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National Oceanic and Atmospheric Administration
NATIONAL WEATHER SERVICE SOUTHERN REGION
Fort Worth, TX

February 8, 1979 OA/WFS3x1

TO: All WSFOs, Southern Region

FROM: OA/WFS3 - Paul L. Moore

Paul L. Moore

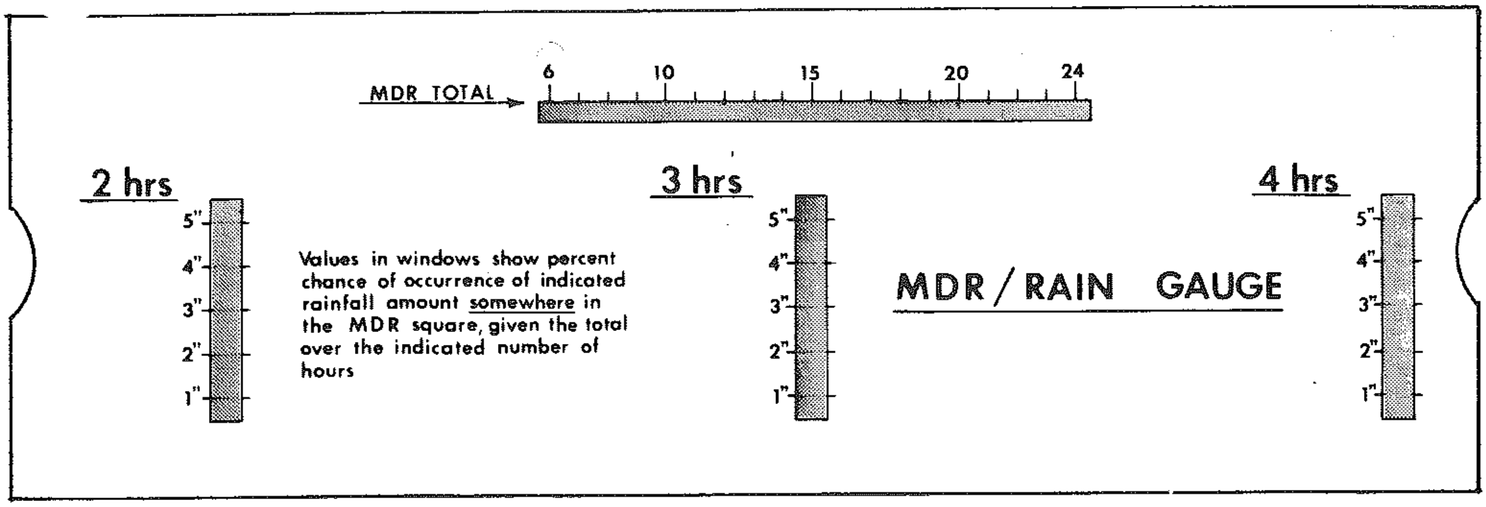
SUBJECT: MDR Technical Memorandum #99 and Sliderule

The MDR code with 40 km resolution has been in operational use for a year. During that year, in the Southern Region alone, nearly a dozen important flash flood events come quickly to mind: Palo Duro Canyon, Center, Albany, Kirbyville, and The Hill Country; all in Texas. Elsewhere; Little Rock, Montgomery, Mobile Bay, New Orleans, Memphis.... Our review of these events convinced us that in many of them - not all - a judicious use of radar information, especially MDR data, could have resulted in timely alerting of the flood potential. In some of these cases - again, not in all - the data were properly utilized.

The enclosed Tech Memo provides a general review of radar information as applied to the estimation of rainfall. It contains a full analysis of several of the above flood events and shows the particular utility of MDR data. Two keys to using MDR data are, first, knowing how to use it, and second, finding the time to use it! In large part the second problem is solved if the first can be mastered. We hope all forecasters will be encouraged to study the Tech Memo carefully and incorporate some of the ideas it contains into their work procedures. Of particular importance is the concept that no "magic number" exists for MDR sums. Changing conditions over the forecast area can lessen or heighten the potential for serious consequences and, thus, change the threshold at which action is warranted. To emphasize the fact that any given MDR total has associated with it a range of rainfall probabilities we've redesigned the familiar nomogram and produced a sliderule version.

As we have frequently indicated over the past year, your input is vital if we are to refine the probabilistic MDR/rainfall conversion. We particularly need to study "null cases" when MDR totals suggest large rainfalls but no verifying evidence can be found. Conversions shown on the sliderule are based on theory and analysis of "general" cases. It is likely that your own experience will lead you to a modification of the values - if so, ink in the changes and let us know how it works.

DO-IT-YOURSELF MDR SLIDERULE...



Values in windows show percent chance of occurrence of indicated rainfall amount somewhere in the MDR square, given the total over the indicated number of hours

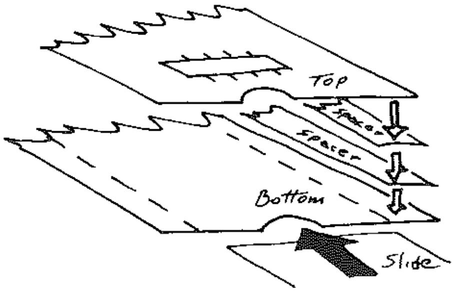
MDR / RAIN GAUGE

(Glue strip here)

Assembly instructions:
1. Cut out (carefully!)
2. Glue together (carefully!!)

Special notes –
Glue two slide spacer strips top & bottom – be sure to align carefully with the dotted lines on backpiece or slide might wobble. Trim if necessary.

Before assembly – cut out shaded areas on top piece – use razor knife.



Bottom

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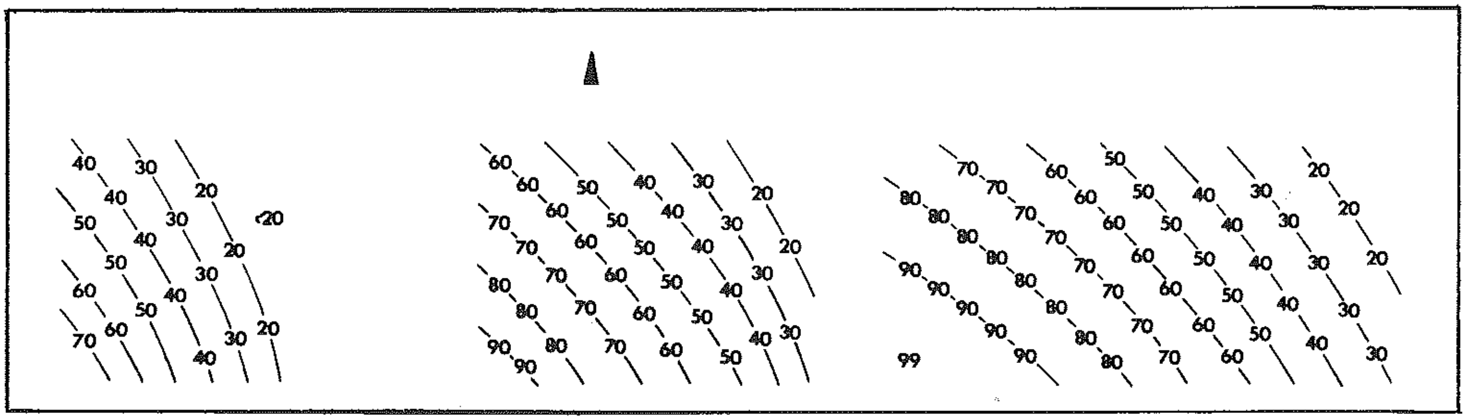

Slide spacers – double-up top & bottom

NOAA Technical Memorandum NWS SR-99

MANUALLY DIGITIZED RADAR DATA - Interpretation and Application

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1. INTRODUCTION

The National Weather Service (NWS) operates more than a hundred radars. About sixty of these are 10 cm wavelength network radars while the remainder are 5 cm sets intended primarily for local warning purposes. Radars provide almost complete coverage of the Nation east of the Rockies. West of the mountains weather information is extracted from Federal Aviation Agency (FAA) Air Route Traffic Control (ARTC) radars. Network and ARTC radars operate continuously and at least once each hour coded observations are transmitted which allow preparation of a composite facsimile map showing weather over the country as seen by radar (Fig. 1). Local warning radars (LWRs) are operated on an as-needed basis when threatening weather occurs and when their observations are transmitted they are incorporated in the analyzed radar data set.

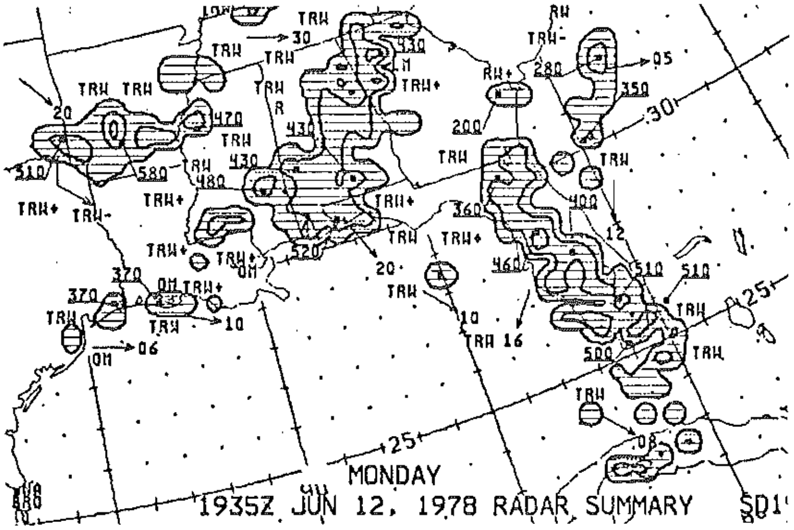

Figure 1. Portion of facsimile radar chart. Note contouring of echoes at VIP levels 1-3-5 and notations of echo characteristics.

A major change in the facsimile map was made in early 1978. Prior to that change the map was hand-drawn, but initiation of the high resolution, nationwide manually digitized radar (MDR) program allowed more timely, efficient and accurate computer generation of the composite map, complete with echo annotation (motion, tops, etc.). The MDR program is a refinement of an earlier NWS effort, begun in 1973, wherein network observations were manually encoded using a coarser-mesh grid (Moore, et al., 1974). Each of these manual efforts are built on many earlier studies which clearly demonstrated the potential of digital (computer compatible) radar information (Russo, 1961; Kessler, 1961; Kessler and Wilson, 1971; Wilk and Gray, 1970). The MDR program can be considered an interim step between use of the earlier azimuth-range (AZRAN) reporting code (Fig. 2) and a fully automated digitizing procedure built along the lines of D/RADEX (Digitized Radar Experiment) which has undergone field testing at several sites (Saffle, 1976).

