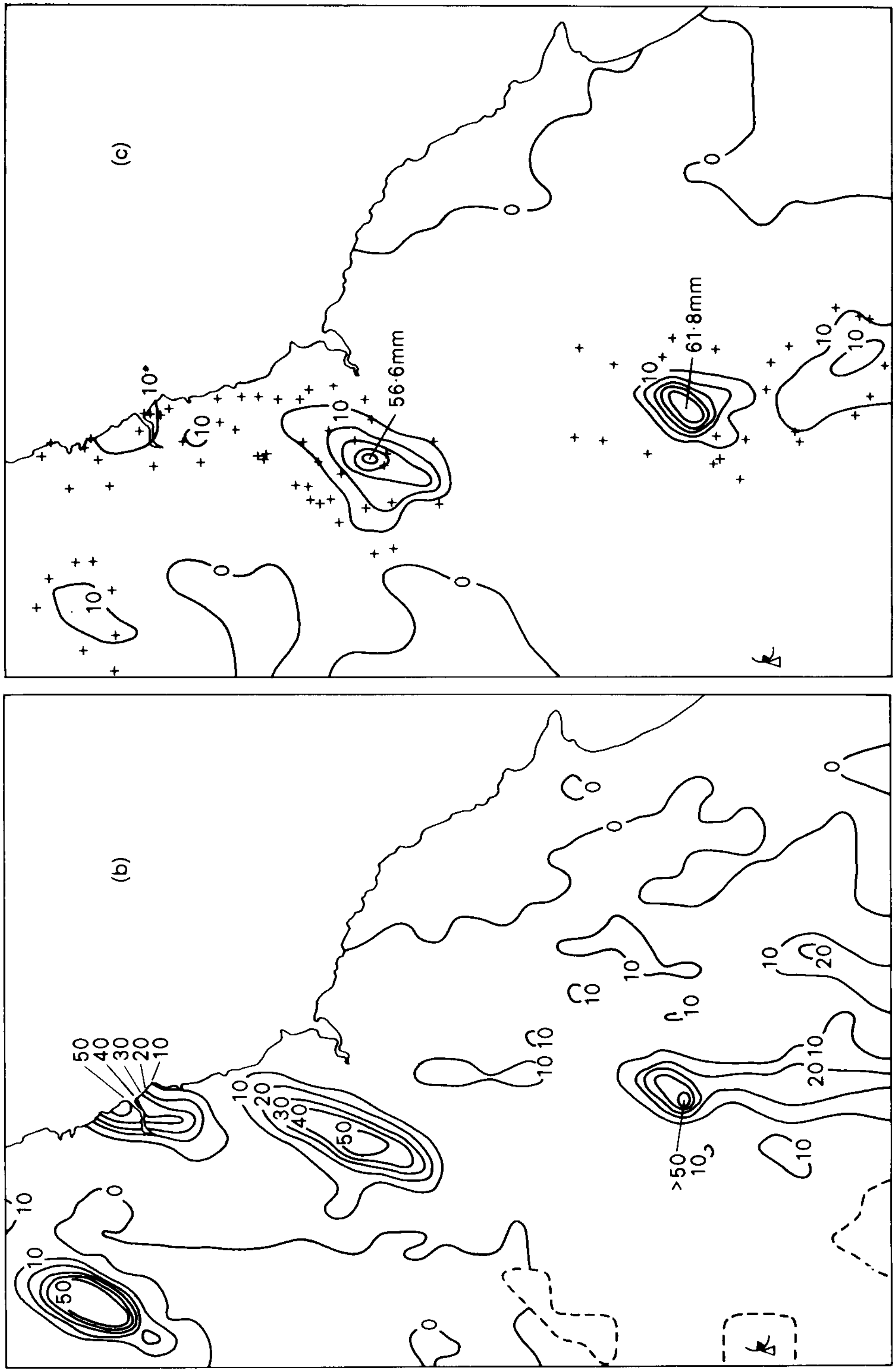


Figure 3. Rainfall distribution (mm) for the period 0900 GMT on 2 June to 0900 GMT on 3 June 1982 using (a) the full daily gauge network, (b) radar only, and (c) the combination of (a) and (b). The positions of daily gauges in the vicinity of the heavy rain are shown as crosses and the short-period rain recorders are shown as ringed dots. Isohyets are at 10 mm intervals.


