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A TEST OF SOME OBJECTIVE ANALYSIS PROCEDURES FOR MERGING RADAR AND RAIN-GAGE DATA

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1. INTRODUCTION

The Hydrologic Rainfall Analysis Project (HRAP) being conducted by the National Weather Service (NWS) Hydrologic Research Laboratory is directed toward developing objective analysis techniques for preprocessing, quality controlling, and operationally merging rainfall data from multi-radars, rain gages, and, when feasible, satellites into data bases that may be accessed by any user having access to the computer files (Greene, Hudlow, and Farnsworth, 1979). Summary rainfall products from the HRAP data bases eventually should be available to all users having access to the AFOS (Automation of Field Operations and Services) national distribution circuit. The results from this research will provide immediate improvements in the accuracy and timeliness of the flood forecasts prepared by the NWS River Forecast Centers (RFC's), and should improve the inputs to and the evaluation of quantitative precipitation forecasts. Flash flood warnings issued by the Weather Service Offices also will be enhanced by the use of objectively analyzed rainfall data from digital radars--data which can be acquired in near real time.

A part of HRAP is to determine how best to combine radar and rain gage data operationally and to merge radar data from multiple radar sites. The selection of appropriate analysis techniques for these purposes may depend on the density of rain gages, whether the analysis is being performed in real-time with a minicomputer at the radar site or with a large remote computer, and the space and time scales to be resolved.

One basic category of analysis to be applied to the multivariate merging problem is so called "objective analysis." Several objective analysis techniques to derive areal rainfall distributions from radar and rain gage data, which have produced useful results in post facto analyses, have been developed by previous investigators. Additional tests and evaluation of the most promising of these techniques are being made prior to operational implementation. In the current investigation, two candidate techniques [the Brandes, 1975, and the Crawford, 1978] are being compared and tested to determine their relative accuracies for various gage densities and space and time scales. Although there have been several tests of each of these analysis techniques [Brandes, 1975; Wilson, 1975; Brady, 1976; Hildebrand and Wildhagen, 1977; Crawford, 1978; Hildebrand et al., 1979; and Eddy, 1979] there has yet to be comprehensive comparisons between the two using the same input and "ground-truth" data bases. One way to make comparisons between these procedures is to make parallel analyses from a set of radar data and a corresponding set of rain gage data having a density such that it may be used as "ground truth." Such an evaluation typically is hampered by the limited availability of clean, high-quality data sets comprised of edited radar and dense rain gage observations. It is further complicated by the large data management effort required to handle the large number of data sets needed to give the experiment statistically significant results. Finally, the restricted size of most dense rain gage networks limits the maximum spatial scale that can be evaluated, although larger scales may still be of interest for some hydrologic forecasting applications.

Comparisons of various analysis procedures was the topic of the "Workshop: Application of Objective Analysis Procedures to Radar Hydrology" conducted by the NWS Office of Hydrology in July 1978. The conclusions by the participants of this Workshop were that the various analysis techniques should be tested on a common data set to evaluate how they behave with various gage densities including sparse ones typical of the operational environment, to establish the computing resources required, and to see how accurately they represent the rain field for various space and time scales. One way proposed for this evaluation was to do a simulation using some comprehensive, high-quality set of radar data as "truth," and by adding noise components, to simulate data from both radar and rain gage observing systems.

This paper describes such a simulation approach to evaluate various objective analyses techniques and gives one example application.

2. EXPERIMENTAL DESIGN

In a manner as suggested at the 1978 Workshop, this experiment starts with a known grid rainfall analysis. Differences in rainfall amount, or "noise" values, are introduced on this field to simulate separate "radar" and "rain gage" data sets. The steps involved, visualized in Figure 1, are:

(a) Select an original, grided rainfall analysis (O) that is known.