Unfortunately, the fully automated system is some years in the future and in the interim MDR data represent the only source of quantified realtime radar information for a large area. In following sections we will briefly describe the program and show a variety of applications in which MDR data have yielded useful results. The data have been applied to weather watch and diagnostic procedures, aviation briefing, quality control of radar data, forecast verification, and have shown potential in a variety of hydrologic applications. Archived MDR data should prove useful in improving initial-moisture analysis of numerical models, in developing dynamical-statistical forecast techniques, and in such straight-forward applications as a synoptic climatology of radar echoes. Almost certainly the availability of radar information in computer-compatible form will continue to enhance development in a number of areas.

2. DESCRIPTION OF THE MDR PROGRAM

A full description of the NWS's radar reporting program, including MDR, is provided by NOAA (1978). Additional details of the MDR program are given in NWS Technical Procedures Bulletin No. 240, "The Radar Guidance Program." The following is intended only as an overview.

Each hour radar stations encode their PPI scope display by overlaying a grid similar to that in Fig. 2. The hourly observation is coded in both the usual AZRAN code and in the MDR code. The individual squares of the station's grid (each about 20 nmi square) constitute a portion of the national grid (Fig. 3). Since there is considerable overlap of station grids, the same echoes are frequently reported by more than one radar; in general, in subsequent processing the largest (most significant) digit is selected.

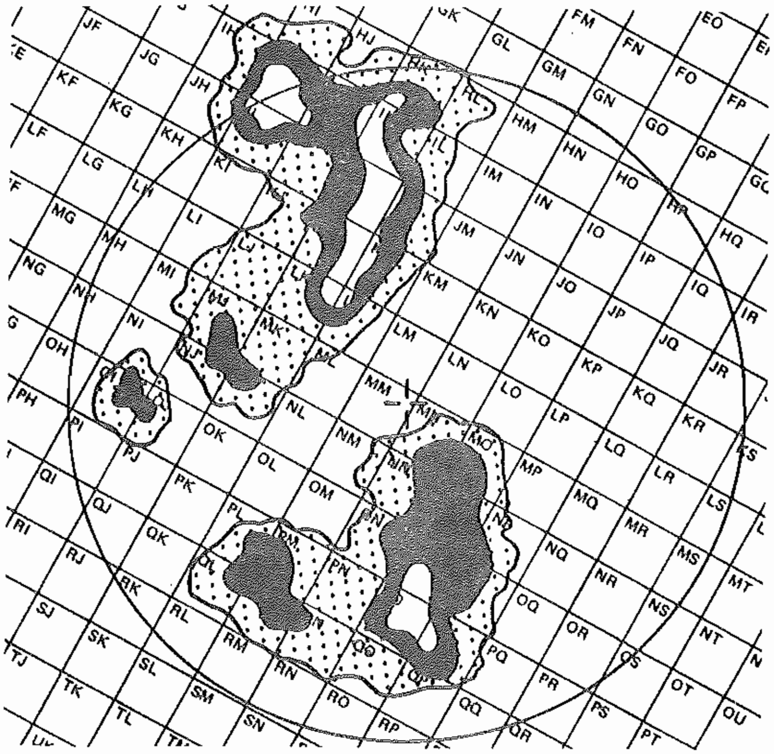

Figure 2. Example of radar observation from station "ABC". The MDR portion of the observation begins with "↑" and terminates with the "Φ".

ABC 1933 AREA 6 TRW+/NC 339/165 15/125 159/130 215/115
269/115 A2325 MT 370 AT 351/75 TOP 340 AT 179/80
↑HJ231 II3332 JH23233 KJ233 LI1133 MI1220022 NI22201222
OI22000232 PL22133 QL22212Φ

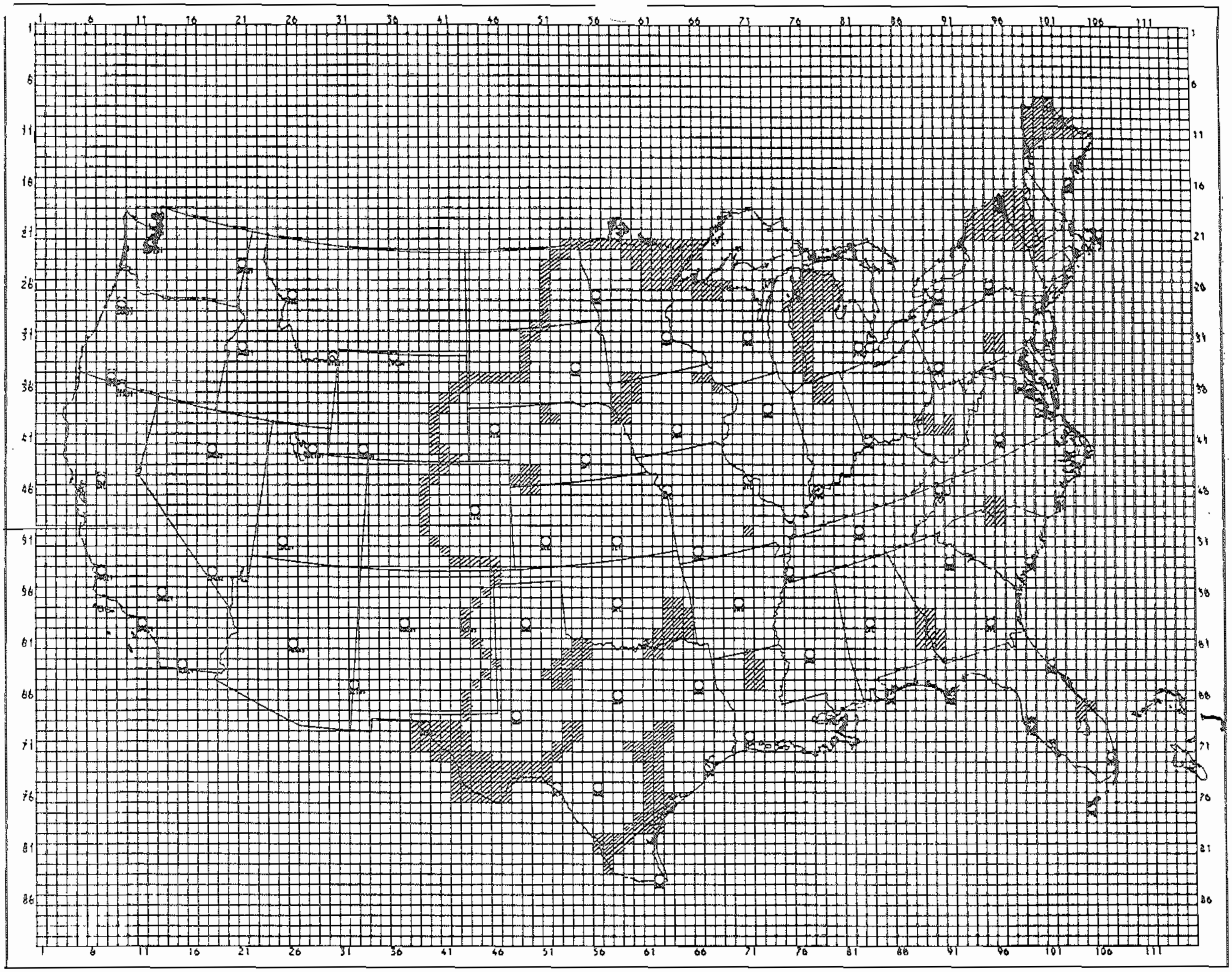

Figure 3. The MDR grid. Network and ARTCC radars shown by circles. Shading indicates MDR squares partly beyond ~100nmi - max effective hydrologic range of 10cm radars. LWRs "fill" most of these gaps. No attempt is made to show range limitations of western (mostly ARTCC) radars. Factors such as terrain may make other squares questionable: data should be used with caution in such areas.

The MDR code is shown in Table 1; code digits are simply VIP (Video Integrator and Processor) levels except that 8 and 9 are used for echo intensities beyond 125 nmi range. The coding procedure requires that the operator indicate for each square the maximum VIP level at the time of observation. Note that (unlike the original MDR program) no indication is made of echo coverage - of any intensity - within the square. Echoes in any row of the grid are encoded as a string of intensity digits with a pair of letters preceding the first digit representing the row/column identifier of the first digit's square.

TABLE 1. MDR INTENSITY CODE TABLE.

MDR VALUE	VIP LEVEL	ECHO INTENSITY	RAINFALL RATE (IN/HR) STRATIFORM	CONVECTIVE
1	1	LIGHT	< 0.1	< 0.2
2	2	MODERATE	0.1 - 0.5	0.2 - 1.1
3	3	HEAVY	0.5 - 1.0	1.1 - 2.2
4	4	VERY HEAVY	----	2.2 - 4.5
5	5	INTENSE	----	4.5 - 7.1
6	6	EXTREME	----	> 7.1
8 - 9		UNKNOWN	----	----

While MDR data from any station can be plotted by hand a major advantage of the digital report is that it allows computer composites of mapped radar data. The facsimile chart (Fig. 1) is one example, but the data are available more quickly and frequently from the teletypewriter request/reply (R/R) system. Figure 4a shows one of several R/R sectional maps which are available each hour approximately thirty minutes after observation time (observations are made and transmitted at about half past each hour). A rough geography is included with the mapped digits but plastic overlays are used for