(c)
56·6mm
61·8mm
(b)
>50

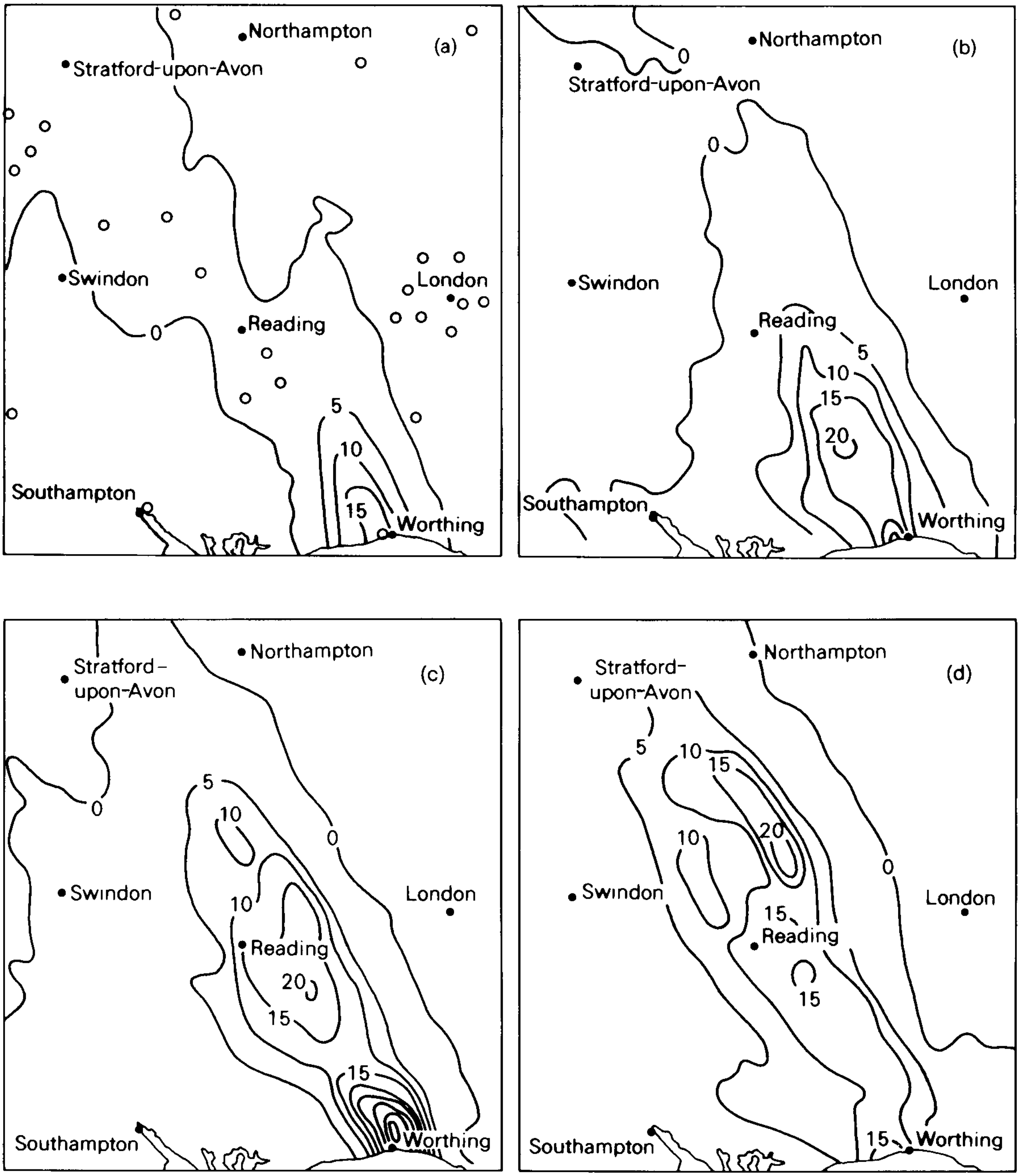


Figure 4. Rainfall distributions on 20 September 1980 for the periods (a) 1800–1900 GMT, (b) 1900–2000 GMT, (c) 2000–2100 GMT, and (d) 2100–2200 GMT. The positions of short-period rain recorders are shown by circles. Isohyets are at 5 mm intervals.

collecting centres. The only daily rain-gauge data available in near-real time are those from about 150 weather observing stations in the Meteorological Office's synoptic network (mean gauge spacing 40 km, but very irregularly distributed). The previous results (Section 5.1) indicate that in both uniform and localized heavy rainfall radar data could usefully supplement daily rainfalls from the sparse synoptic network to improve the MORECS rainfalls, aided by the capability of radar data to be processed automatically and transmitted rapidly. The same up-to-date daily rainfall information can be used for forecasting the risk of imminent crop and animal diseases and for the automatic dissemination of daily rainfall amounts on teletext systems (e.g. Prestel or CEEFAX). It should be emphasized, however, that the combination using such a sparse network of gauge data will have to incorporate a scheme to identify and correct for the bright band.

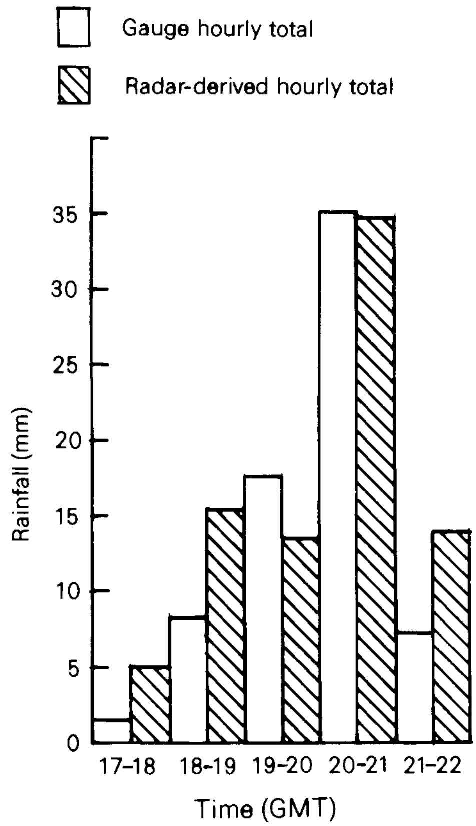


Figure 5. Comparison of hourly rainfall totals at Worthing on 20 September 1980, as measured by the recording rain-gauge and by radar.

7. Conclusion

Recent research and development work in the Hydrometeorological Branch of the Meteorological Office on supplementing rainfall data from rain-gauges by those from radar has been discussed. A description has been given of how the radar data are processed, archived and finally combined with the gauge-derived data to form representative rainfall distributions on daily and sub-daily time scales over large areas of the United Kingdom.

Observations from rain-gauges provide accurate information on rainfall at a point but have limited representativeness for surrounding areas.

Furthermore, many of them are available well after an event, or from sparse networks, and require a large degree of manual processing. The incorporation of radar data will enable catchment areal rainfall totals and statistics to be determined directly, automatically (without the need for much manual processing) over large areas and on all time scales. It is expected that the addition of information from radar will enable the range of hydrometeorological services provided by the Meteorological Office to be enhanced.

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The estimation of point rainfall over the south-west peninsula by gauges and radar

By B. R. May
(Meteorological Office, Bracknell)

Summary
The capability of radar and gauges in determining hourly and daily rainfall at an ungauged point is investigated statistically using data from the Cornish peninsula in mainly frontal rain conditions. The analysis involves both the probability of inferring correctly the occurrence or non-occurrence of rain at the point in any hour or day and the accuracy of the estimate of amount.

Notation

g gauge rainfall
g^* estimated gauge rainfall
r rainfall estimated from radar
R root-mean-square value of $\lg(g^*/g)$
d distance of separation
n sample size
se(R) estimated standard error of R
$P(S)_G$ probability that test and calibration gauges register the same (rain or no rain) for the same hour or day
$P(S)_U$ probability that co-located gauge and radar observations register the same

Subscripts for g:
- c calibration value
- t test site value

Subscripts for R:
- G gauge only
- U uncalibrated radar
- C calibrated radar

1. Introduction

For many years now rainfall has been measured by surface gauges. At present there are about 6500 gauges measuring daily totals and 200 gauges measuring hourly totals in the United Kingdom whose observations are incorporated in the National Rainfall Archive held by the Meteorological Office at Bracknell. These data are used for many diverse purposes, for instance, rainfall climate studies, horticultural applications, design studies for drainage systems, calculations of soil moisture deficits, forecasting research and resource planning.

More recently radar observations of rainfall have become available but these observations have different features from gauge data.

Gauges measure rainfall at a point on the ground and by avoiding overshelter by trees or buildings (and their wake effects) and overexposure in windy sites reasonable standardization of measurements can be achieved. Standard daily gauges collect the rainwater which is measured manually each day but hourly gauges use the float and siphon or tipping-bucket principle combined with a recording device. Considerable organization and manual effort is required in collecting and processing gauge observations.

Measurement of rainfall by radar involves projecting a nearly horizontal beam of centimetre-wavelength radio waves which is scattered by raindrops. The strength of the returned radio waves depends upon the size of the raindrops but the signal is contaminated by noise due to random motions of the drops. To improve the signal-to-noise ratio the returned signals from volumes swept by the radar beam (usually standing on 5 km × 5 km squares) are integrated so that the resulting rainfall rate estimate is for an area and not a point. In practice radar observations are subject to several errors. These are:

(i) Drop-size distribution errors. For simplicity a single conversion from returned signal strength to rainfall rate is used appropriate to the typical drop-size distribution for widespread frontal rain. For the smaller drops of drizzle or the large drops of convective rain the conversion is incorrect.

