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The operational use of digital radar data for flash flood monitoring

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Abstract. Observation of rainfall on a fine temporal and spatial scale and prediction in the short period (0–2 h) are prime ingredients of a flash-flood monitoring system. This system should include information on the intensity, speed and direction of movement, configuration, and orientation of the storm. The instantaneous remote-sensing capability of radar allows it to detect accurately, with good resolution, storm rainfall patterns and the spatial discontinuities and temporal fluctuations associated with these patterns. Radar coupled with a dedicated digital computer provides the means in real-time to observe automatically and accumulate rainfall amounts. Through extrapolation future rainfall totals may be estimated thereby giving alert to potential flood producing conditions.

L'emploi opérationnel des données digitales de radar pour l'observation des crues soudaines

Résumé. L'observation de la pluie pour une échelle temporelle et spatiale définie, aussi bien que la prévision pour une courte durée (0 à 2 h) sont les éléments primordiaux d'un système de prévision des 'crues brutales'. Ce système devrait inclure des données sur l'intensité, la vitesse et la direction des déplacements, la configuration, ainsi que l'orientation de l'orage. Sa capacité de percevoir à distance instantanément permet au radar de détecter exactement, avec un bon pouvoir de résolution la configuration générale des averses orageuses, ainsi que les irrégularités spatiales et les variations temporelles qui accompagnent ces orages. Le radar, combiné à un ordinateur, procure les moyennes en temps réel, ce qui permet d'observer et de cumuler automatiquement les hauteurs de précipitations. On peut calculer ainsi par extrapolation les totaux futurs des précipitations permettant ainsi de donner l'alerte pour des conditions susceptibles de produire des crues brutales.

INTRODUCTION

The distribution of rainfall as described by conventional raingauge observations is probably the least representative of any of the hydrometorological variables of general economic significance. The remote-sensing capability of radar allows it to detect rainfall patterns instantaneously with considerable accuracy. Until recently, the operational use of quantitative radar data has been limited due to the laborious task of manually processing these data. Automatic radar-signal processing currently is undergoing operational testing and evaluation as part of the Digitized Radar Experiment (D/RADEX) of the National Weather Service. Computer processing of digital radar data in real-time adds a new dimension to flash flood monitoring. D/RADEX comprises a network of four WSR-57 weather radars coupled with mini-computers located in the midwestern United States. In the digitizing process radar video returns are quantized into ten discrete intensity levels (0–9) and recorded in a polar format in range bins, approximately 2 km in length, extending from 18 to 230 km for each 2° azimuthal interval. Figure 1 is an example of a digital radar scan that has been mapped on a 4 km × 4 km rectangular grid.

RADAR PRECIPITATION ESTIMATES

The amount of power returned to a radar from a hydrometer target is related to the intensity of precipitation. Quantitative precipitation estimates from weather radar measurements are obtained through the use of an empirical relationship between rainfall rate, R (mm/h), and the radar reflectivity factor Z (mm^6/m^3). To develop