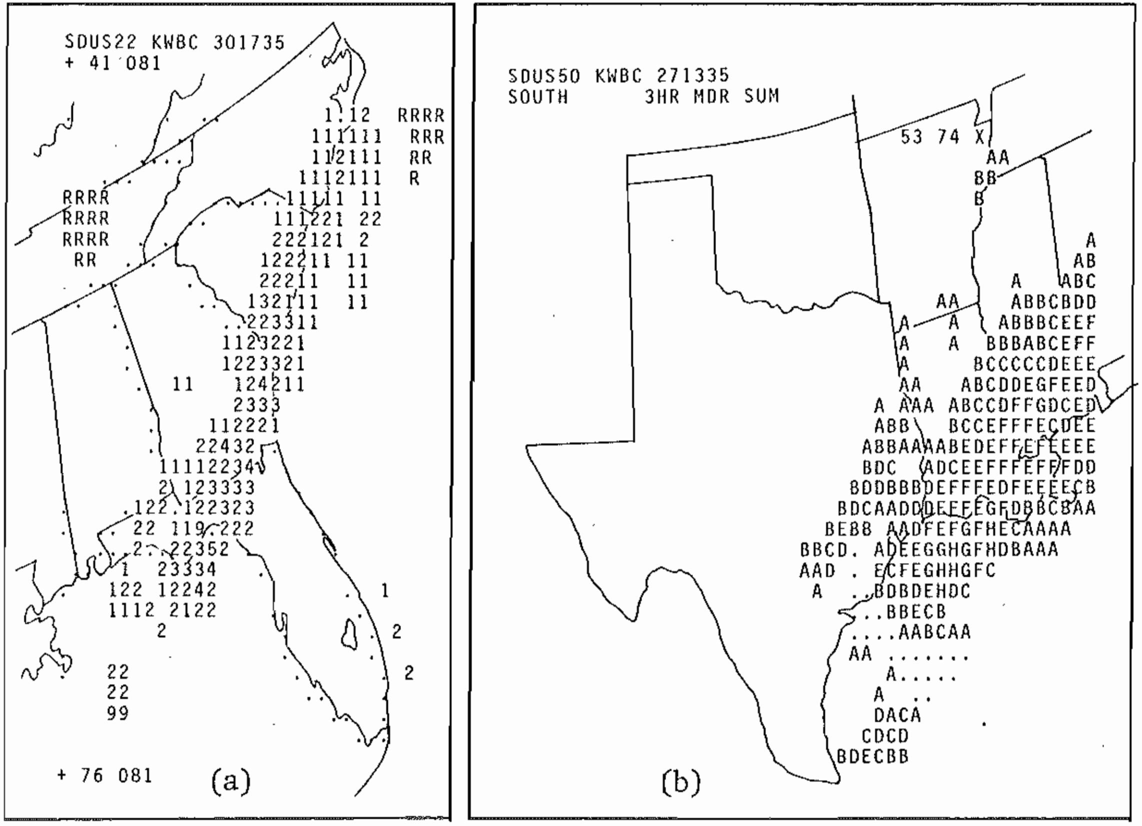

Figure 4. (a) Hourly sectional (southeast) MDR plot from Request/Reply, with geographic overlay added. (b) 3-hour MDR sum plot (southern sectional) from R/R. Code is simple letter/number substitution.

greater detail. The plotted digits represent the maximum reported echo intensity for each square including data from local warning radars, when available. 8s and 9s will appear on the plot unless replaced by more definitive intensity observations from a radar closer than the one transmitting the 8 or 9. Hourly sectional maps are also available by R/R which show three- and four-hour sums of digits for each square (Fig. 4b). Sums are represented by letters: A=1, B=2, ...X=24. Such maps have proven useful for noting echo persistence, particularly of heavy rain echoes, and for early warning of potential flash flood situations. Mapped MDR data are compatible with the new NWS automated system - AFOS - and will be available for immediate call-up as that system becomes fully operational. In addition, AFOS programming capabilities for local use should lead to additional MDR displays tailored for individual office needs. Various local use MDR applications are detailed in following section, but before discussing the utility of MDR data it will be useful to establish a baseline from which to evaluate radar information. Simply presenting the data in a convenient digital form does not eliminate the various problems and limitations inherent in radar information.

3. LIMITATIONS OF RADAR (AND MDR) DATA

Figure 5 depicts a number of factors which can lead to under- or overestimation of precipitation rates at different ranges from the radar site. These factors are largely dependent on radar characteristics (emitted power, beam width, wavelength, minimum detectible signal and so on) and so may be more or less significant at any given time for network versus local warning radars. For example, consider the effects of rain falling at the radar site, or between the radar and the target. Long wavelength radars are largely unaffected, even in heavy rain, but short wavelength LWRs can be attenuated by as much as three VIP levels (NWS, Weather Radar Manual). Thus, when heavy rain is suspected one should guard against being misled by a low VIP level from even a nearby LWR; the possibility of attenuation must be considered. The list in Fig. 5 is not necessarily complete. There are conditions under which some factors may switch columns and on occasion, poor radar calibration can lead to improper rainfall rate estimates. When radar observers annotate their reports with indications of electronic problems (e.g., "ROBEPS"), these should be understood and heeded. For quantitative estimates of rainfall intensity range is of paramount importance. Shaded squares in Fig. 3 show the limit of useful hydrologic range for network radars. Beyond about 100 nmi, even over flat terrain, such estimates become very poor. All users of radar information should have a good understanding of the significance of the factors affecting radars serving their area of responsibility. What are the characteristics of the local radar, for example? Does terrain significantly affect particular sectors of the surveillance area? Are cloud bases characteristically high so that evaporation, wind shear or frozen precipitation results in returns not indicative of precipitation reaching the ground? Battan (1973) provides additional reference for many of these problems, as does the NWS Weather Radar Manual.

Fig. 5 is presented primarily as a caution that radar observations, like other environmental measurements, are subject to inherent limitations. No data should be used without judicious scrutiny. Aside from electromagnetic gremlins another class of problems can arise when data are encoded, transmitted and decoded. Such problems should be carefully considered when using MDR data.

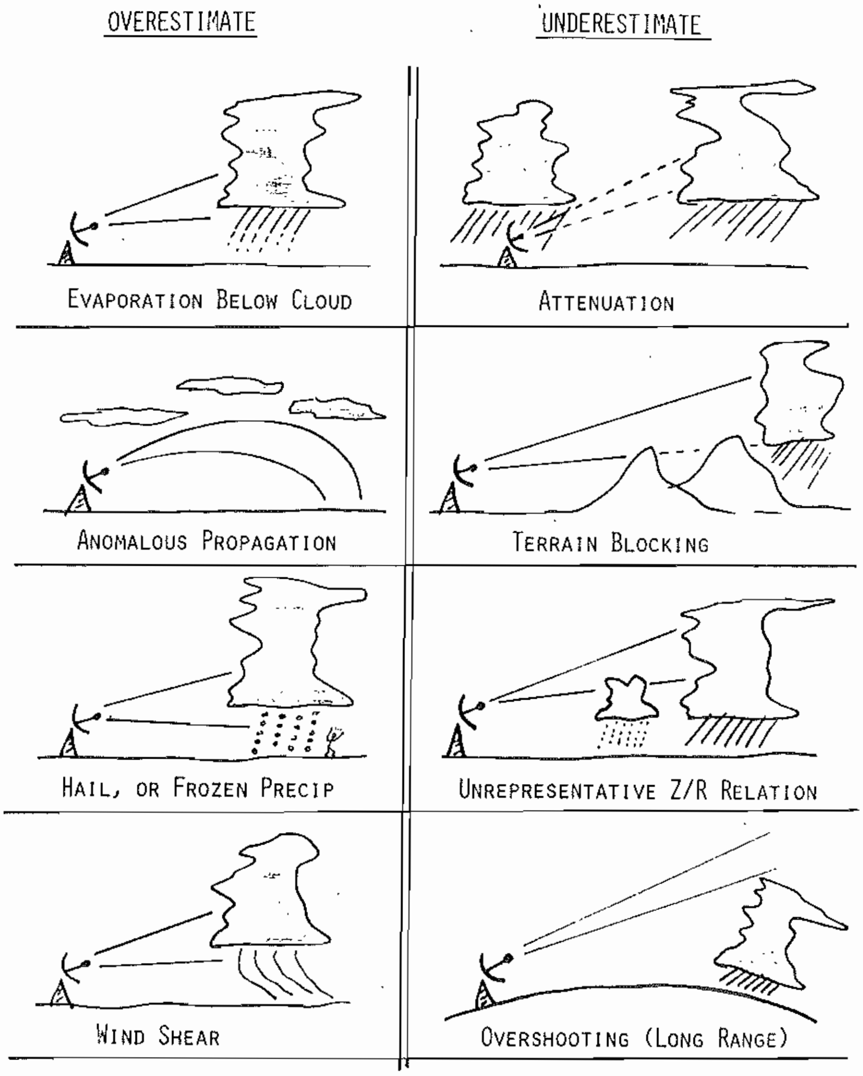

Figure 5. Some factors which can complicate rainfall estimation from radar data.

The subject of quantitative rainfall estimation by radar, based on frequent high-resolution observations, has been investigated extensively. However, different considerations and special problems are presented in the real-time use of MDR data as a result of the sampling constraints in a manual system.

MDR grid squares are large relative to characteristic sizes of intense thunderstorm echoes and since the MDR digit carries no information about coverage within the square we can only estimate what the coverage might be. (For many uses, fortunately, knowledge of coverage may not be as important as indications that heavy rain is there and, from repeated digits in a square, knowledge that heavy rain is persisting.) It is possible, nevertheless, to make inferences about coverage if we know (or assume) something about echo size. Much remains to be learned about "average" sizes and life-spans, and distributions of these characteristics, for echoes of various intensities but present knowledge allows at least a subjective evaluation for MDR/rainfall conversion. Uncertainty about areal coverage is a major limitation to deterministic judgements with MDR data: we must think instead in terms of the likelihood that a reported echo covers any given spot in the square. It is almost certainly true that the area enclosed by a VIP 6 contour is smaller than that enclosed by a VIP 5 contour. (The most intense rain cells are also short-lived.) The same holds true for VIP 5 and VIP 4 echoes, VIP 4 and VIP 3 echoes, and so on. But an echo is, in general, a "nest" of successively smaller VIP levels. It appears reasonable to assume further that the VIP 4 echo which surrounds a VIP 5 or VIP 6 peak intensity is at least as large, on the average, as a VIP 4 echo which does not. Furthermore, the rain area with the stronger peak intensity probably lasts longer; again, on the average. (It is easy, and dynamically logical, to present a special case where the opposite is true: very small, intensive and short-lived thunderstorms.) We believe it is safe to say, however, that in terms of rainfall the significance of a VIP 5 echo, say, lies not so much in the fact that such a peak intensity represents intense rainfall (over a very small area) but rather in the fact that it suggests a more significant area of VIP 4 rainfall than would be present if the VIP 5 were not seen. Thus, successively higher MDR digits represent, on the average, greater exposure of more area of the MDR square to heavier rainfall.

Aside from the coverage problem one must also realize that the MDR digit represents only a "once-an-hour" snapshot view. As a result of echo movement and varying intensity over the hour any given point affected by an echo in the MDR square may be exposed to the "reported" MDR intensity for only a part of the hour. For any given point in the square, its "exposure factor" to rain of a given intensity is dependent on echo size, duration and motion -- all factors we can only infer from the reported hourly digits and factors which are in turn dependent on the meteorological situation. Another factor for consideration is that VIP levels are assigned to rainfall intensity ranges (Table 1). Each VIP or MDR digit represents a range of rainfall rate which varies by a factor of roughly two from lowest to highest intensity. To properly assess the rainfall rate and determine the exposure factor additional information must be gleaned from:

a. Subjective evaluation of the existing weather system...

   -are copious moisture and sustained vertical motion indicated?
   -does moisture extend through a deep layer?

b. Examination of the general nature of echoes - from "live" or remoted scope display...