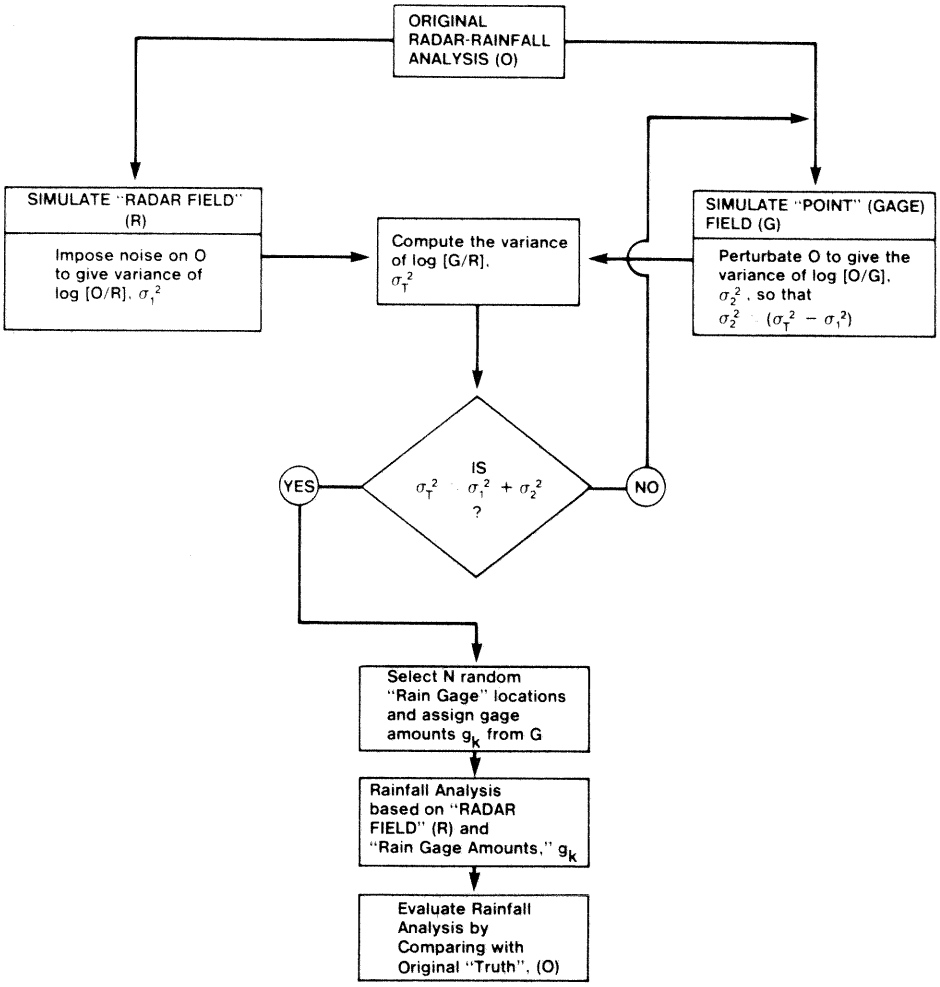

Figure 1. Flow diagram of steps in simulation experiment

(b) Simulate the "radar field" (R) by imposing a noise component on O to give a variance σ_1^2 of the logarithmic ratio of the original rainfall analysis and the simulated radar field, i.e., log [O/R]. The noise generator or function, which is described later in this section, contains parameters for adjusting σ_1^2 to a pre-selected value.

(c) Simulate the "point" or gage field (G) by perturbating the original rainfall analysis (O) to obtain the variance σ_2^2 of the ratio of log [O/G]. The method used to perturbate or modulate O to obtain G has a parameter to control the amount of disturbance put on O. This method is also discussed later in this section.

(d) Compute the variance σ_T^2 of the logarithmic ratio of the point field to the simulated radar field, i.e., log [G/R].

(e) Test to see if the variance σ_T^2 is approximately equal to the sum of the variances σ_1^2 and σ_2^2. This is an iterative process in which steps (c) and (d) are repeated until satisfactory variances are obtained.

(f) When step (e) is completed, N random "rain gage" locations are selected that fall within the analysis grid by use of a random number generator which selects a pair of Cartesian coordinates representing the gage position. For each location a "gage reading" or amount, g_k, is assigned by selecting the value of the nearest grid point in G. Note that beginning with this step the process may be repeated for various numbers of N to simulate different gage spacing and densities.

(g) Derive an areal rainfall analysis based on the "radar field" (R) and the set of "rain gage observations" (g_k) by use of the analysis technique being evaluated.

(h) Evaluate the areal rainfall analysis for various gage densities and space and time scales by comparing with the original radar "truth" field (O).

2.1 Simulated Radar Field

The task at hand is to simulate an error or "noise" field which represents the difference between the "true" rainfall analysis (O) and the radar estimated rainfall field (R). Let this difference be represented by the function

$$D(i,j) = m(i,j) + s(i,j)\varepsilon(i,j), \qquad (1)$$

where $m(i,j)$ = the expected value or the mean which in this application signifies the bias at a point (i,j) in the noise field;

$s(i,j)$ = the standard deviation measured at point (i,j) in the noise field; and

$\varepsilon(i,j)$ = a sample from a zero mean, unit variance, correlated random field.

Equation (1) is quite general in that it can be used to generate a noise field which is interpreted as additive, multiplicative, or logarithmic noise, depending on the value and units of m(i,j) and s(i,j).