(ii) Obstruction of the radar beam by hills or buildings which obscure the region beyond and cause spurious bright reflections.

(iii) Enhanced reflections from wet ice particles if the beam intersects the melting layer.

(iv) Anomalous propagation from long distances in abnormal atmospheric conditions.

(v) Incomplete filling of the radar beam or square at the ground surface by rain.

(vi) The correspondence between co-located gauge and radar observations can be affected by rain observed by radar above the surface being swept away by wind and not reaching the gauge beneath, and by low-level growth or evaporation beneath the radar beam.

Thus there are many reasons why co-located gauge and radar observations of rainfall can differ. However, the advantages of radar observations, in that a single radar can observe rain over a circle of about 100 km radius every five minutes with the data being available centrally and promptly for automatic processing and dissemination, are a compelling reason for studying ways of combining gauge and radar observations to exploit their respective features. Browning (1978) and Collier (1980) give more complete descriptions of the characteristics and processing of radar rainfalls.

Since the radar observes areal rainfall it would be appropriate to make comparisons with areal rainfalls estimated from gauges as the agreement would be expected to be better. Gauges capable of measuring hourly rainfalls are usually separated by many kilometres which removes any possibility of estimating areal rainfalls over 5 km × 5 km squares. The alternative adopted here is to assume that the radar observation is an estimate of the point rainfall at all points within the square. In slowly varying spatial variations of rainfall the areal rainfall would be a good approximation to a point close to the centre of the square but the displacement of a gauge from the centre adds a further contribution of error to the comparisons. For daily rainfalls many more gauges are available and it is feasible in many areas to estimate 5 km × 5 km areal rainfalls for comparison with radar. Since one of the objects of this work is to compare, for both hourly and daily rainfalls, different methods of estimating rainfalls, point-gauge rainfalls are used throughout.

The work described here demonstrates, in terms of probability rather than pictorially, the accuracy with which point rainfall can be estimated. There are so few hourly gauges that hourly rainfall fields with a 5 km resolution corresponding to those depicted by radar observations cannot be drawn, so 'pictorial' comparisons cannot be made. Rainfalls at fixed points but random times are investigated instead to show how gauge and radar observations compare, for both hourly and daily rainfalls.

The practical problems of drawing maps of point rainfall from gauge or radar observations (or combinations of both) are not dealt with here.

This work was undertaken as the first step in a project to improve the information available to the Meteorological Office's customers concerning the occurrence and amount of rainfall at specified ungauged points. The aim is to give a probability of occurrence of rain, an estimate of the amount and a probability that the amount lies between specified limits, based on nearby gauge or radar observations.

2. Method of analysis

2.1 *Estimation of rainfall amount*

Consider an estimate of the hourly or daily gauge rainfall g^* at a point where the true (observed) rainfall is g. The relative error of the estimate represented by the ratio g^*/g is used here so that, if required, the ratios for different sizes of rainfalls can be combined sensibly. For any reasonable method of estimating g^* the mean value of a sample of g^*/g values would be expected to be close to 1.0 but with individual values in the range 0 to $\gg$1.0 so that their distribution will be skew. To reduce the skewness $\lg(g^*/g)$ is used rather than g^*/g.

The average measure of a sample of $\lg(g^*/g)$ values is represented by their root-mean-square (rms), R. Table I gives the mean ratio g^*/g (or g/g^*, since $\lg(g/g^*) = -\lg(g^*/g)$) as a function of R.

Table I. *Equivalence of R and g^*/g.*

R	g^*/g (or g/g^*)
0.0	1.0
0.1	1.3
0.2	1.6
0.3	2.0
0.4	2.5
0.5	3.2
0.6	4.0
0.7	5.0
0.8	6.3
0.9	7.7
1.0	10.0

Estimated standard errors of R are given in brackets or as error bars in the figures and these have been calculated from the expression $\mathrm{se}(R) = R\,[\{1-(\bar{x}/R)^4\}/2n]^{1/2}$, where $\bar{x}$ and n are the sample mean and size ($x = \lg(g^*/g)$). There is a 68% probability that the true value of R lies between R+se(R), a 96% probability that it lies between R+2se(R) etc., with corresponding limits for g^*/g.

In this work estimates of point rainfall are made in three ways which can best be explained with reference to Fig. 1. Two gauges A and B within co-located radar rainfall squares are separated by a distance d km. One of the gauges is regarded as a source of calibration values or rainfall estimates (subscript c) and the other as the test site (subscript t) where comparisons are to be made. Denoting gauge rainfall by g and radar rainfall by r we can estimate g_t^* by:

(i) using $g_t^* = g_c$ so that $\lg(g^*/g) = \lg(g_c/g_t)$ – Gauge only

(ii) using $g_t^* = r_t$ so that $\lg(g^*/g) = \lg(r_t/g_t)$ – Uncalibrated radar

(iii) using $g_t^* = r_t.(g_c/r_c)$ so that $\lg(g^*/g) = \lg\{(r_t/g_t).(g_c/r_c)\}$ – Calibrated radar.

Values of g_t, g_c, r_t and r_c are for the same hour or day, i.e. the calibrations and comparisons are simultaneous. Values of r/g and g/r are often referred to as assessment and calibration factors respectively. By taking different pairs of sites the variation of R_G and R_C with d can be established and for a particular pair of sites, by interchanging them as calibration and test sites an indication can be obtained of the scatter of R_G and R_C for a particular distance of separation d.

R_G, R_U and R_C are measures of the accuracy of the three methods of estimating gauge rainfall and can be assumed to be appropriate to estimation at ungauged locations.

It is stressed that the method of simply transferring an observation from one place to another to simulate estimation at a distance would not be used in practice where more elaborate methods involving interpolation procedures would be appropriate. However, it does allow a simple comparison to be made of the relative performance of the three estimation methods.

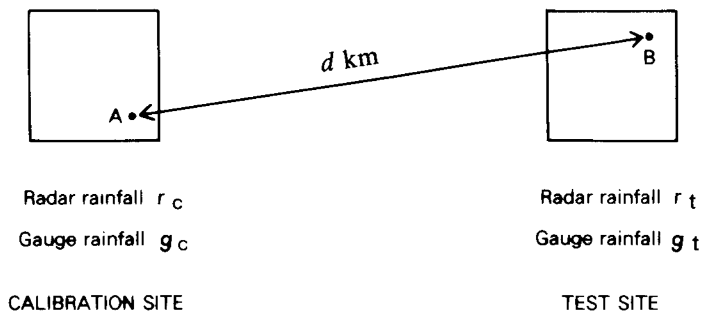

Figure 1. Calibration and test sites for estimating gauge rainfall from radar rainfall, showing calibration (A) and test (B) gauges with their associated 5 km × 5 km radar rainfall squares.