   -do echoes seem to be large, slow-moving or long-lived?
   -even if intense echoes are absent, do heavy or even moderate echoes seem unusually large and long-lived?

In the final event the result will be a probabilistic assessment of the rainfall likely at any given point in an MDR square. This is a very important point and crucial to the proper utilization of MDR data for rainfall estimation: PROPER INTERPRETATION OF MDR DATA REQUIRES THAT WE ASSUME A PROBABILISTIC APPROACH. But such thinking is certainly not foreign to the meteorologist. The forecaster expresses the likelihood of rain at points within an area by means of probability (PoP) forecasts; likewise, given information from an area (an MDR square) it is reasonable to think in terms of the probability of rainfall amounts at points within the area. Similarly, we are accustomed to using to the fullest a single rainfall observation from a relatively large area, but how representative is the observation? In truth, the nature of the system which produced the rain requires us to consider the single report probabilistically: we generally assign a high probability that it is "representative" while accepting the fact (perhaps unconsciously) that adjacent points received more or less rain. Problems of assessing rainfall over an area are similar whether we use MDR or single raingage observations. Thus, while we have stressed the limitations and considerations which apply to MDR data the careful reader will realize that the unique nature of the data - particularly its high temporal and spacial resolution - warrant its full application. Following sections will show how MDR data have been used. Special attention will be given first to probabilistic quantitative rainfall estimation - with emphasis on heavy rainfall - although the data have wide utility aside from such estimations.

4. MDR FORECAST APPLICATIONS

A. More About Estimating Rainfall

As explained in the previous section a single hour's MDR digit is ambiguous in its indications of rainfall within a given square, but experience has shown that a succession of digits for the same square lessens this ambiguity. A series of MDR 4's, for instance, suggests a large and/or slow moving system, quite possibly with more intense (VIP 5+) echoes briefly occurring between observations. (The latter possibility is based on our subjective evaluation of large and very heavy rain systems.) While we would probably consider it unlikely that any given spot in the square received the maximum possible rain (~4.5 in) during the hour from a single MDR 4, a succession of MDR 4's in the same square would increase the possibility. We might conclude that the most likely maximum rain at some point from a single MDR 4 would be, say, 0.5 in, but the most likely maximum total from four-hour's succession of MDR 4's might be 4 to 5 in - considerably more than four times the single hour's amount.

From theoretical and empirical considerations (of many rain events) we have developed the nomogram in Fig. 6 which shows, for two- to four hour MDR totals in a grid square, the probability of given maximum rainfall amounts at some location in the square.* The time periods were chosen to correspond with the "short-fuse" lead times of flash flood-producing rainfall and our emphasis on use of the nomogram has been toward estimating the likelihood of such heavy rainfall. Since the MDR digit tells us nothing about areal coverage within a square it is always possible that during an hour a given spot receives no rain, regardless of the hour's digit. As echoes persist in the square, however, this possibility lessens. For a given time interval, the

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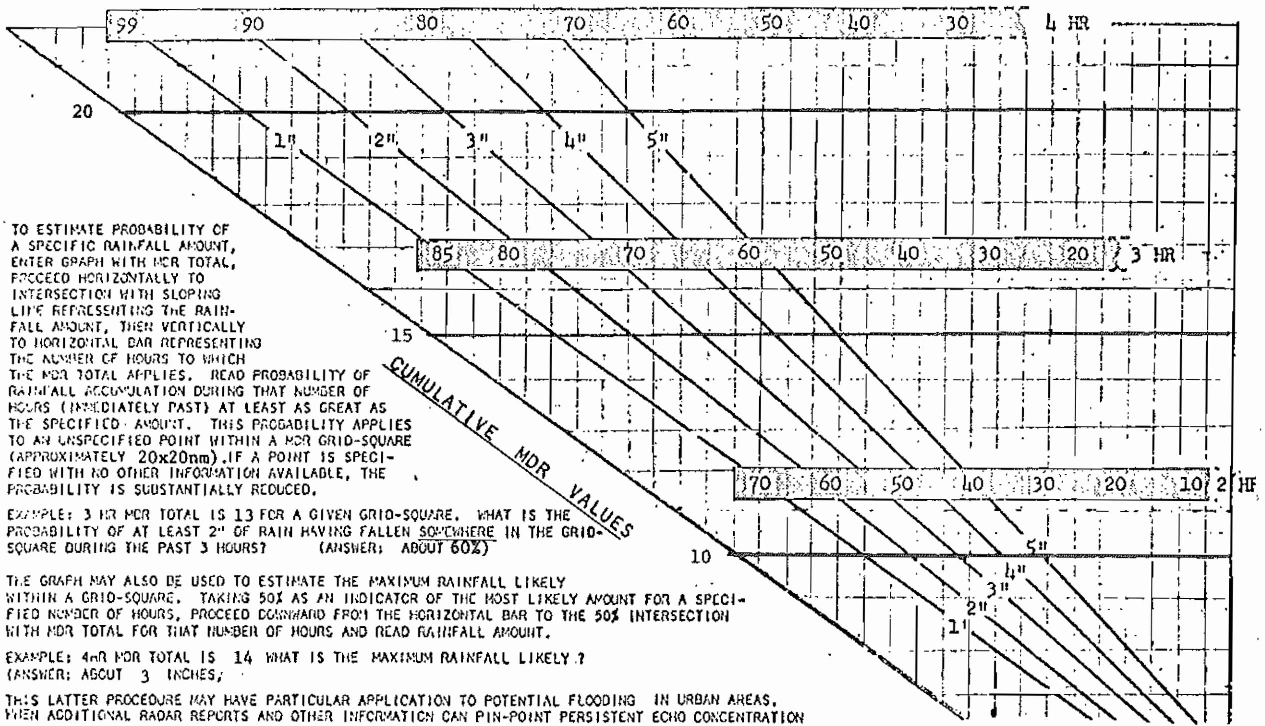
*Fig. 6 is modified form of the nomogram developed for the original MDR data. Attached as an endpiece to this Technical Memorandum is a "do-it-yourself" slide rule which, when assembled, provides the same guidance as Fig. 6.

MDR Total Versus Probability of Various Rainfall Amounts



TO ESTIMATE PROBABILITY OF A SPECIFIC RAINFALL AMOUNT, ENTER GRAPH WITH MDR TOTAL, PROCEED HORIZONTALLY TO INTERSECTION WITH SLOPING LINE REPRESENTING THE RAINFALL AMOUNT, THEN VERTICALLY TO HORIZONTAL BAR REPRESENTING THE NUMBER OF HOURS TO WHICH THE MDR TOTAL APPLIES. READ PROBABILITY OF RAINFALL ACCUMULATION DURING THAT NUMBER OF HOURS (IMMEDIATELY PAST) AT LEAST AS GREAT AS THE SPECIFIED AMOUNT. THIS PROBABILITY APPLIES TO AN UNSPECIFIED POINT WITHIN A MDR GRID-SQUARE (APPROXIMATELY 20x20nm). IF A POINT IS SPECIFIED WITH NO OTHER INFORMATION AVAILABLE, THE PROBABILITY IS SUBSTANTIALLY REDUCED.

EXAMPLE: 3 HR MDR TOTAL IS 13 FOR A GIVEN GRID-SQUARE. WHAT IS THE PROBABILITY OF AT LEAST 2" OF RAIN HAVING FALLEN SOMEWHERE IN THE GRID-SQUARE DURING THE PAST 3 HOURS? (ANSWER: ABOUT 60%)

THE GRAPH MAY ALSO BE USED TO ESTIMATE THE MAXIMUM RAINFALL LIKELY WITHIN A GRID-SQUARE. TAKING 50% AS AN INDICATOR OF THE MOST LIKELY AMOUNT FOR A SPECIFIED NUMBER OF HOURS, PROCEED DOWNWARD FROM THE HORIZONTAL BAR TO THE 50% INTERSECTION WITH MDR TOTAL FOR THAT NUMBER OF HOURS AND READ RAINFALL AMOUNT.

EXAMPLE: 4HR MDR TOTAL IS 14 WHAT IS THE MAXIMUM RAINFALL LIKELY ? (ANSWER: ABOUT 3 INCHES)

THIS LATTER PROCEDURE MAY HAVE PARTICULAR APPLICATION TO POTENTIAL FLOODING IN URBAN AREAS. WHEN ADDITIONAL RADAR REPORTS AND OTHER INFORMATION CAN PIN-POINT PERSISTENT ECHO CONCENTRATION OVER A METROPLEX THE FORECASTER CAN DETERMINE IF RAINFALL RATES ARE LIKELY TO BE AVERAGING IN EXCESS OF, e.g., ONE INCH PER HOUR. THE FIRST PROCEDURE CAN PROVIDE GUIDANCE IN THE ISSUANCE OF FLASH FLOOD WATCHES OR WARNINGS, WHICH ARE PREDICATED ON PROBABILITIES. AGAIN, EFFORTS SHOULD BE MADE TO OBTAIN ADDITIONAL DETAILED METEOROLOGICAL INFORMATION AS WELL AS TO CONSIDER RFC FLASH FLOOD GUIDANCE AND OTHER HYDROLOGIC FACTORS.

(2/15/78 - Highly tentative, subject to revision as MDR data become available for analysis.)

Figure 6. Nomogram for estimating rainfall amounts associated with MDR totals over 2- to 4 hours. Note that MDR/rainfall conversion is done in a probabilistic sense.

greater the sum of MDR digits the greater is the possibility of a given rainfall total somewhere in the square. The difficult task, of course, is assigning the probabilities! - those in Fig. 6 are based on "average" cases. We suggest that the "50%" rainfall can be considered the "most likely maximum" somewhere in the square but this amount should be subjectively adjusted to account for "wetter" or "drier" than usual systems. The 50% probability on the nomogram should be considered as applying to rain situations with the most frequent (the "usual") combination of echo size, persistence and speed of movement - all of which can cause variations in the point rainfall for the same MDR total. If in the forecaster's judgement the meteorological situation results in an unusual combination of these factors which is particularly favorable for large point rainfall - a combination which would be expected to occur, say, only 30% of the time - then the 30% level should be used in lieu of 50%. It will be seen that a lower probability level (for the same MDR total) results in a larger probable maximum rain estimate. On the other hand, if the MDR digits are known to be associated with short-lived, rapidly moving and/or relatively small echoes (even though perhaps of high intensity) the "50%" rainfall amount should be considered an overestimate of "most likely maximum" rainfall.