Generating the noise field in this manner we can produce a correlated field which is non-homogeneous in the variance and mean. Although radar errors are correlated from one grid box to another, physical reasoning indicates that radar errors are not homogeneous. By approximating the noise field in this way we have the flexibility to include non-homogeneous terms displaying a prescribed correlation.

The problem is to generate the unit variance $\varepsilon(i,j)$ with an appropriate technique that depends heavily on the structure of the covariance of the noise field, i.e., the covariance matrix. Two methods may be used for generating this field:

(a) In the first method, thousands of random variables are generated, i.e., one for each radar bin. This requires the formidable task of decomposing the large covariance matrix (see Valencia and Schaake, 1972 and Noble, 1969).

(b) In the second, which is used in this study, the problem is changed from generating thousands of correlated random variables to generating one random field in two dimensions which is sampled at thousands of points.

For a random field, the correlation may be described by a correlation function. In this case, the correlation of the unit variance will be assumed to be the isotropic single exponential so that covariance between any two points (x_1,y_1) and (x_2,y_2) in the field is given by

$$E[\varepsilon(x_1,y_1)\varepsilon(x_2,y_2)] = \exp\{-\alpha[(x_1-x_2)^2 + (y_1-y_2)^2]^{1/2}\}, \qquad (2)$$

where α is the correlation parameter and E is the expectation operator. Note that α has units of inverse length and α^{-1} is the distance at which correlation falls to a value of ($1/e \simeq 0.37$).

The random field is generated as the sum of equal amplitude cosine waves with random orientation and phase (assuring isotropy). The frequency of each cosine term is a random variable generated such that the chosen correlation function, Equation 2, is preserved. In particular, for each point located at (x,y) in a field, (see Mejiá and Rodríguez-Iturbe, 1974):

$$\varepsilon(x,y) = \sqrt{\frac{2}{n}} \sum_{i=1}^{n} \cos[w_i(x\cos\beta_i + y\sin\beta_i) + \theta_i], \qquad (3)$$

where β_i is sampled from a uniform $0\text{-}2\pi$ distribution (orientation),

θ_i is sampled from a uniform $0\text{-}2\pi$ distribution (phase),

n is the number of harmonics,

$\sqrt{\frac{2}{n}}$ is a normalization constant,

and w_i is sampled from the radial spectral distribution function G(w) of the chosen correlation function. In particular, the function G(w) for the single exponential is

$$G(W) = 1 - (1 + w^2/\alpha^2)^{-1/2}$$

which can be inverted to give

$$w_i = \alpha\{[1 - G(w_i)]^{-2} - 1\}^{1/2} \qquad (4)$$

with $G(w_i)$ being a uniformly distributed random variable over the interval 0-1.

The random field $\varepsilon(x,y)$ generated by Equation (3) has zero mean, unit variance, and, as $n \to \infty$, the correlation structure of Equation (2). It is also homogeneous and isotropic (Mejía and Rodriguez-Iturbe, 1974). However, convergence is relatively slow so that a number of terms (say $n = 50$) should be used.

The noise field is formed through the application of the following steps:

(a) Generate n independent values of β_i uniformly distributed from 0 to 2π.

(b) Generate n independent values of θ_i uniformly distributed from 0 to 2π.

(c) Generate n values of $G(w_i)$ uniformly distributed from 0 to 1; use Equation (4) to compute w_i.

(d) Use Equation (3) to find the value of $\varepsilon(x,y)$ at the center of any radar grid box using the known location (x,y) and the n values of w_i, β_i, and θ_i selected in steps (a), (b), and (c).

(e) Multiply $\varepsilon(x,y)$ by the standard deviation $s(x,y)$ and add the mean value error $m(i,j)$ for each radar grid box.

The adopted procedure has a number of advantages for the study at hand:

(a) It is easy to adjust the mean and variance of the error field to generate additive, multiplicative, or logarithmic noise.

(b) The mean and variance need not be homogeneous.

(c) The structure of the error field is controlled with a single value (α) which determines the degree of correlation. This simplifies sensitivity analysis.

(d) The procedure is computationally feasible for a large number of radar grid boxes.