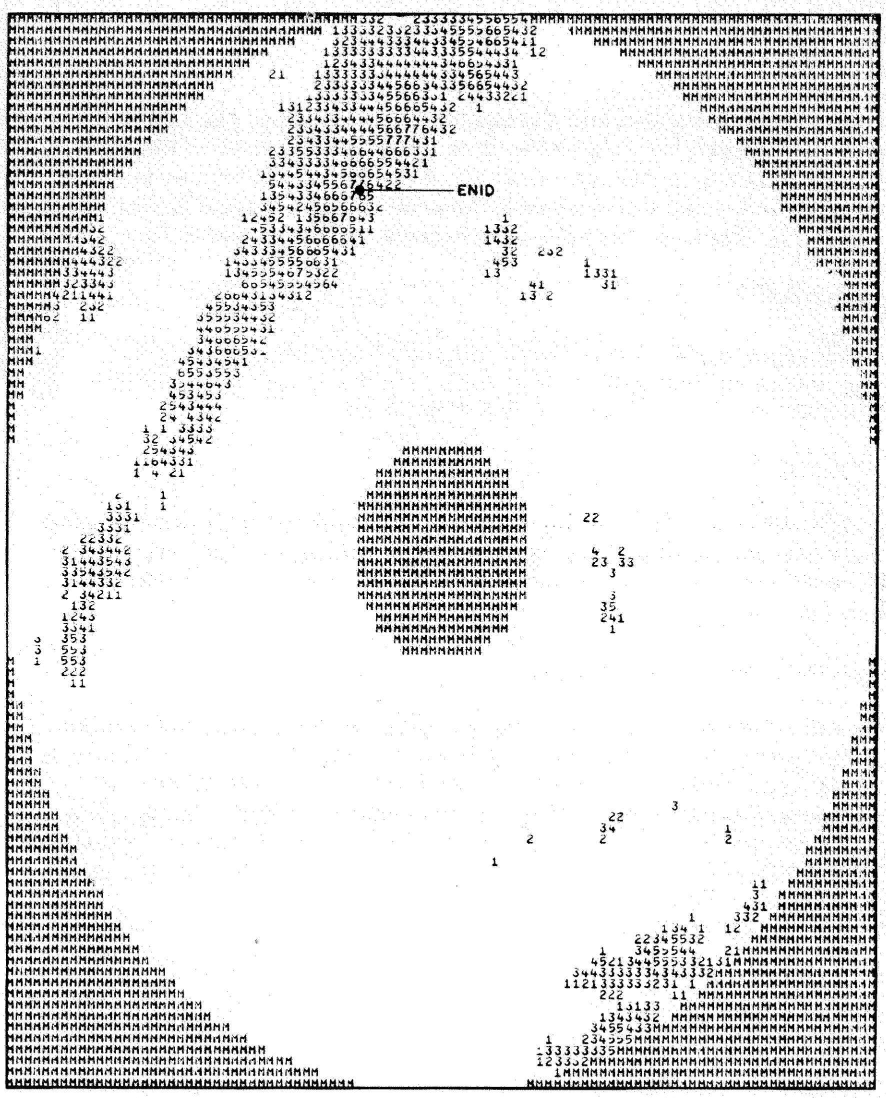

FIGURE 1. Digital radar pattern for 1800 CST, 10 October 1973. In this computer printout the distance between adjacent characters is less than the distance between lines, so that shapes are stretched along the vertical axis.

the Z–R relationship, the radar reflectivity factor and returned power are related through the radar equation

$$\overline{P}_r = \frac{C\,|K|^2}{r^2} Z$$

In this simplified form $\overline{P}_r$ is the average power returned to the radar receiver from a volume of precipitation particles, $|K|^2$ is the dielectric factor, C is a constant determined from the characteristics of the radar, and r is the range to the precipitation target. If Rayleigh scattering is assumed (valid when the drop diameter d is small in comparison to the radar wavelength)

$$Z = \sum_i d_i^6$$

Many investigators have developed empirical Z–R relationships. The main feature of these relationships is the disagreement among them which can be attributed to: errors in radar calibration, the radar beam is not filled uniformly with hydrometers, and variations in in-cloud dropsize distribution due to meteorological factors (Greene, 1971). The most commonly used equation is (Marshall and Palmer, 1948)

$$Z = 200R^{1.6}$$

D/RADEX experience has demonstrated that rainfall rates obtained from the Marshall–Palmer equation must be increased by a factor of 2.25 to be consistent with the observed data. Applying this factor, we obtain

$$Z = 55R^{1.6}$$

In the field application this equation is adjusted continually using observed raingauge data to remove any consistent bias. Brandes (1974) has suggested the construction of objectively analysed correction factor maps based on integration of radar and observed raingauge data.

APPLICATION TO FLASH FLOODS

Observation of rainfall on a fine temporal and spatial scale and accurate prediction in the short period (0–2 h) are prime ingredients of a flash flood monitoring system. In addition to quantitative precipitation measurements, the observational system should include information as to the speed, components of motion, configuration, and orientation of the storm system. Given this information, the system developed for D/RADEX provides the user with an estimate of how much rain falls in a given time interval over a given basin in real-time.

The objectives of the current development effort are:

(1) To derive rainfall from digital radar data each 10–15 min and to obtain accumulated totals of these estimates on a 4 km × 4 km grid for the region within the effective hydrological range of the radar (about 150 km).

(2) To provide guidance to the forecaster by making a short period (2 h or less) prediction of spatially accumulated rainfall.

The prediction of rainfall is formed by extrapolating observed rainfall patterns. The predicted values are obtained through use of mean motion vectors obtained from a pattern recognition analysis of the rainfall patterns observed by radar. The procedure used to obtain objectively the mean pattern motion vectors is to obtain the best pattern match between sequential radar derived precipitation patterns by use of cross-correlation techniques. The technique found to be the most amenable to the radar mini-computer environment is an adaptation of the binary matching procedure used to determine cloud pattern motions from satellite image data (Leese *et al.*, 1970).