Where decision making is based on less than optimum information one must not lose sight of the possibility of greater or lesser amounts than the "most likely". Fig. 6 allows consideration of the range of probabilities. Suppose, for example, that based on the nature of the terrain, antecedent rainfall and perhaps flash flood guidance rainfall estimates from a River Forecast Center (RFC) it is determined that serious consequences would result from a 5 in rainfall at a community. A three-hour total of 11 in the community's MDR square would indicate a 50% chance of about 1.5 in, the most likely maximum three-hour rainfall in the square. But Fig. 6 reveals further that there is about a 30% chance of 5 in - the critical amount - somewhere in the square. Depending on the seriousness of the consequences of such rainfall this may or may not be a sufficiently high probability for action. In any event, it should certainly require an intensified weather watch and telephone requests for rainfall reports.

B. Flash Flood Alerting

A primary use of Fig. 6 is in rapid alerting of the possibility of flash flood producing rainfall. Operational considerations dictate that any such tool be uncomplicated and therefore amenable to rapid and easy use. A straight-forward summing of MDR digits and use of the nomogram fills this requirement. Unfortunately, the tool does not provide definitive answers but must be used with understanding and judgement. It should be emphasized that radar is not a precipitation forecast tool, *per se;* it shows only on-going precipitation. Flash flood alerting, therefore, requires close monitoring of radar data for first clues that sufficient rain has either fallen or is imminent, given persistence of the current situation. In the first two examples which follow we show how the data were useful in two quite different flood situations: one a classic "short fuse" localized event, and the other a flash flood event somewhat slower in development which was part of widespread record-breaking rainfall and flooding. Both events occurred in Texas in the summer of 1978. A third example shows a "routine" application of the data in an event of lesser significance. Finally, an example is presented to show the utility of MDR data in depicting and "tracking" the pattern of heavy rainfall during a flood event.

Palo Duro Canyon Flash Flood -- May 26-27, 1978

Palo Duro Canyon State Park is a ruggedly beautiful erosion feature of the Texas High Plains near Amarillo. Unfortunately, it also meets the requirements for a disastrous flash flood: a winding stream which can quickly rise high enough, from even brief local thundershowers, to cut off all exit roads from the Park interior; rock-hard terrain and sheer bluffs which localize and concentrate runoff, minimizing reaction time; a privately-owned earthen dam a few miles upstream which receives runoff from a large drainage area. Finally, at least on Memorial Day weekend in 1978, poor communication existed between Park Headquarters on the rim of the Canyon and campsites deep inside the Park. These features are sufficient to "red flag" the MDR square containing the Park and put forecasters on watch for the first signs of possible heavy rain.

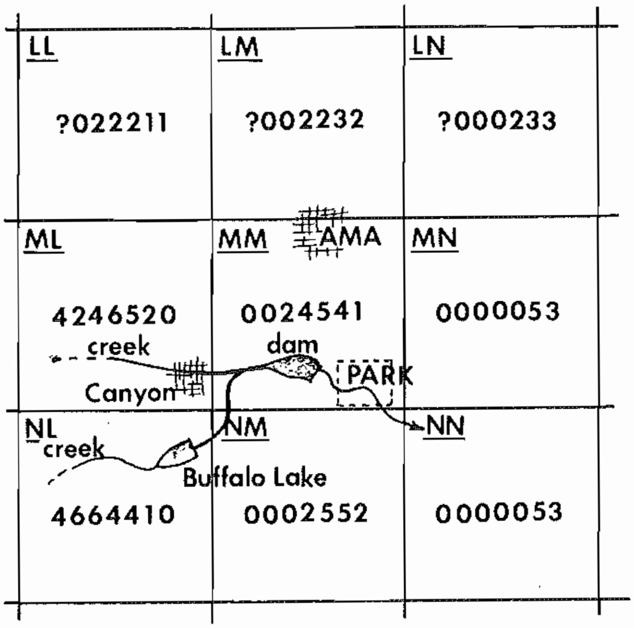


Figure 7. Small portion of Amarillo MDR grid, data for May 26, 1978. In each square digits are consecutive hours, starting with 435pm (leftmost). Note 4-6-5 between 635 and 835pm in Canyon square.

Fig. 7 shows a portion of the MDR grid with hourly reports from the Amarillo WSR-57. (Incidentally, we have found this procedure of plotting successive digits within each MDR grid square a handy way to keep up with an evolving weather system.) Between 430 and 830pm (CDT) the square just southwest of the Park contained the sequence of digits 4 - 6 - 6 - 4 - 4; this would be taken as almost certain indication of heavy rain in the square _except_ that caution was required because hail was known to be occurring. Several events, especially in West Texas, have shown that hail frequently results in spuriously high VIP levels, in relation to reported rainfall. A tornado was also reported in this square during the early evening. In fact, heavy rain _did_ fall in the square, but the runoff contributed little to the subsequent flood since Buffalo Lake, virtually dry before the event, filled and held the water.

The square containing the city of Canyon and the watershed of Palo Duro Creek, just west of the Park, is the square of critical importance. An estimated storm total maximum rainfall of 8 in was measured just west of Canyon between about 8 and 930pm. Note the MDR sequence of 4 - 6 - 5 between 630 and 830pm. It is unknown just how significant hail might have been in the Canyon square but there is no doubt that severe weather in the vicinity (high wind, hail and the earlier tornado) effectively distracted attention of local officials to the extent that they failed to notice, or at least report, excessive rainfall.* The three-hour MDR total of 15 at 830pm indicates a 50% probability of about 4.5 in somewhere in the square. Considering the "flashy" characteristics of the terrain in the vicinity of Canyon this rainfall amount, and the relatively high probability of at least this much, are sufficient to generate great concern -- as indeed they did.

Heavy rain ended abruptly after about 9pm in Canyon, thunderstorms having moved eastward toward the Park. But the very heavy runoff west of town drained quickly into Palo Duro Creek, flooded a residential area of Canyon and killed three people near midnight, then moved downstream in the classical "wall of water" to Tanglewood Reservoir, killing one more person. Heavy rains near the dam before midnight, coupled with the flood waters from upstream, rapidly filled the lake and it overflowed in the early morning hours of the 27th, seriously compromising the earthen structure. About 200 holiday campers in the Park were awakened around 5am by the rushing and rapidly rising flood waters. There were no fatalities in the Park but many escapes were little short of miraculous.

This event illustrates the significance of MDR data for flagging potential flash flood situations. It also shows the extreme importance of knowing the local terrain. While the Park is known to be a potential disaster area because of flooding, in this case lives were lost and more damage was done upstream along a dangerous creek but in a "safer looking" area! Also, the MDR data look more significant in the square southwest of the Park but little flooding occurred because a dry lake saved the day. Three hours of heavy to intense rainfall in a square of critical importance to Canyon and the Park were clearly signalled by MDR data perhaps an hour or more before flooding became very serious and lives were lost.

Texas Hill Country: Record Rain and Flooding - August 1-3, 1978

Between evening of August 1st and morning of August 3rd excessive rains of over 30 in fell in the Texas Hill Country, northwest of San Antonio. Although only about half the peak amount, a raingage trace from ten miles west of Hunt (Fig. 8) reflects the nature of the storm - peak rainfalls of 10 to 20 in occurred on successive nights! Fig. 9 shows the storm total rainfall with two centers of over 30 in and an area of about 1200 sq mi enclosed within the 10 in isohyet. Note that the area of heaviest rain was centered in an MDR grid square ("KM" as seen by the Hondo WSR-57).

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*The Canyon Fire Chief, contacted by the Amarillo WSO about 9pm, indicated great concern about severe weather and verified the earlier tornado and its effects. He failed to mention, however, that shortly after 8pm one of his men had reported water running "knee deep" over a flat stretch of Hwy 60 just west of Canyon!

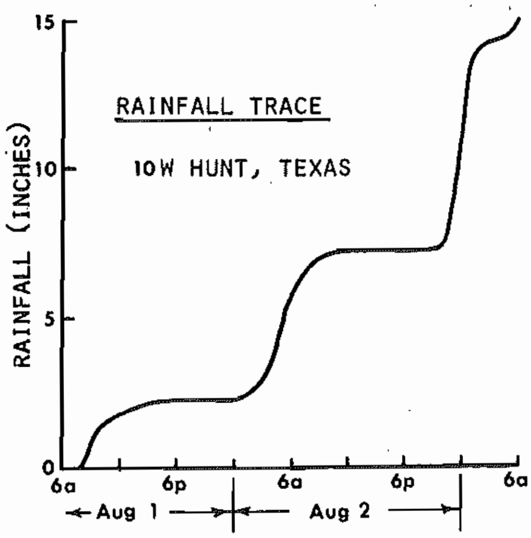

Figure 8. Rainfall trace from vicinity of heavy rain showing two-night character of event.

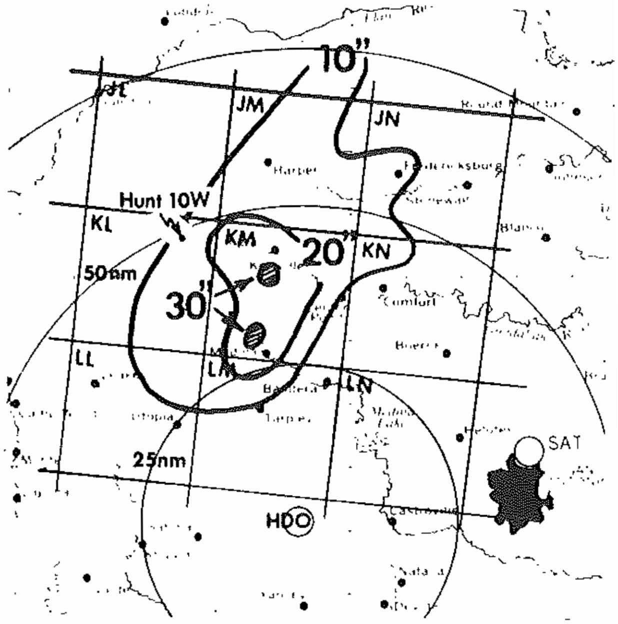

Figure 9. Storm rainfall, August 1-3, 1978.

The total rainfall was excessive on each night of the storm but it appears that on the first night, at least, no single hour was characterized by intense rainfall. A probable reason for this was the tropical nature of the rain system, augmented by a deep moisture supply coming in part, at least, from the Pacific.* Later the same week, and again later in the month, similar excessive rainfall events elsewhere in Texas were characterized by relatively low VIP levels.

Table 2 shows hourly MDR values for Hondo's square "KM" and an analysis of those data. With no more information than that supplied by the MDR data no analyst would conclude, with certainty, that rainfall of 15 in or more fell in the square on the first night; however, the data are sufficient to suggest that heavy rain was likely in the square. Radar data from the two nights are quite sufficient to support rainfall on the order of 30 in. The reported MDR values, even though never greater than VIP 4 on the first night, when taken along with additional data were indicative of flood producing rainfall. In fact, forecasters at WSFO San Antonio used the data accordingly.