2.2 *Inference of occurrence of rain or no rain*

Also in this paper are given some estimates of the success rate of inferring the occurrence or not of rain at the test site (on a yes/no basis) from observations of the occurrence of rain at the calibration gauge and from the co-located radar observation. Specifically $P(S)_G$ is the probability that the test and calibration gauges register the same (either rain or no rain) for the same hour or day and $P(S)_U$ is the probability that the co-located gauge and radar observation register the same.

3. The data

The data used in this investigation are hourly and daily (09 to 09 GMT) point rainfalls measured by gauges at five sites in the Cornish peninsula, Goonhilly, Culdrose, Drift, St Mawgan and the Scilly Isles, and simultaneous co-located radar rainfalls measured by the Camborne radar. The radar observations are of areally averaged rainfall within 5 km × 5 km squares containing the gauges. Table II gives details of the sites and the intersite distances. Fig. 2 shows the location of the sites and the Camborne radar.

The rainfall observations cover the period 23 September 1979 to 19 March 1980 during which most of the rain was widespread and fairly uniform. For those parts of the analysis involving amounts of rain, only hours with $g_t \geqslant 2.0$ mm or days with $g_t \gg 4.0$ mm were used and these were distributed evenly throughout the period. For the analysis of probability of occurrence of rain, hourly rainfall observations for 1000 hours from 23 September to 4 November 1979 were used, but for daily rainfall data from the whole period of 179 days were used. The Scilly Isles gauge was not used in the hourly rainfall analysis.

Table II(a). *Site details.*

Site	Distance of gauge from centre of radar square (km)	Distance from Camborne radar (km)
Culdrose	0.8	15
Drift	1.8	22
Goonhilly	1.1	22
St Mawgan	1.7	34
Scilly Isles	1.2	77

Table II(b). *Inter-site distances.*

Sites		Distance between gauges (km)
Culdrose	— Goonhilly	7
Culdrose	— Drift	25
Goonhilly	— Drift	30
Culdrose	— St Mawgan	40
Goonhilly	— St Mawgan	43
Drift	— Scilly Isles	55
Drift	— St Mawgan	57
Culdrose	— Scilly Isles	77
Goonhilly	— Scilly Isles	83
St Mawgan	— Scilly Isles	110

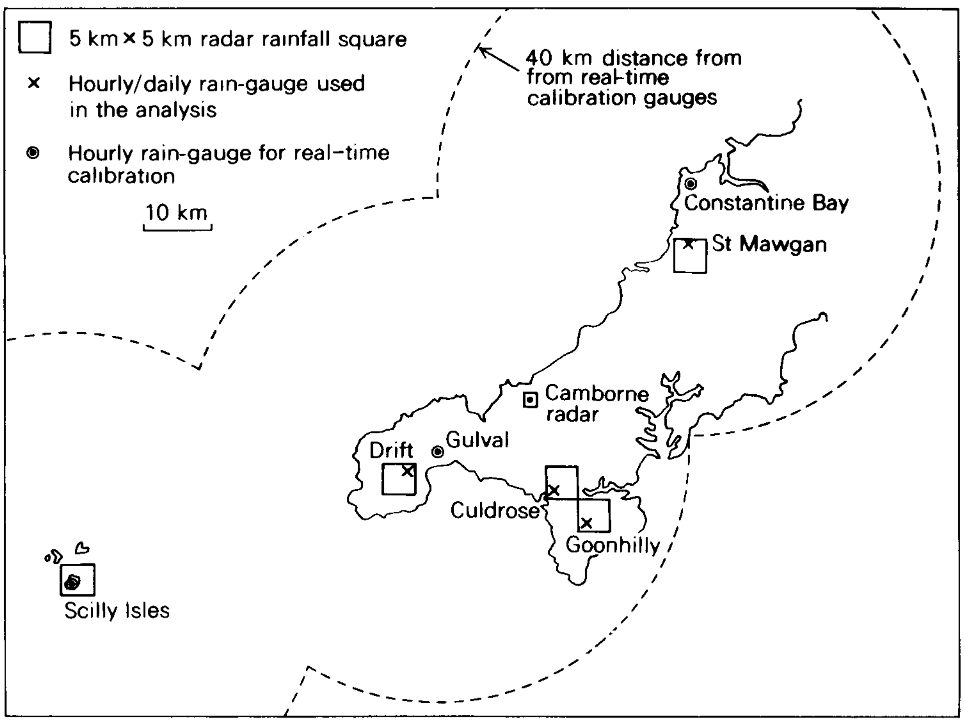

Figure 2. Location of rain-gauges and associated radar rainfall squares.

The gauge rainfalls were observed with tilting-siphon recorders with a resolution of 0.1 mm; the resolution of the radar observations is 0.031 mm. No quality control of the data was carried out apart from eliminating observations for some hours during which the gauges or radar were obviously malfunctioning. In the case of radar these appeared as identical rainfalls for all locations for several successive hours. About 100 hours spread over 7 days in 4300 hours of data were lost in this way. No attempt has been made to determine whether any of the propagation effects described in Section 1 were present — it was assumed that the radar observations were authentic and were of typical quality. They were supplied by the Meteorological Office Radar Research Laboratory, Malvern. The five locations used are the closest ones to Camborne from which hourly observations are available during the specified period.

4. Results and discussion

4.1 *Probabilities of successfully inferring the occurrence or not of rainfall*

Values of $P(S)_G$ for both hourly and daily rainfalls are plotted against d in Figs 3(a) and (b). Trend lines have been drawn and extended to an assumed value of near 1.0 at $d = 0$ km. Values of $P(S)_U$ for each site are given in Table III.

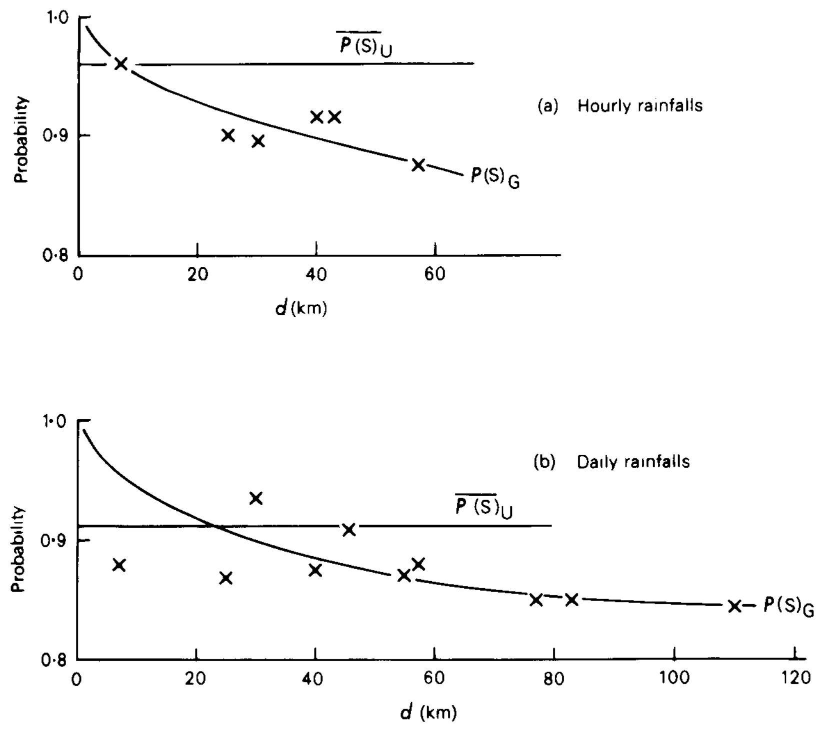

Figure 3. $P(S)_G$ as a function of distance d where $P(S)_G$ is the probability of correctly inferring rainfall occurrence at a point from observations at a nearby gauge. Also shown is the mean probability $\overline{P(S)}_U$ of co-located radar and gauge observations registering the same occurrence.