In this experiment the "radar field" (R) is simulated by

$$R(i,j) = O(i,j) \cdot 10^{[\varepsilon(i,j) \cdot s(i,j) + m(i,j)]} \qquad (5)$$

$$\text{and} \quad \begin{array}{l} i = 1,2,\ldots\ldots\ldots p \\ j = 1,2,\ldots\ldots\ldots q \end{array} ,$$

where p and q are the dimensions of the analysis grid; $\varepsilon(i,j)$ is computed by use of Equation (3); $m(i,j)$ is the systematic bias; and $s(i,j)$ is a non-homogeneous standard deviation function for a logarithmic variate formed by taking the logarithm of the ratio of the true value to the true value plus error, defined by

$$s(i,j) = \gamma \left[\frac{|\overline{\nabla O(i,j)}|\, O_{max} + O(i,j)\, |\overline{\nabla O}|_{max}}{2\, |\overline{\nabla O}|_{max}\, O_{max}} \right]^{\delta} \qquad (6)$$

where

$|\overline{\nabla O(i,j)}|$ is the average absolute value of the gradient computed in four directions around the point (i,j);

$|\overline{\nabla O}|_{max}$ is the maximum absolute gradient in the O field;

$O(i,j)$ is the original rainfall analysis at the point (i,j);

O_{max} is the maximum rainfall value in O;

and γ and δ are parameters used to tune the degree of variance to be imposed on O to get R.

2.2 Simulated Point (Gage) Field

The simulation procedure used here is designed to perturbate the original field (O) with high frequency "noise" so that the variability of the difference between the original field and the perturbated field (G) will approximate that expected due to gage and radar spatial sampling differences, i.e. the part of the variability in the gage to radar ratios resulting from the disparity between gage point measurements and radar areal measurements. The procedure should be designed to simulate rain gage values which are consistent with the original field (O). The gage values should have greater variance than the radar values in the original field due to the sampling differences. The theoretically correct approach is to simulate the rain gage values as a "conditional simulation." If the underlying probability structure of the point rainfall field is known (e.g. a Gaussian field with known covariance and mean functions), then the mean and variance at any point can be computed conditional on the known areal average values from the O field. The gage values then can be sampled from a probability distribution with the conditional mean and variance (and any higher moments such as skew). The difficulty with the conditional simulation approach is that the underlying probability structure of the point rainfall field must be known (or estimated).

An easier approach, which still borrows from the idea of conditional simulation, is to assume a conditional mean and variance for each gage location in a simpler fashion. For example, the conditional mean of a gage value in the (i,j) grid square can be assumed equal to the values of $O(i,j)$, and the conditional variance of a gage value in the (i,j) square can be assumed to be a parameter "a^2" times the variance (σ^2) of the O field in the area around grid (i,j) [(e.g. the nine grid values centered on (i,j)]. Using this simplified approach, the gage values would be simulated as

$$G(i,j) = O(i,j) + \omega(i,j) \qquad (7)$$

where $\omega(i,j)$ is a random variable with mean value zero and variance of $a^2\sigma^2$. The parameter "a" should be adjusted so that the total variance between simulated gage and radar fields agrees with the value selected for σ_T^2 (see figure 1).

3. PARTITIONING OF VARIANCE AND EXAMPLE APPLICATION

To illustrate the application of the theory to the experiment, an example is presented. For this example, the GATE (GARP Atlantic Tropical Experiment) daily rainfall analysis for June 28, 1974 (Hudlow and Patterson, 1978) was selected as the original radar-rainfall analysis (O). Before the "radar" and "gage" fields can be simulated from the original field, estimates of σ_T^2, σ_1^2, and σ_2^2 must be obtained.

Table 1 gives estimates of σ_T^2 reported by several investigators for the time scale and data sets as indicated. Although there are insufficient cases in Table 1 to justify fitting an analytical expression relating σ_T^2 to duration, the limited number of cases appear to show that some inverse correspondence between σ_T^2 and duration does exist.

The two 1-hr estimates for σ_T^2 (Table 1) are in reasonably good agreement when one considers that they were derived from data sets collected in two very different parts of the world, although both are from convective rainfall cases. Also, a significant part of the variability entering the second estimate may result from interpolation errors (see comments column of Table 1).

The largest two variances given in Table 1 are probably both unrealistically large. The Smith and Cain (1978) value is the only one appearing in Table 1 that was derived from data collected in an operational environment where less attention can be devoted to the calibration and maintenance of the radar system and where errors in the rain gage reports may go undetected. Also, anomalous propagation conditions occur relatively frequently in the Monett, Mo. area, which could partially explain the higher variance. The first 24-hr σ_T^2 value given in Table 1 (0.25) is probably too high because of the manner in which the radar estimate was selected (see comments column). This is because the location of the two data types relative to each other can be in error by as much as 4 km due to navigational uncertainties. However, the second 24-hr σ_T^2 estimate appearing in Table 1 is probably too low because the second method not only removes the variability from navigational uncertainty but also removes much of the variability resulting from spatial sampling differences.

For purposes of the example application presented here, using as the original rainfall analysis the daily radar field from GATE for June 28 (Julian day 179), a 24-hr σ_T^2 value of 0.08 was selected. The corresponding standard deviation expressed as a gage to radar ratio (factor) is 1.91.