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*In such a very moist environment persistence, size of echoes, and maximum rainfall for a given VIP level are apparently increased by entrainment of moist, rather than dry, air into convective cells from the surroundings.

TABLE 2. TEXAS HILL COUNTRY FLOOD, AUGUST, 1978

	TIME	SQR "KM" MDR	4 HR SUM	CONFIDENCE 30%	CONFIDENCE 50%	VIP LVL RAIN* LWR	VIP LVL RAIN* MED	VIP LVL RAIN* UPR
First Night (Aug 1-2)	730p	3	7	TOO LOW TO ESTIMATE		1.0	1.5	2.0
	830	2	8			~.25	.5	1.0
	930	2	8			~.25	.5	1.0
	1030	0	7			0	0	0
	1130	2	6			~.25	.5	1.0
	1230a	2	6			~.25	.5	1.0
	130	3	7			1.0	1.5	2.0
	230	3	10	→3.0"		1.0	1.5	2.0
	330	3	11	3.75"	→.5"	1.0	1.5	2.0
	430	3	12	4.5"	1.5"	1.0	1.5	2.0
	530	4	13	5.5"	2.25"	2.0	3.0	4.5
	630	4	14	→ >6"	3.0"	2.0	3.0	4.5
	730	3	14	>6"	→3.0"	1.0	1.5	2.0
	830	1	12	4.5"	1.5"	-	-	-
				→~10"	→~4"	11"	17"	25"
Second Night (Aug 2-3)	730p	0	0	TOO LOW		0	0	0
	830	4	4			2.0	3.0	4.5
	930	4	8	1.0"		2.0	3.0	4.5
	1030	4	12	→4.5"	1.5"	2.0	3.0	4.5
	1130	5	17	>6"	→5.5"	4.5	5.5	7.0
	1230a	4	17	>6"	5.5"	2.0	3.0	4.5
	130	4	17	>6"	5.5"	2.0	3.0	4.5
	230	3	16	→ >6"	4.5"	1.0	1.5	2.0
	330	4	15	>6"	→4.0"	2.0	3.0	4.5
	430	3	14	>6"	3.0"	1.0	1.5	2.0
	530	4	14	>6"	3.0"	2.0	3.0	4.5
	630	0	11	→3.75"	.5"	0	0	0
				→ ~15"	→~10"	~20"	~30"	~42"

*HOURLY RAINFALL AMOUNTS AS ESTIMATED FROM VIP LEVELS. SEE TABLE 1 FOR CONVECTIVE RAINFALL RATES.

A conspicuous feature of the MDR data on the first night was the seven-hour string of VIP 3, or higher, echoes in the same square. Only two MDR 4's were reported, although remember that these are hourly "snapshot" values. The significance of the data is not so much intensities as persistence. In the middle columns of the table we show four-hour MDR sums and maximum rainfall amounts which these sums imply somewhere in the square at 30% and 50% confidence limits. These amounts are taken from the MDR flash flood nomogram. For example, the four-hour sum of 11 at 330am (CDT) implies a 50% chance that about 0.5 in fell somewhere in the MDR square between 1130pm and 330am. But there is a 30% chance that as much as 3.75 in fell in the square during the four-hour period. For the first night we can estimate, probabilistically, that there was a 50% chance of around 4 in in the square. HOWEVER, THE PROBABILITY WAS 30% THAT AS MUCH AS 10 in FELL! 30% is a significant probability limit for heavy rain in this case because the subject MDR square covers a very "flashy" section of Hill Country terrain. Over flat country we would tend to place less emphasis on the significance of a 30% probability; our "threshold" might be, say, 50%. The important thing to note is that there is no "magic number" which is the threshold for action; not a VIP 5 or VIP 6, nor a total of 12, 18 or 21. It is essential that we define local probability limits, dependent on terrain, antecedent conditions, and characteristics of the rain-producing system, which will prompt us into action.

Even more important than the MDR values and totals themselves is the implication from these data that echoes were large and quasi-stationary. Radar film confirmed that echoes persisted within the same MDR square hour after hour and, most importantly, covered large portions of the MDR square. Realtime WBRR images and/or contact with radar operators can yield the same confirmation. Such knowledge allows us to refine the probabilistic approach, based on many storms and average characteristics, and think instead in terms of this particular storm. If echoes are large and long-lived there is a good chance that much of the MDR square experiences rain at the indicated VIP level. The rightmost columns of the table show hourly rainfall amounts assuming lower, median and upper limits to each VIP level's assigned rainfall rates. In general, even though echoes persist hour after hour we cannot assume that the same point remains under an echo <u>unless</u> we have reason to assume further that echoes are unusually persistent and large. This was a characteristic feature of the subject storm. Thus, we can be conservative and assume a lower limit to rainfall rates and still arrive at an estimate of over 10 in within the square on the first night. Excessive rainfalls from median or upper limit rainfall rates are possible, but probably unlikely in this event; nevertheless, the radar data are still clearly suggestive of very heavy rainfall.

The lower half of Table 2 shows data for the second night. As indicated by the Hunt 10W rainfall trace the area generally received heavier rain the second night. Radar reflectivities were higher and there was no doubt from these data that heavy rain was falling. Note the ten-hour string of MDR values of VIP 3 or greater, generally VIP 4. Even at the 50% confidence level rainfall of 10 in is indicated. Again, considering the very large and persistent echoes, lower-limit rainfall rates suggest totals of around 20 in for the square for this second night.

Early Morning Flood: Montgomery, Alabama - May 9, 1978

RFC flash flood guidance for Zone 10, containing Montgomery, was 2.1 in/3 hrs on this day. Shortly after midnight heavy thunderstorms moved into the area from the west, producing the series of MDR digits shown in Table 3 for square "NO", as seen by the Centreville WSR-57 radar, about 50 nmi away. Note six consecutive hours with MDR 5! Also shown in Table 3 are hour-by-hour estimates, from Fig. 6, of (A) the likelihood of a maximum rainfall of "2" in the square, and (B) the "most likely maximum" - from the 50% value - given the two- to four-hour MDR totals.

TABLE 3. MONTGOMERY, ALABAMA, FLOOD: MAY 9, 1978

TIME (CDT)	MDR (KM)	(A) PROB OF 2" MAX	(B) MOST LIKELY MAX AMT (50%)	MGM RAIN (HR ENDG)
0135	0			0 (2a)
0235	5	→?]-50%]-70%]-85%	→?]-2"]-4.5"]-» 5"	.14 (3a)
0335	5			.86 (4a)
0435	5			.09 (5a)
0535	5			.87 (6a)
0635	5			1.98 (7a)
0735	5			1.29 (8a)
0835	0			T (9a)
				5.23"

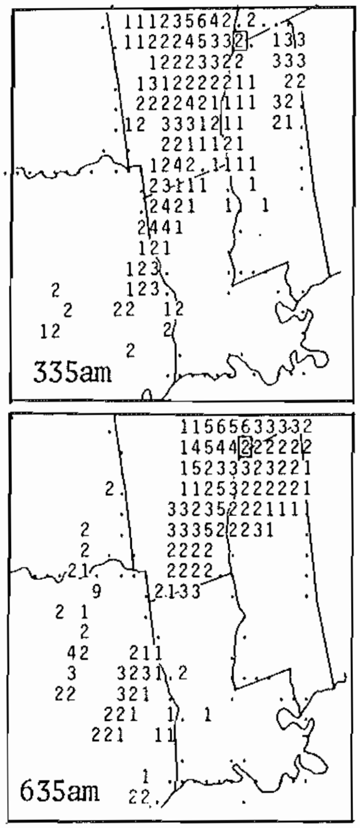
Since from a single hour's occurrence of VIP 5 almost any rainfall amount less than about 8 in (including no rain!) is possible in the square we can do little with the first MDR 5 other than recognize the real potential for exceeding the flash flood guidance value. A close contact should be maintained with the radar operator for additional details. By 335 CDT the two-hour total of 10 suggests a most likely maximum rainfall of about 2 in somewhere in the square during the two-hour period. An hour later, a third MDR 5 leads to a three-hour total of 15 and an estimated 70% chance of 2 in during the three hours - the most likely maximum amount is about 4.5 in. By this time it is probable that the flash flood guidance value has been exceeded somewhere in the square. Additional information from the radar operator could well indicate where.

Table 3 also shows hourly rainfall observations from the WSO in Montgomery (located in the extreme eastern portion of square "NO"). Notice that by 5am only a little over an inch of rain had fallen. It is not surprising, however, that as intense thunderstorms continued in the square the WSO eventually was exposed to very heavy rainfall. Greatest 1-, 2-, 3- and 4-hour rainfalls at the WSO were 1.98 in, 3.27 in, 4.14 in and 4.23 in, respectively. Since we cannot judge how representative this single rain gage is for the storm as a whole, it seems reasonable to conclude that these observations are in general agreement with estimates from the MDR nomogram. Notice that the greatest 2-hour rainfall of 3.27 in has associated with it a probability of about 40%, based on an MDR total of 10. An interesting question is, "What portion of the MDR square experienced rain of this intensity during the storm?" For the storm total rainfall, the nomogram might lead one to overestimate the likely maximum rainfall, at least as measured at Montgomery, but, of course, heavy rainfall indicated as beginning earlier elsewhere in the grid square may well have produced larger storm totals.

Finally, it is interesting to compare this example with the previous example of record flooding in the Texas Hill Country which came from seemingly less intense rainfall. How does one explain extremely heavy rainfall from a series of MDR 3s and 4s and "only" a few inches from a series of MDR 5's? The answer lies in the differing natures of the weather systems and clearly illustrates the need for a sound meteorological analysis and probabilistic approach (see Section 3). It should be noted that, meteorologically, this third example compares more favorably with the first example than with the second!

Memphis and Vicinity Flood: A Fast-Mover -- December 3, 1978

Around midnight on December 2nd, 1978, severe weather developed in northwestern Louisiana and moved rapidly northeastward into Arkansas. Several tornadoes were spawned and, as the weather system organized and continued to intensify, the threat of flood-producing rainfall from numerous heavy thunderstorms increased. Throughout the morning of the 3rd individual thunderstorms moved in excess of 40 kts but new cells formed continuously, exposing some locations to multiple storms. Fig. 10 shows portions of hourly R/R MDR plots during the storm. Also shown is a well-written



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WWUS1 RWRC 031630
⬍MEMSPSMEM
SPECIAL WEATHER STATEMENT
NATIONAL WEATHER SERVICE MEMPHIS TN
1030AM CST SUN DEC 3 1978

HEAVY RAIN MOVING ACROSS WEST TENNESSEE

NUMEROUS THUNDERSTORMS THAT OCCURRED OVER WEST TENNESSEE DURING THE
NIGHT AND EARLY MORNING HOURS HAVE DUMPED LOCALLY HEAVY RAINS OF TWO TO
FOUR INCHES IN PLACES. THESE RAINS WILL CAUSE A RISE IN STREAMS ACROSS
WEST TENNESSEE AND MAY CAUSE SOME LOCAL FLOODING.