Table III. *Values of* $P(\mathrm{S})_{\mathrm{U}}$ *for individual sites*

Site	Hourly rainfalls	Daily rainfalls
Culdrose	0.97	0.94
Goonhilly	0.96	0.93
Drift	0.94	0.92
St Mawgan	0.96	0.92
Scilly Isles	—	0.85
Mean	0.96	0.91

From Figs 3(a) and (b) it can be seen that the probability $P(\mathrm{S})_{\mathrm{G}}$ of inferring correctly the occurrence or not of rainfall at a point from observations by a nearby gauge is generally high, $\geqslant 0.87$ within a distance of 60 km for both hourly and daily rainfalls, and falls only slightly for daily rainfalls to 0.85 at 110 km. The probability $P(\mathrm{S})_{\mathrm{U}}$ of co-located radar and gauge observations registering the same (from Table III) is also high for both hourly and daily values. The individual site values are in good agreement for hourly rainfalls. For daily rainfalls the probability decreases steadily with distance from the radar. In Figs 3(a) and (b) the mean values of $P(\mathrm{S})_{\mathrm{U}}$ have been superimposed upon the trend lines of $P(\mathrm{S})_{\mathrm{G}}$ with d. For hourly rainfalls the distance from the calibration site at which $\overline{P(\mathrm{S})}_{\mathrm{U}} \approx P(\mathrm{S})_{\mathrm{G}} = 0.96$ is well determined at 7 km; for daily rainfalls the distance is less well determined because of scatter but $P(\mathrm{S})_{\mathrm{U}} \approx P(\mathrm{S})_{\mathrm{G}} = 0.91$ at about 25 km. If greater probabilities of correct inference at ungauged points than these are required then they can only be obtained from nearby gauges at distances less than 7 km and 25 km for hourly and daily rainfalls, implying networks of gauges at regular spacings of about 10 (i.e. $\approx 7 \times \sqrt{2}$) and 35 km respectively. However, the improvement in probability to be obtained by using gauges over using radar is small even with these networks of gauges. The high values of $P(\mathrm{S})_{\mathrm{U}}$ indicate that radar well defines areas of rain and no rain for both hourly and daily rainfalls.

It is stressed that these results are appropriate to widespread rain conditions. The small advantage of using closely spaced gauges will be further decreased in localized heavy rainfall situations where the continuous spatial coverage of radar becomes increasingly beneficial.

4.2 *Errors of estimates of point rainfall*

4.2.1 *Variation of* R_{G}, R_{U} *and* R_{C} *with rainfall amount.* A relative error in the estimate of a small rainfall is likely to be less important than the same error in a larger rainfall. For instance, an error of $R =$ 0.3 (equivalent to a factor of 2.0 or 0.5 in g^*/g) in a rainfall of $g = 2$ mm h^{-1} would be less important than for $g = 20$ mm h^{-1} if that rainfall was being estimated in near real time as part of an operational flood control scheme. The general variation of R_{G}, R_{U} and R_{C} with g_t is therefore of interest. There are insufficient data for the variation of errors of R_{G} and R_{C} with g_t for a fixed d to be studied so that general mean errors only are given for distances up to 60 km from a calibration site for hourly rainfalls and up to 100 km for daily rainfalls. For R_{U} the values are means for all sites combined, i.e. for distances up to 80 km from the radar. The errors are calculated for bands of g_t values beginning at 2.0 to 2.9 mm for hourly rainfalls and beginning at 4.0 to 5.9 mm for daily rainfalls. R_{G}, R_{C} and R_{U} are plotted in Figs 4(a) and (b) as a function of g_t and the points are joined by lines as a visual aid.

Fig. 4(a) shows that for gauge-only estimates of hourly rainfalls R_{G} increases rapidly from near 0.50 for amounts close to 4.0 mm to 1.0 for amounts greater than or equal to 8.0 mm. For uncalibrated radar observations R_{U} is more uniform over this rainfall range, varying between 0.34 and 0.50; R_{C}, for calibrated radar observations, is also uniform, varying between 0.30 and 0.46. Generally then, radar observations estimate rainfall amounts at ungauged points with a greater uniformity of error (which is also smaller) than gauge estimates which have large errors, particularly for heavy rainfalls. It is to be expected, therefore, that peaks in the spatial distribution of hourly rainfall are liable to be more flattened when estimated by nearby gauges than when observed by radar.

Fig. 4(b) shows that for daily rainfalls the errors of all three estimation methods tend to decrease slowly with increasing rainfall amount at least up to 30 mm, and that for rainfalls greater than this amount calibrated radar observations are the most accurate.

Generally the R values for daily rainfalls are relatively smaller than for hourly rainfalls. It is suggested that this result is consistent with daily rainfall having a smoother spatial distribution than hourly rainfall, at least when the rainfall is widespread.