One approach to estimating σ_2^2 is based on theoretical considerations of the characteristics of the structure or correlation functions generated by the areal rainfall process (as measured by radar) versus the one generated by the point rainfall process (as measured by a very dense rain gage network). For the purpose of the experiment described here, the predominant variability contributing to σ_2^2 is considered to arise from differences in sampling characteristics; i.e. from differences between point measurements and areal averages over the respective radar data bin containing the point. Although the mathematics have not been formulated at the time of this writing, by making certain assumptions, it seems logical that σ_2^2 can be estimated from knowledge of the variance and correlation function of the areal process. Gandin (1963) illustrates how an estimate for the root-mean-square error in the data resulting from purely random measurement errors can be estimated by extrapolating the structure function to zero lag. Effectively the differences in the areal and point values can be thought of as random measurement differences resulting from dissimilar sampling characteristics and, therefore, similarities exist between Gandin's work and the application sought here. Investigation along these lines is planned for the near future.

Another approach for obtaining an estimate of σ_2^2 would be based on analysis of very high spatial resolution radar data. Such analyses are planned for the future using the digital radar data collected with the shipboard radar aboard the <u>Gilliss</u> during GATE. The <u>Gilliss</u> radar was equipped with a programmable video integrator and processor that permitted the radial resolution to be varied with range to match the azimuthal resolution (Yeager, 1975). For GATE, a radial resolution of 250 m was retained out to a range of 64 km. Azimuthal integration was 1°, giving an azimuthal resolution at 64 km approximately equal to 1 km and better for closer ranges. From these polar data, it should be possible to derive a rather accurate Cartesian grid network with a basic resolution of 1/2 km x 1/2 km. Then, from the Cartesian data, a curve of root-mean-square difference versus areal difference (between 16 km^2 and smaller size areas down to 1/4 km^2) can be derived. Finally, an estimate for σ_2^2 can be obtained by extrapolating this curve to 16 km^2 areal difference.

Until more objective techniques can be developed for estimating σ_2^2, a value equal to 30% of σ_T^2 was selected for the example daily analysis presented here. Therefore, for a $\sigma_T^2 = 0.08$, $\sigma_2^2 \simeq 0.025$ and $\sigma_1^2 = \sigma_T^2 - \sigma_2^2 = 0.055$. The σ_2^2 of 0.025 is approximately equal to the difference between the 0.08 value for σ_T^2 and the second estimate of σ_T^2 for the 24-hr scale appearing in Table 1.

To specify the noise field, which is generated in terms of the logarithm of the ratios of O/R, for the radar simulation, another parameter in addition to σ_1^2 is needed. The other parameter is the decorrelation distance, which is defined as the lag distance at which the autocorrelation coefficient decreases to e^{-1}. Some insight into the decorrelation distance for convective rainfall gage to radar ratios may be obtained by examining figure 2 which is a plot of the autocorrelation coefficient for gage to radar ratios from three Brandes' (1975) analyses using radar data from the National Severe Storms Laboratory (NSSL), and the gage data from the networks as indicated. Two cases (April 28, 1974 and April 7, 1975), which were derived from dense rain gage data from the ARS (Agriculture Research

Table 1. Estimates of σ_T^2 based on comparisons between observed radar and rain-gage data.

Time Scale (Integration Period)	Data Set	Variance of Log(G/R), σ_T^2	Investigators	Comments
1 hr	North Dakota Convective Events	0.12	Cain and Smith (1976)	300 1-hr events analyzed. Each radar estimate taken as value from data bin with center nearest gage location.
1 hr	GATE Shipboard Radar and Gage Data	0.18	Derived from data presented by Hudlow and Patterson (1979)	Based on comparisons between measurements made with collocated shipboard radar and gage systems for 80 1-hr events. The radar estimates at the ship were interpolated from surrounding data using an objective analysis model.
1.33 hr average period	Summer rainfall in Alberta, Canada	0.15	Humphries and Barge (1979)	196 1-hr events analyzed. Each radar estimate taken as value from data bin with center nearest gage location.
3 hr	Summer rainfall in Monett, Missouri	0.45	Smith and Cain (1978)	913 3-hr events analyzed. Each radar estimate taken as value from data bin with center nearest gage location. Radar data from operational D/RADEX system.
24 hr	GATE Shipboard Radar and Gage Data	0.25	Derived from data presented by Hudlow and Patterson (1979)	153 daily events analyzed using gage data from remote ships (nominally 165 km range). Each radar estimate taken as value from the data bin containing the daily mean ship (gage) position.
24 hr	"	0.06	"	153 daily events analyzed using gage data primarily from remote ships (nominally 165 km range). Each radar estimate taken as the value in closest agreement with the rain gage, from the set of nine data bins consisting of the one containing the daily mean ship position plus the eight surrounding bins.
450 hr	GATE Shipboard Radar and Gage Data	0.04	Derived from data presented by Hudlow and Patterson (1979)	23 events, each nominally 450 hr in duration were analyzed using gage data primarily from remote ships (nominally 165 km range). Each radar estimate was taken as the average of the values from the set of four data bins consisting of the one containing the Phase mean ship position plus the three nearest neighboring bins.