THE RAINS ARE EXPECTED TO END OVER WEST TENNESSEE THIS AFTERNOON
HOWEVER PERSONS SHOULD REMAIN ALERT FOR ANY ACCUMULATION OF WATER.
EARLY REPORTS INDICATE THE HEAVIEST RAINFALL HAS BEEN IN NORTHWEST
TENNESSEE.

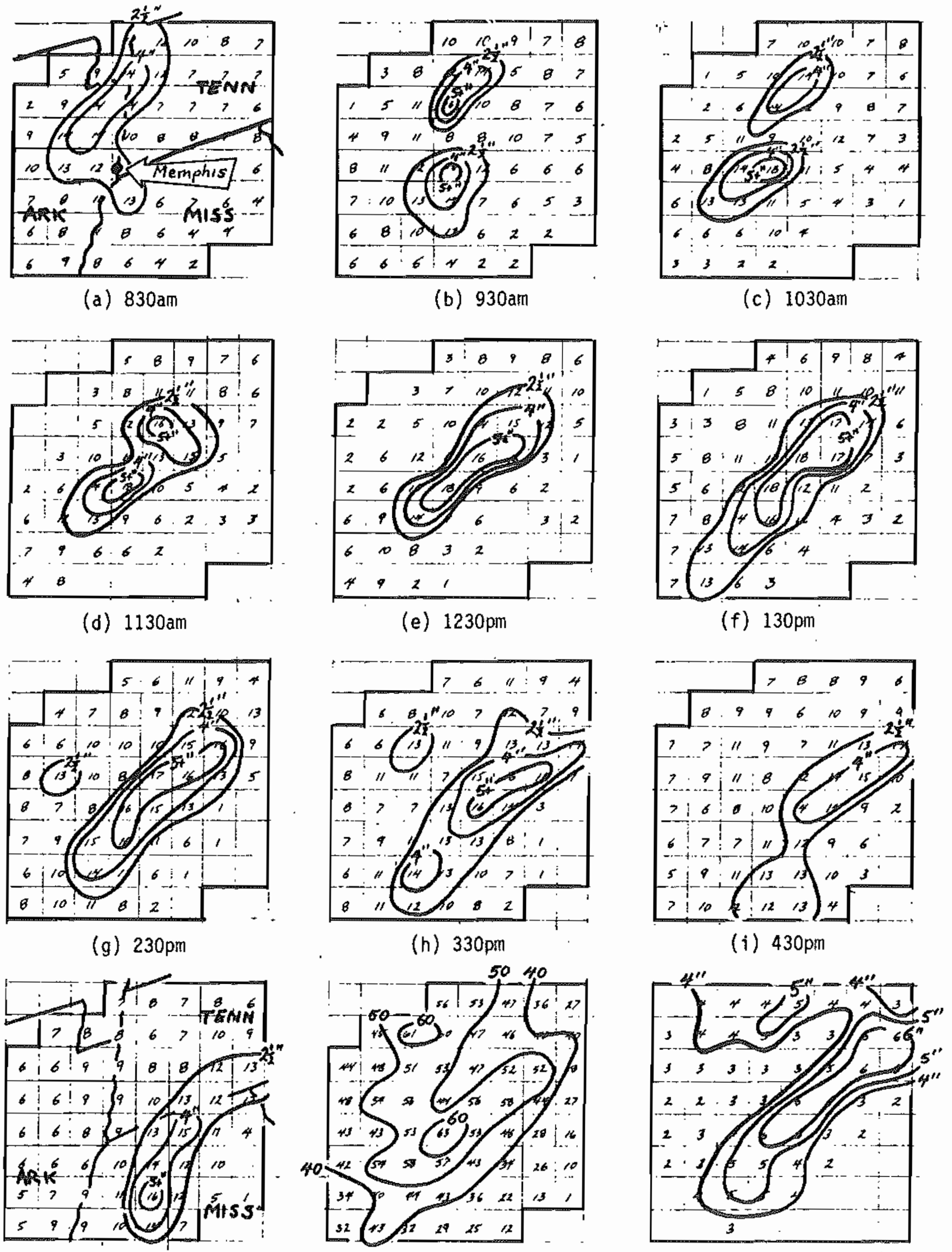
FURTHER STATEMENTS WILL BE ISSUED AS NEEDED.
```

Figure 10. Hourly R/R MDR plots and Special Weather Statement from WSFO Memphis. Memphis MDR square is boxed.

Special Weather Statement issued by the WSFO at Memphis; one of several which recognized quite early the threat of local flooding. It is probable that forecasters chose to use such statements in lieu of a Flash Flood Watch because widespread heavy rains were not anticipated with the fast-moving system.

Fig. 11 shows an hour-by-hour series of three-hour MDR sums for the area of interest. Using Fig. 6 the three-hourly sums can be converted to rainfall amounts at any chosen probabilistic level. We have used the 50% "most likely maximum" value so the analyses show the most likely maximum rainfall which has fallen <u>somewhere</u> in each square during the three-hour period ending at the time shown on each figure. The final figures in the series show the storm total MDR sums and the measured rainfall, averaged to the extent possible in each MDR square. Maximum rainfall measurements in this storm were about 8 in, generally heaviest in the Memphis area. Serious problems were presented by extensive urban flooding but there were no fatalities.

When presented as in Fig. 11 the MDR data reveal interesting characteristics. Notice that while individual thunderstorm cells moved rapidly toward the northeast the heavy rain "threat" advanced steadily and much more slowly (~5-10 kts) toward the east-southeast! RFC flash flood guidance rainfall rates for Western Tennessee on December 3rd were as low as 2-3 in/3 hr in some zones so the possible three-hour rainfall maxima shown in the figures represent a significant threat. The time-continuity of the rain maxima associated with this system, at least as indicated by the MDR data, provides a valuable forecast tool. A pattern



(a) 830am (b) 930am (c) 1030am

(d) 1130am (e) 1230pm (f) 130pm

(g) 230pm (h) 330pm (i) 430pm

(j) 530pm (k) Storm total MDR (l) Averaged rainfall

Figure 11. (a)-(j) Three-hour MDR sums ending at time shown. Contours at 2.5", 4" and 5+" correspond with "most likely max" rainfall from MDR sums of 12, 14 and 16, respectively. (k) Storm total MDR sums. (l) Storm rainfall averaged to nearest inch in each MDR square. Compare patterns in (k) and (l).

recognition and echo tracking program has been developed for use with MDR data and appears to work well with systems such as this (Smith, 1975). After additional testing this computer routine should become available for local use on the NWS AFOS system.

The hourly analyses in Fig. 11 reveal that the greatest threat of heavy rain occurred in the MDR square containing Memphis. A "most likely" three-hour maximum rainfall in excess of five inches was indicated each hour from 930am until 230pm and some 4-hour totals indicated an 80% probability of 3 inches or more.

Indeed, the Memphis square seems to have received the heaviest rainfall, in agreement with the location of maximum MDR totals for the storm. However, the pattern correlation of storm total MDR and averaged rainfall is not as good as has been observed in some other heavy rain cases. Part of the problem might be that rainfall observations do not adequately portray the distribution of heavy amounts. Having a rain gage at the location of the maximum rainfall would be fortuitous. Even with data obtained after the fact it is not possible to be certain of the maximum in some grid squares. However, it appears in this case that the poor correlation more likely is attributable to the speed of cell movement. Except in the region of the elongated maximum, the rain evidently fell in only a few hours. As noted in section 4a, one should not be surprised at poor correlation between point rainfall and MDR sums over short time intervals.

In assessing the threat indicated by the hourly analyses in Fig. 11, the forecaster should bear in mind the qualifications placed on the MDR/rainfall nomogram: in unusually fast-moving systems MDR sums are likely to overestimate the rainfall potential. In such instances knowledge of individual cell movements and assessment of the "train echo" effect of multiple cells over the same location can sharpen estimates of rainfall.

5. Hydrologic Applications of MDR Data

While short-period sums of MDR digits have proven useful for flash flood forecasting, the Fort Worth RFC has developed procedures for utilizing slightly longer-period sums in their routine river forecast procedures. Based on their experience these MDR applications are being expanded to other RFCs. Six-hour MDR accumulations - for periods matching the standard data collection times (00-06 GMT, 06-12 GMT, etc.) - are generated by NOAA computers in Suitland, MD for the MDR grid shown in Fig. 3. The RFCs extract for their use the digit sums from those portions of the national grid which cover their areas of responsibility.

The RFCs have shown that MDR data are useful in four ways:

1. The data allow determination, with reasonable certainty, of where it did <u>not</u> rain during the six-hour summation period.
2. The areal pattern of storm coverage can be quickly determined for the RFC area of responsibility.
3. Substation rainfall reports, available usually for 24-hour periods, can be partitioned into six-hour periods by using established distribution ratios from six-hourly MDR sums.
4. Estimates of rainfall amount can be made from MDR probability nomograms.

Note that a (probabilistic) estimate of rainfall amount is only one of many uses of MDR data in an RFC. It is interesting to note that the number of MDR grid squares, at least in some areas, is many times greater than the number of realtime substation observations available to the RFC on any given day. Often an MDR observation represents the only information from a data-sparse region.

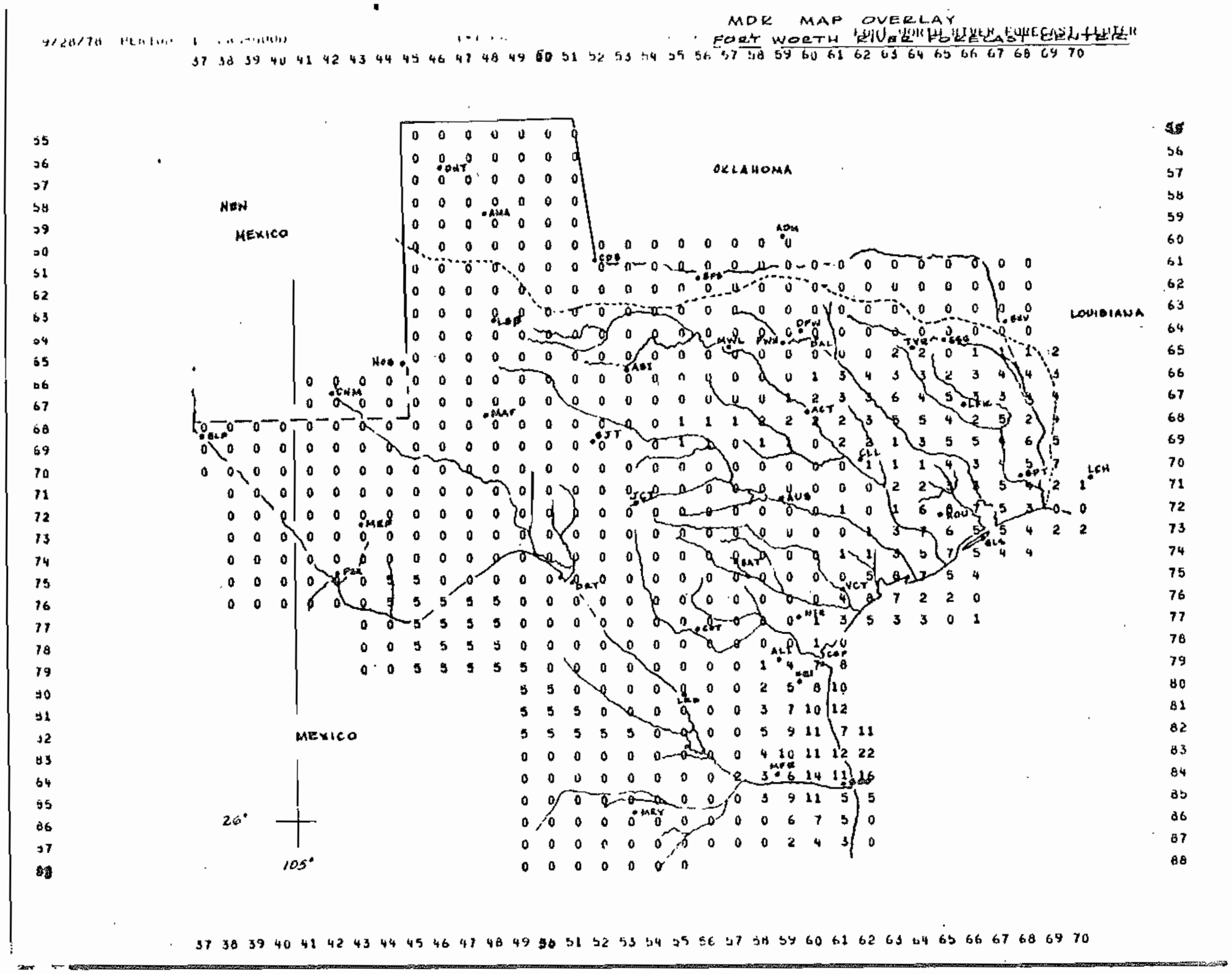


Figure 12. Six-hour MDR sum, with overlay, produced by RFC, Ft. Worth.