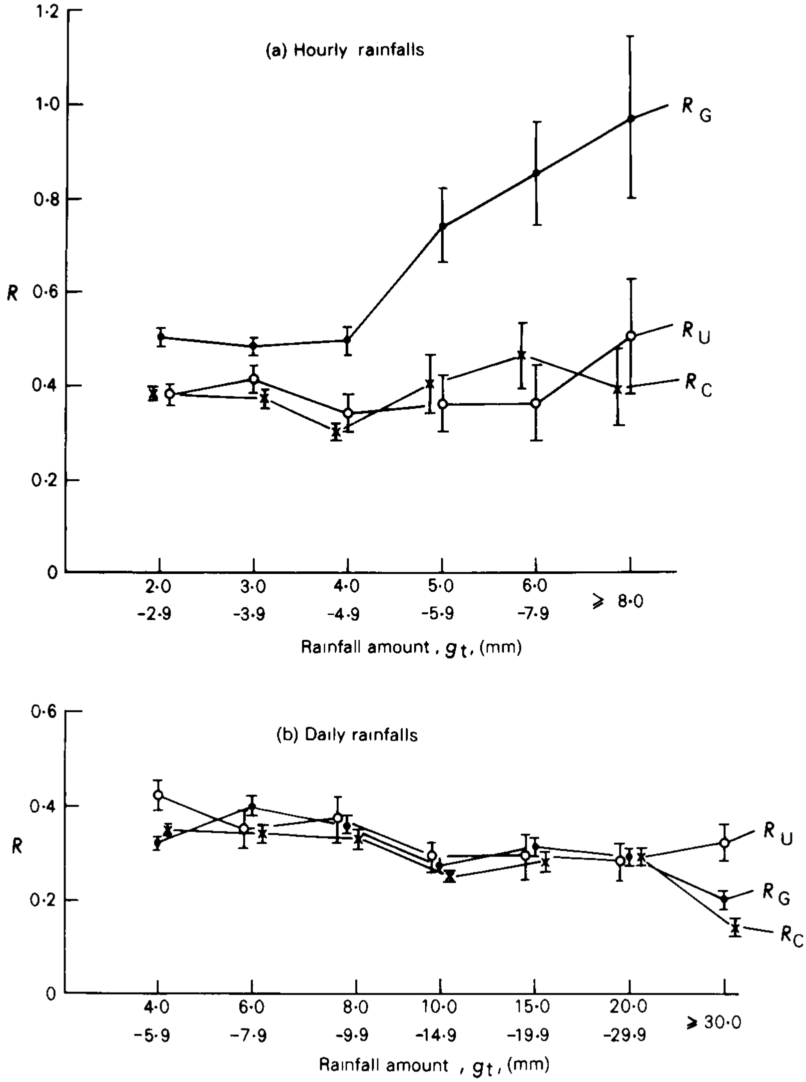

Figure 4. Variation of rms values R_G, R_U and R_C with rainfall amount; standard errors are shown.

4.2.2 *Errors of uncalibrated radar observations.* Values of R_U together with their standard errors are given in Table IV for the individual sites in order of distance from Camborne along with the overall mean values for all sites combined.

Ideally it is desirable that uncalibrated radar observations should be of uniform accuracy over the area of radar coverage. The values of R_U in Table IV show that in practice they vary from site to site. The variations do not appear to be related simply to the distance of the site from the Camborne radar or to distance from the gauge to the centre of the radar square (as given in Table II), so these values are assumed to be generally representative of the spatial variability of errors of uncalibrated radar observations. The general mean R_U for daily and hourly rainfalls are almost equal.

Table IV. *Values of R_U with their standard errors for individual sites.*

Site	Hourly rainfalls (for all $g_t \geqslant 3.0$ mm)		Daily rainfalls (for all $g_t \geq 4.0$ mm)	
	n	R_U	n	R_U
Culdrose	32	0.40 (0.04)	43	0.34 (0.04)
Goonhilly	33	0.36 (0.04)	56	0.40 (0.04)
Drift	50	0.46 (0.04)	55	0.40 (0.04)
St Mawgan	26	0.30 (0.04)	45	0.30 (0.03)
Scilly Isles	—	—	43	0.31 (0.03)
Mean	141	0.38 (0.02)	242	0.36 (0.02)

4.2.3 *Variation of R_C and R_G with distance d.* Because of the spatial variability of hourly or daily rainfall amount and type it is to be expected that R_C and R_G vary with d. Fig. 5 shows the values of R_C and R_G plotted as a function of d for hourly rainfalls; Fig. 6 shows the same for daily rainfalls. There are two values for each d because for a pair of sites each site can act as either the calibration or the test site and the difference between the values gives an indication of the uncertainty in the trend lines. These lines have been extended back to near-zero values for $d = 0$ km on the assumption that the ratio g_c/g_t for two gauges tends to unity as d tends to zero and generally in this case the gauges will be within the same radar square so that $r_t = r_c$ and hence $(r_t/g_t).(g_c/r_c)$ also tends to unity in the same way.

From Figs 5 and 6 we see that R_C and R_G increase with d in a systematic fashion from near zero to values which exceed the mean values of R_U from Table IV. From these results the following conclusions can be made.

To achieve a modest accuracy in estimated hourly or daily rainfalls at an ungauged point of $R = 0.40$ ($\triangleq g^*/g = 2.5$) uncalibrated radar rainfalls can be used directly. A greater accuracy of $R = 0.30$ ($\triangleq g^*/g = 2.0$) requires the use of calibration gauges at a distance of less than 12 km for hourly rainfalls (50 km for daily rainfalls) irrespective of whether the estimate is made with or without the use of radar observations. For an even greater accuracy of $R = 0.20$ ($\triangleq g^*/g = 1.6$) these distances decrease rapidly to 4 km and 7 km for hourly and daily rainfalls respectively. It appears therefore that the use of dense networks of gauges is inevitable if rainfall estimates of high accuracy are required.

It is of interest to determine approximately the distances from a calibration gauge within which

(a) the errors of gauge-only estimates are less than those of uncalibrated radar observations (i.e. $R_G < R_U$) which can reveal the spatial equivalence of gauge and radar observations,

(b) the errors of calibrated radar observations are less than those of uncalibrated radar observations ($R_C < R_U$) which define an area of benefit of calibration, and

(c) the errors of calibrated radar observations are less than for gauge-only estimates ($R_C < R_G$) which indicates the capability of calibrated radar observations to improve on gauge-only estimates.

The results are shown most clearly by plotting the ratio of the corresponding individual values of R_G, R_C and R_U against *d;* in the case of (a) and (b) above we are effectively comparing the error at each site resulting from the use of calibrated radar or gauge-only estimates with the error which would be observed from using uncalibrated radar estimates. The variations of R_G/R_U, R_C/R_U and R_G/R_C with *d* for hourly rainfalls are shown in Fig. 7; corresponding results for daily rainfalls are shown in Fig. 8.

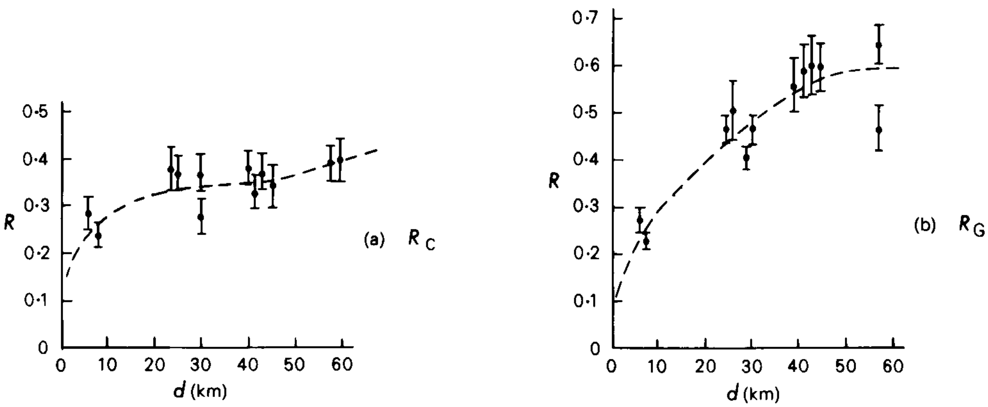

Figure 5. Variation of R_C and R_G with *d* for hourly rainfalls.