Binary matching is a technique for computing a form of the two dimensional cross-correlation between two binary arrays. In the application of this technique to digital radar data a threshold echo intensity level is selected and all pattern values equal to or greater than this threshold value are set equal to 1 and all values less than the threshold level are set equal to 0. Let A be an $m \times m$ array of 0's and 1's and B be an $n \times n$ array ($n > m$) of 0's and 1's representing the binary patterns for times

t_0 and t_1, respectively. The number of hits N_{ij} (the count of the coincidence of 1's between arrays A and B_{ij}) at the spatial lag (ij) is defined to be

$$N_{ij} = (A, B_{ij}), \text{ where } |i|, |j| \leqslant \frac{n-m}{2}$$

That is, N_{ij} is the scalar product of matrices A and B_{ij}, where B_{ij} is the $m \times m$ subarray of matrix B corresponding to the lag (ij), see Fig.2. The convention is to define $B_{00}(i = 0, j = 0)$ to be the $m \times m$ subarray of B with the same origin as A with positive i to the right and positive j upward.

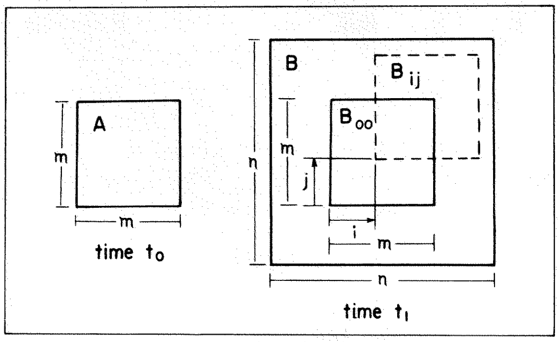

FIGURE 2. Graphical depiction of binary matching arrays. A and B_{00} have the same origin in space.

The percentage of hits H_{ij} at lag (ij) is given by

$$H_{ij} = \frac{N_{ij}}{\left(\frac{P(A) + P(B_{ij})}{2}\right)}$$

where $P(A)$ and $P(B_{ij})$ represent the number of 1 bits in A and B_{ij}, respectively. The best pattern match, as indicated by the location lag (ij), yielding the highest percentage of hits gives the mean vector displacement of the rainfall patterns in the time interval from t_0 to t_i. The extrapolation vector used to forecast the movement of rainfall patterns is formed from a time weighted combination of the last six mean vector displacements. The binary matching cross-correlation technique which is used in the flash flood monitoring system requires a grid with fixed boundaries. Thus, the mean vector displacement of rainfall patterns, hence the extrapolation vector, may be affected by echo patterns moving in or out of this fixed grid during the time interval between two successive patterns (Greene, 1972). These vectors also may be affected by movement of the echoes in or out of the ground clutter region (ranges less than 40 km).

CASE STUDY: ENID, OKLAHOMA STORM, 10–11 OCTOBER 1973

A storm that demonstrated that digital radar data can be an invaluable tool in flash flood forecasting occurred in the central United States on 10–11 October 1973. A stationary front on 10 October stretched from the Nebraska–Missouri border southwestward across Kansas and Oklahoma into the Texas Panhandle. There was strong advection of warm moist unstable air from the Gulf of Mexico northward across central Texas and Oklahoma. The conditions of low level moisture, instability, and lifting over the stationary frontal surface provided the ingredients for strong convective activity and heavy precipitation along and behind the stationary front. Figure 1 shows a part of this system which brought heavy rains to the Central Plains States. Severe flash flooding occurred at Enid, located in north-central Oklahoma, where a record rainfall of 39.83 cm fell in less than 24 h. The National Severe Storms Laboratory (NSSL) at Norman, Oklahoma, collected and archived digital data for this storm. These data were processed by use of the flash flood monitoring software