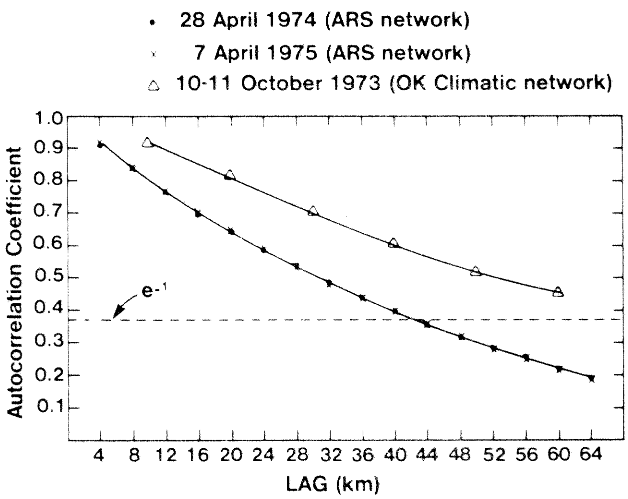

Figure 2. Autocorrelation coefficient vs. lag distance for three Brandes (1975) analyses based on total storm accumulations using radar data from the NSSL Norman WSR-57 and rain gage data as indicated.

Service) network and an analysis performed on a 4 km grid, give virtually the same curve; the lower one shown in figure 2. The other case, the upper curve, also uses NSSL radar data from the classic Enid, Oklahoma storm which occurred October 10-11, 1973, but the rain gage observations were collected over the more sparse Oklahoma Climatic network and the analysis was performed on a 10 km grid mesh. Since the lower curve is derived from a dense gage network it should be an accurate representation of the structure of the field of gage to radar ratios for these two convective storms. Based on an "e folding distance" of approximately 42 km obtained from the lower curve, we chose a decorrelation distance of 40 km (α = .025) for input into Equation (4).

For the sake of expediency, the method used to simulate the sample "gage" field presented in this section has been further simplified from that described in section 2.2. In this simplified approach, $\omega(i,j)$ can assume only two possible values for a given variance:

$$\omega(i,j) = + a\sigma \qquad (8)$$

or

$$\omega(i,j) = - a\sigma \quad , \qquad (9)$$

with the positive value used when $O(i,j)$ is greater than or equal to the local mean value of the nine bins centered on (i,j) and the negative value used when $O(i,j)$ is less than the local mean.

Using the original field and the simulation procedures as described above, the isohyetal analyses shown in figures 3, 4, and 5 were generated. Figure 6 is a multivariate analysis derived from the simulated radar data displayed in figure 4 and randomly selected gage samples from the simulated gage data displayed in figure 5. The isohyets for all four figures were constructed by using only every fourth data point.

As is consistent with the relative magnitudes of the partitioned components of the total variance ($\sigma_T{}^2$) and with the difference in decorrelation radii inherent to the two simulation procedures, the magnitude of the modifications to the original field and the areal extent of the modifications are greater on the simulated radar field (figure 4) than on the simulated gage field (figure 5). Both simulations seem quite realistic when compared back to the original field.

The multivariate analysis presented in figure 6 was derived using the Brandes (1975) objective analysis procedure. Ten rain gage locations were randomly simulated (see figure 6) and "gage" values were sampled at these locations from the simulated gage field shown in figure 5. For this example multivariate analysis, the Brandes' initial weighting factor, EP, was set equal to 800 [see Brandes (1975), p. 1341, for an explanation of the EP parameter].

The analysis shown in figure 6 illustrates that the sparse network of gages (approximately one gage per 3500 km^2) is insufficiently dense to produce a reliable calibration field in the heavy mesoscale rain area. Close examination of figures 3 through 6 shows that the final multivariate analysis is superior to the simulated radar analysis in areas within close proximity to the gages, but in fact inferior in some areas considerably removed from a gage. The latter is especially obvious in the heavy mesoscale rain area where radar estimates that are initially too large compared to the original or gage fields are made even larger by the multivariate analysis. This occurs because the gage to radar ratios surrounding the mesoscale area are greater than one. The multivariate analysis could be improved by tuning the weighting factors and obviously the analysis would improve with an increasing density of rain gages. Such sensitivity studies for various space and time scales are planned for both the Brandes (1975) and Crawford (1978) objective analysis procedures.