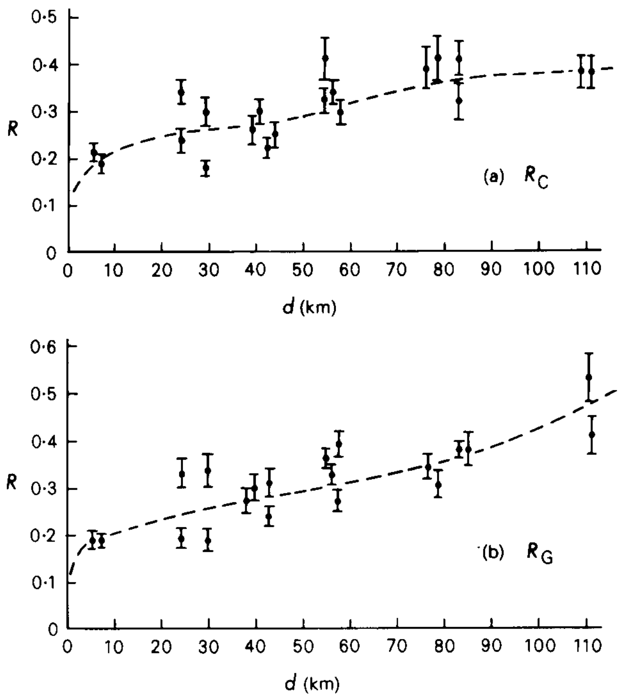

Figure 6. Variation of R_C and R_G with *d* for daily rainfalls.

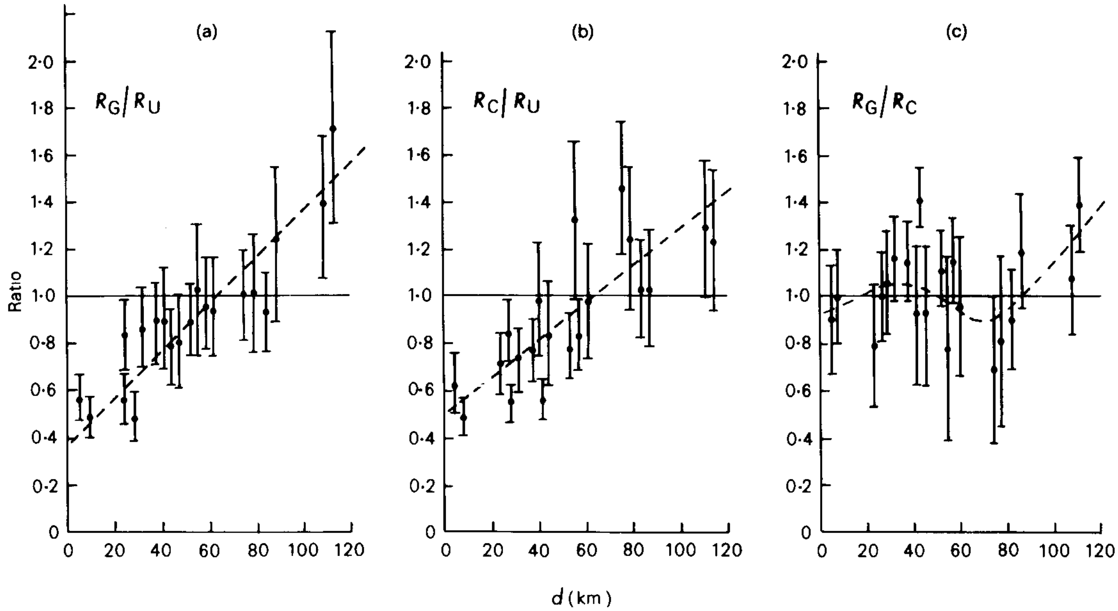

Figure 7. Variation of ratios of R_G, R_U and R_C with d for hourly rainfalls.

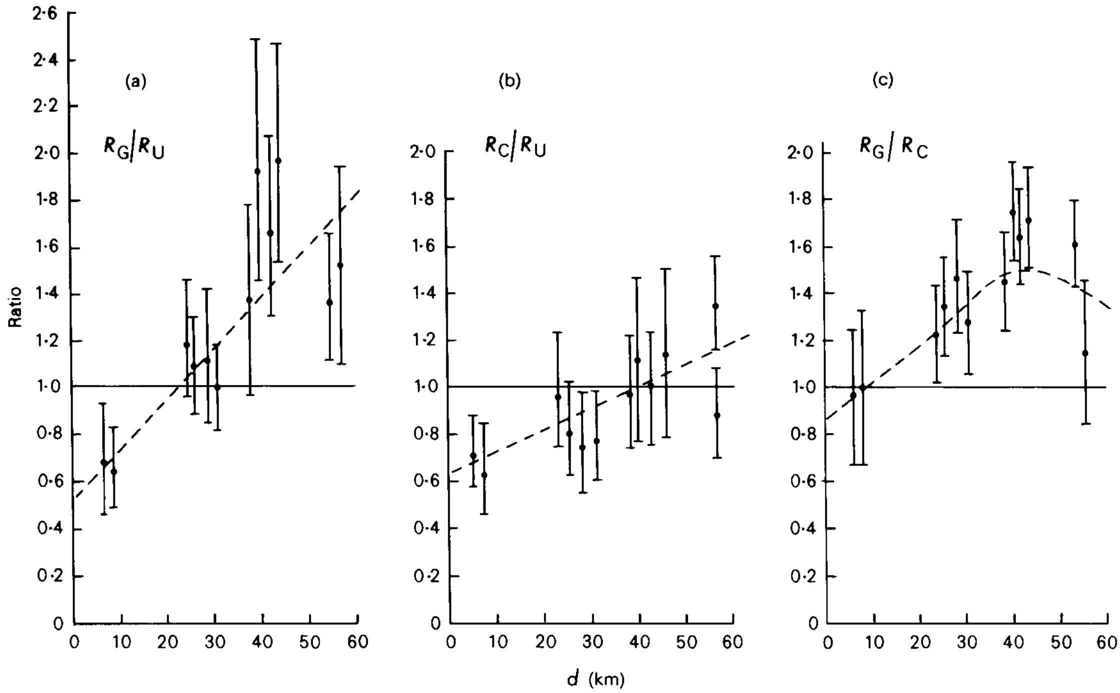

Figure 8. Variation of ratios of R_G, R_U and R_C with d for daily rainfalls.

For both hourly and daily rainfalls, in spite of the large standard errors, there are clear trends for R_G/R_U and R_C/R_U to increase with distance d, from values of about 0.5 to 0.7 for $d=7$ km to over 1.0. Trend lines, fitted by eye, give the distances within which R_G/R_U and $R_C/R_U<1.0$ in Table V.