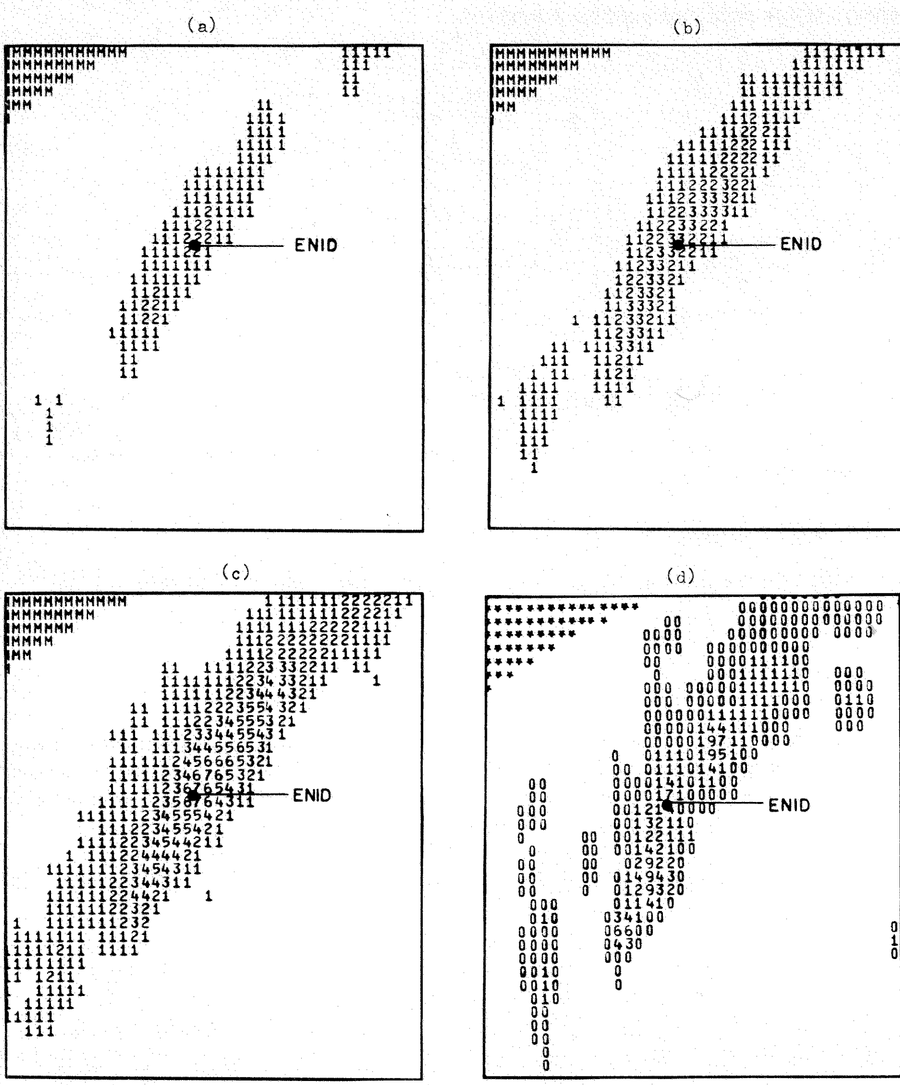

FIGURE 3. Radar derived rainfall totals and predicted totals for the Enid, Oklahoma storm. The multiplication factor to convert integers to rainfall totals (mm) is 25 mm.

(a) Accumulated rainfall 1800 to 1830 CST, 10 October 1973.
(b) Accumulated rainfall 1800 to 1900 CST, 10 October 1973.
(c) Accumulated rainfall 1800 to 2000 CST, 10 October 1973.
(d) Predicted rainfall accumulation 1900 to 2000 CST, 10 October 1973.

developed under the D/RADEX project. Sample outputs derived from data for the period 1800 to 2000 CST 10 October are presented in Fig.3. This storm system displayed two characteristic indicators of flash flood producing storms: echoes of moderate or strong intensity, and persistent or quasi-stationary echo patterns. This is illustrated in Figs. 3(a), (b), and (c) by the large radar inferred rainfall accumulations which occurred in short time intervals. Rainfall totals can be obtained by multiplying the digits by 25 mm. Figure 3(c) has areal rainfall totals of 175 mm which, if displayed to the forecaster in real-time, will assist greatly in the preparation of flash flood warnings.

The large scale motion of this storm system was adequately identified and described by the binary matching procedure; however, individual features that formed and propagated northward along the frontal zone were masked out by the threshold procedure in the binary matching routine. This led to errors in the one-hour extrapolation totals for 1900 to 2000 CST, Fig.3(d). The values can be compared with the radar observed values for the same period by subtracting the values in Fig.3(b) from those in 3(c). The smaller scale features could be identified and tracked if a clustering procedure were employed (Duda and Blackmer, 1972). The problem is that sophisticated tracking procedures have storage and processing time requirements that do not lend to the radar mini-computer.

CONCLUSIONS

In this paper one severe flash flood producing stormhas been analysed objectively through the use of the computer software package under development for flash flood monitoring. Additional storms are being investigated currently which will lead to further software modifications. Nevertheless, the results of this study show that the real-time automated operational use of digital radar data holds real promise for the detection, identification, and prognosis of potentially severe flash flood producing storms.

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