4. SUMMARY AND FUTURE PLANS

The objective of this aspect of the Hydrologic Rainfall Analysis Project (HRAP) is to determine how best to combine radar and rain gage data from multiple radar sites for the purpose of operationally providing rainfall estimates to the NWS River Forecast Centers and other users. Two objective analysis techniques, the Brandes (1975) and Crawford (1978), and variations thereof, are being tested and evaluated to determine their accuracy for various time and space scales and densities of gages. These evaluations are being accomplished in two phases:

(a) Phase I involves evaluation by use of the "simulation" approach described in section 2; a sample application was presented in section 3. Comprehensive comparisons between the analysis techniques will be made using the same "simulated radar," "simulated gage," and "ground truth" data bases. The experiment will be run for a large number of original rainfall analyses for several different rainfall accumulation periods (e.g. hourly, six-hourly, and daily) while varying the rain gage density.

(b) In Phase II, all promising objective analysis techniques will be tested and evaluated in a quasi-operational environment by use of near

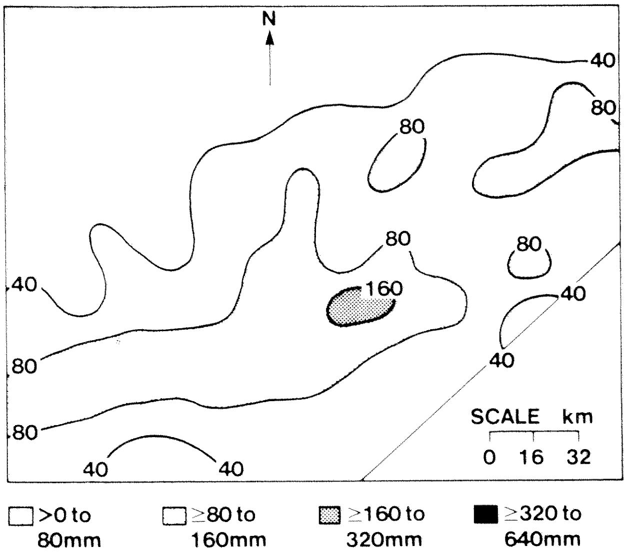

Figure 3. Original radar-rainfall analysis: GATE radar-rainfall analysis for June 28, 1974