For hourly rainfalls R_G/R_C appears to be slightly less than 1.0 for $d<7$ km but at greater distances is clearly greater than 1.0. In comparison, for daily rainfalls there is no obvious trend of variation of R_G/R_C with d, certainly for $d<100$ km. The distances at which $R_G/R_C = 1.0$ are also given in Table V.

Table V. *Critical distances for* R_G, R_C *and* R_U.

	Approximate distances (km) from a calibration site within which		
	$R_G<R_U$	$R_C<R_U$	$R_G<R_C$
Hourly rainfalls	25	40	7
Daily rainfalls	60	65	>100?

For hourly rainfalls, calibrated radar observations are more accurate than uncalibrated ones within 40 km from a calibration site, so that for all locations to benefit from the calibration of radar observations regularly spaced calibration sites should be no more than 55 ($\approx 40\times\sqrt{2}$) km apart. The corresponding gauge spacing for daily rainfalls is 90 km. Gauge-only estimates are more accurate than uncalibrated ones within 25 km and 60 km from a calibration site, which indicates that for estimates of rainfall at all locations from gauges only to be at least as accurate as those from uncalibrated radar, the spacing of gauges should be no more than 35 km and 85 km for hourly and daily rainfalls respectively. Similarly reasoning for hourly rainfalls indicates that if gauges are more than about 10 km apart then at all locations calibrated radar observations are more accurate than gauge-only estimates; alternatively, for gauge spacings of less than 10 km the addition of radar observations does not improve the accuracy of estimates obtainable from gauges only but for spacings greater than 10 km it does. For daily rainfalls the corresponding spacing is uncertain but could be as large as 140 km.

The Camborne radar rainfall observations are reputed to be less accurate than those from other modern radars such as the radar installed at Hameldon Hill in the Pennines. More accurate radar observations would presumably result in a decrease in the distance at which $R_C = R_G$. Lee (private communication) has demonstrated that for Hameldon Hill radar observations of daily rainfall totals in widespread uniform rain the gauge spacing for $R_C = R_G$ is closer to 15 km compared with the approximate (and uncertain) spacing of 140 km for Camborne observations. It is not suggested that all this large reduction in gauge spacing is attributable to the superiority of Hameldon Hill radar data: part of the reduction is believed to be caused by the greater complexity of Pennine topography, and hence rainfall distributions, making it easier for the addition of radar observations to improve on rainfall estimates from gauges alone. More accurate radar observations would also result in a decrease in the distance at which $R_G = R_U$ by an uncertain amount but the effect on the distance at which $R_C = R_U$ is likely to be small because both R_C and R_U would be reduced.

It must be stressed that the analysis here is simplified in the interests of clarity. Normally a gauge-only estimate of rainfall at an ungauged site would not be made from a single distant gauge but from a surrounding group of gauges. The same principle applies to calibrated radar estimates – the calibration factor g/r would be estimated from several surrounding gauges not simply one gauge — so it is argued that the essential feature of Figs 7(c) and 8(c) would not be materially changed by a more sophisticated analysis

An alternative method of combining gauge and radar observations involving the analysis of the time variation of 15-minute calibration factors from a few widely spaced gauges to identify types of rain and their areas of applicability has been investigated using Hameldon Hill radar observations (Collier *et al.* 1983). It appears to be able to reduce R to about 0.23 over large areas in both frontal and convective rain.

5. Real-time calibration of radar rainfalls

It has been proposed to use three interrogable gauges at Constantine Bay, Gulval and Scilly Isles (see Fig. 2) for operational use in near-real-time calibration of hourly rainfalls by the Camborne radar. The benefit of these calibration stations in increasing the accuracy of rainfalls observed by radar extends to about 40 km from each site so that together they influence most of the area of the Cornish peninsula. The use of these gauges also increases the probability that at least one of them can provide a calibration factor.

6. Conclusions

From the results described, the following conclusions can be made for hourly and daily rainfalls in mainly widespread rainfall conditions and within a distance of about 80 km from the Camborne radar. They are based on a probability analysis rather than pictorial analysis of radar and ground-gauge observations using the simplest method of estimating rainfalls and calibration factors at a distance. The conclusions would not necessarily be the same if interpolation methods for estimating rainfalls and calibration factors were to be used, as they would be in practice.

(a) Radar observations can define areas of rain with considerable certainty. Comparable success of inferring rain from gauges only would require gauges spaced less than 10 km apart.

(b) Gauge estimates of hourly rainfall at nearby ungauged points have errors which increase rapidly with rainfall amounts greater than 4 mm; for daily rainfall the errors decrease with amounts up to 30 mm. In contrast, hourly and daily rainfall amounts are observed by radar (uncalibrated or calibrated by gauges) with an error which is less dependent on rainfall amount.

(c) For high-accuracy estimates of rainfall at ungauged points, dense networks of gauges are needed irrespective of whether radar observations are used or not.

(d) For hourly rainfalls observed by radar, calibration is effective up to a distance of 40 km (65 km for daily rainfalls) from the calibrating gauge.

(e) Camborne radar observations can add useful information to gauge-only estimates of hourly rainfalls at ungauged points for gauge spacings of greater than 10 km. For daily rainfalls the corresponding gauge spacing is uncertain but appears to be about 140 km.

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Notes and news

Papers requested for AAAS meeting

The 65th Annual Meeting of the American Association for the Advancement of Science (Pacific Division) will be held from 10 to 15 June 1984 at San Francisco State University, San Francisco.

The American Meteorological Society and Section W (Atmospheric and Hydrospheric Sciences) of the Pacific Division of the AAAS will, for the seventh year in sequence, co-sponsor paper sessions and other programs. It is expected that the following will be among the topics to be investigated: air–ocean interaction (including El Niño); coastal meteorology, climatology and oceanography; energy; environmental pollution; and urban climatology and meteorology.

Abstracts of papers should be typed on $8\frac{1}{2} \times 11$ inch white bond paper. Title and text of abstract should be camera ready without paragraphs and should fit inside a 5-inch square box, with a 1-inch margin to the left of the box. Special symbols and signs that must be hand lettered should be rendered in reproducible black ink. Author's name, affiliation and address should appear at the bottom of the page. Abstracts will be published in a booklet for distribution to registrants. Each presentation will be allotted 20 minutes, including discussion.

Abstracts should be sent by 31 March 1984 to the Program Chairman: Dr John Lier, Department of Geography, California State University, Hayward, CA 94542 (telephone: 415-881-3193). The Program Chairman should be informed by the abstract deadline of any need for 35 mm, lantern slide, opaque, or overhead projectors, or for special equipment.

Further details will appear in a later issue of the *Meteorological Magazine* and can also be obtained from Dr Alan E. Leviton, Executive Director, AAAS (Pacific Division), California Academy of Sciences, Golden Gate Park, San Francisco, CA 94118 (telephone: 415-752-1554). Non-members of the AAAS are encouraged to attend.

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NOTICES

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