Fig. 12 shows an example of a six-hour MDR plot computer-generated by the RFC. A plastic overlay with rivers and boundaries facilitates interpretation. An important feature of the map is that a complete radar picture of rainfall in the entire RFC area of responsibility is available soon after the end of each six-hour period. The plot eliminates the frequently agonizing wait for substation rainfall reports to filter in, thus defining the magnitude and areal extent of the event.

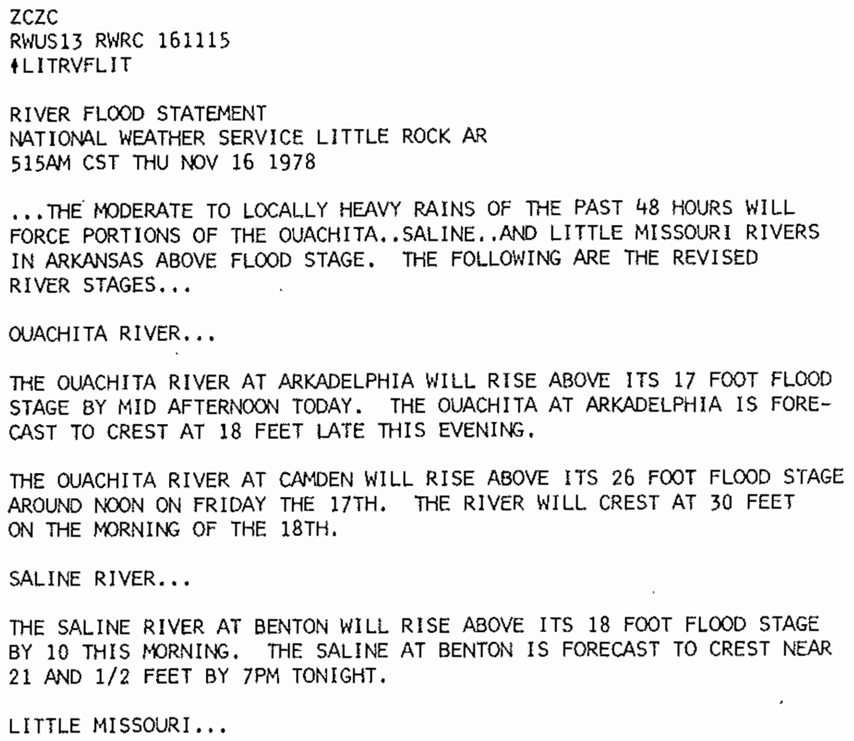
By contouring a specific MDR sum value on successive six-hourly plots the motion can be noted. This can be useful in RFC/WSFO discussions and in evaluating the basis and implications of the meteorological forecast. Actions hinging on expected movement of a rain system may include notifying observers and public officials in the area it is approaching and alerting RFC staff to impending schedule changes.

The Fort Worth RFC has modified its rainfall-runoff program to incorporate, at the discretion of the hydrologist, three levels of MDR utilization. To accomplish this, centers of MDR squares have been assigned a grid point address and data are manipulated by the rainfall-runoff program just as any other rainfall observation. MDR rainfall estimates are assumed applicable at the centers of the grid squares. Once MDR sums are available the river forecaster may exercise one of three options:

a. Ignore MDR data completely.
b. Utilize MDR data to define points having no rainfall and to distribute, from the six-hour MDR summations, the substation 24-hour rainfall reports which have been received. The values of this option lie in shaping the rainfall pattern by the "zero MDR summations" and in filling gaps left by missing rainfall observations. Experience has shown that average basin rainfall amounts are affected only in data sparse areas of the hydrologic network; MDR data do not adversely affect known rainfall amounts.
c. Estimate rainfall amounts from MDR sums and use the amounts as any other observations. A modified version of the flash flood nomogram (Fig. 6) is used and the forecaster preselects an MDR/rainfall probability value of 30%, 50% or 70% for use in the conversion. Use of the 30% option produces the greatest amount of rainfall from the MDR summation; 70% the least amount (See Section 4a).

Building on Fort Worth's experience, the Slidell RFC on the morning of November 16, 1978, achieved a notable milestone in their operations: issuance of river flood forecasts based almost entirely on MDR data alone. Fig. 13 shows a portion of the Little Rock WSFO River Flood Statement written from RFC forecasts prepared about 4am (CST). Had the hydrologists waited for substation rainfall observations before making their forecasts - a normal requirement, of course - the forecasts would have been delayed about six hours! In fact, when the observations became available it was seen that the radar/rainfall estimates were extremely accurate and forecasts required only slight modification to account for isolated centers of heavy rain.

Slidell's achievement was based largely on their careful assignment of a MDR/rainfall conversion factor. Comparison of MDR sums and reported rainfall on the previous day revealed that a "conversion probability" of about 40% was called for with the on-going weather system (rain from widespread frontal over-running with embedded thunderstorms). Having applied meteorological reasoning to diagnose the weather system (see Section 3) the forecaster was able to "fine tune" MDR-rainfall estimates with the few first order rainfall observations available in the early morning hours of the following day and make a remarkably accurate - and early - forecast during a significant rain episode.



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RIVER FLOOD STATEMENT
NATIONAL WEATHER SERVICE LITTLE ROCK AR
515AM CST THU NOV 16 1978

...THE MODERATE TO LOCALLY HEAVY RAINS OF THE PAST 48 HOURS WILL
FORCE PORTIONS OF THE OUACHITA..SALINE..AND LITTLE MISSOURI RIVERS
IN ARKANSAS ABOVE FLOOD STAGE.  THE FOLLOWING ARE THE REVISED
RIVER STAGES...

OUACHITA RIVER...

THE OUACHITA RIVER AT ARKADELPHIA WILL RISE ABOVE ITS 17 FOOT FLOOD
STAGE BY MID AFTERNOON TODAY.  THE OUACHITA AT ARKADELPHIA IS FORE-
CAST TO CREST AT 18 FEET LATE THIS EVENING.

THE OUACHITA RIVER AT CAMDEN WILL RISE ABOVE ITS 26 FOOT FLOOD STAGE
AROUND NOON ON FRIDAY THE 17TH.  THE RIVER WILL CREST AT 30 FEET
ON THE MORNING OF THE 18TH.

SALINE RIVER...

THE SALINE RIVER AT BENTON WILL RISE ABOVE ITS 18 FOOT FLOOD STAGE
BY 10 THIS MORNING.  THE SALINE AT BENTON IS FORECAST TO CREST NEAR
21 AND 1/2 FEET BY 7PM TONIGHT.

LITTLE MISSOURI...
```

Figure 13. Portion of Little Rock river flood statement based on Slidell RFC guidance. The guidance was, in turn, based on MDR indications of rainfall.

6. Conclusion

The implementation of the manually digitized radar program has led to a wide variety of applications of the data and has greatly increased the utilization of radars involved in the program. In this publication considerable emphasis has been placed on hydrologic applications, in large part because of the urgency of the flash flood problem and the relative sparsity of other real-time precipitation data. Other uses and benefits cover a broad range. MDR data have been shown to be useful in updating probability of precipitation forecasts (Moore and Smith 1972, Peters and Barnes 1973). The automated MDR echo tracking and extrapolation program should be even more accurate with the newer data. Reap and Foster (1977) and Charba (1977) use MDR data in their statistical techniques for forecasting thunderstorms and severe local storms. Lewis, et al. (1978) examined the potential of the data for automated flash flood alerting.

Computer compatibility of the data has made it possible to format, display, and archive it for transmission and briefing, development of synoptic climatologies of radar echoes, and quality control of radar information. Use in initial moisture analysis for numerical models is a potential application. New displays which combine satellite and digital information have been proposed as useful forecast aids. Finally, techniques and procedures which are developed with MDR data will be adaptable to the NWS automated radar system which will be installed during the early 1980's.

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