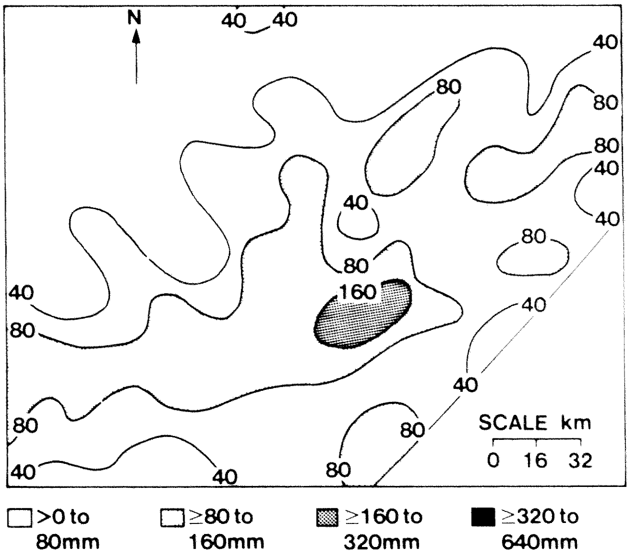

Figure 5. Simulated "point" (gage) field (G) for June 28, 1974

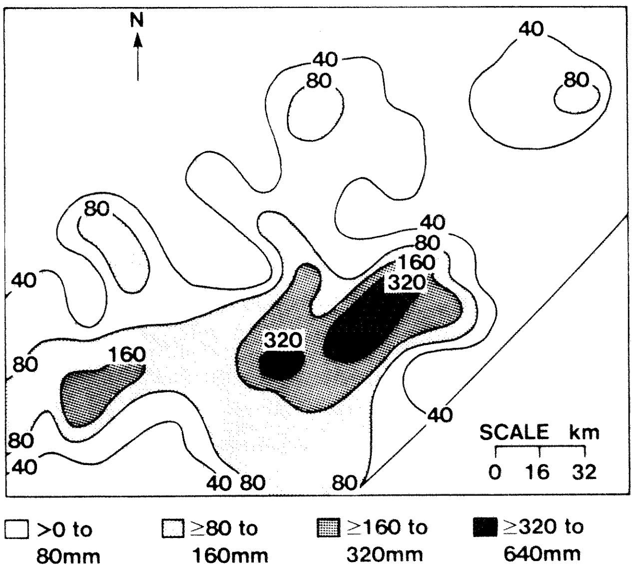

Figure 4. Simulated "radar field" (R) for June 28, 1974

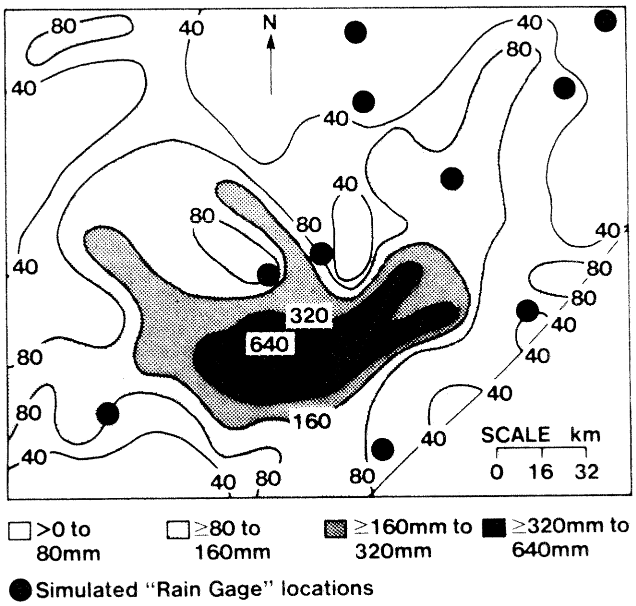

Figure 6. Brandes rainfall analysis based on simulated fields for June 28, 1974.

real-time digital radar and rain gage data. These comparisons will be made from actual rainfall analyses derived by the candidate techniques for a limited area of the Midwestern United States. In this limited area, which is located within the NWS Tulsa River Forecast Center (RFC) area of responsibility, digital radar data currently are collected operationally by three NWS D/RADEX sites: Kansas City, Mo., Monett, Mo., and Oklahoma City, Okla. Radar-rainfall estimates are routinely being derived automatically at these three sites, transmitted to the Tulsa RFC via commercial telephone lines, and received by teletypewriter device. Data in this format are not amenable to additional processing, therefore, software is being developed and equipment purchased to replace the teletypewriter at Tulsa by a system that will automatically record and relay the digital radar-rainfall estimates to a central computer site.

In this two phased approach the modular software that has been developed and tested in Phase I may readily be implemented for use in the operational evaluations of Phase II.

As envisioned in HRAP, the immense volume of data, the timeliness of the data, and the sophisticated processing required by various applications dictates that digital radar processing for rainfall analysis be done in two stages (Greene, Hudlow, and Farnsworth, 1979). Preliminary processing (preprocessing) must be accomplished at the radar site with the radar minicomputer. Such processing will include anomalous propagation (AP) discrimination and real-time quality control to identify any systematic bias in the radar-rainfall estimates. After the on-site preprocessing, the radar-rainfall estimates will be transmitted to a central site, having large-scale data processing capabilities, where radar-rainfall estimates are collected from multiple sites. Prior to merging and compositing, these data also will be further "edited" to remove noise and any biases due to differences in the radar systems that collected the data.

The real-time quality control problem and the possible biases in the data resulting from calibration differences in individual radar systems requires another category of statistical techniques, e.g., one promising category is called "sequential analysis." Sequential analysis, first applied to radar and gage rainfall data by Smith and Cain (1978), has been used to identify systematic biases in the calibration of digital rainfall estimates. Sequential analysis can make use of a limited number of isolated reports from telemetered rain gages and is therefore particularly suited for preprocessing with a minicomputer. A real-time test of this procedure is currently (November 1979) being conducted at the NWS Pittsburgh, Pa., WSR-57 D/RADEX site. We envision that sequential analysis, or some similar method for identifying systematic biases, will become part of the total rainfall analysis system, especially in the preprocessing stage.

The sequential analysis method also can be evaluated during the simulation phase of the experiment (Phase I) to determine the number of gages and samples required to detect various magnitudes of bias within specified time periods. Relatively small biases should be detectable with good statistical confidence if many gage/radar samples are available. Therefore, it may be advantageous to rerun the sequential analysis method at the central site, where data from many more rain gages will be available than typically will be accessible to the radar minicomputer at the preprocessing stage. The application of sequential analysis at the central site to the multiple radar merge problem and how sequential and objective analyses might be coupled will be investigated in the near future.

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