2. An Investigation of Rainfall Estimates Generated by the WSR-88D PPS Algorithm under Various Parameterizations of the 'Z-R' Relationship and 'Hail Cap' Threshold During Two Extremely Heavy 1998 South Texas Precipitation Events

2.1 Introduction

Within a 60 day period from the late summer to early fall of 1998, South Texas (see Fig. 2.0) experienced two extremely heavy precipitation events which produced widespread flooding, flash flooding and loss of life. During both events, ambient environmental conditions were markedly "tropical" in nature, as characterized by a warm, deep, nearly saturated low-level airmass, and were sustained for long time periods (see Figs. 2.1A and 2.1O). What's more, the presence or influence of a tropical storm appears to have played a major role in both instances. The first event was triggered by a tropical storm ("Charlie") and its remnants as it slowly drifted westward across South Texas, affecting the region from August 21-24 (see Fig. 2.2A). It generated local rainfall amounts in excess of 18" (NOAA/NWS, 1998-1). The second event was caused by a nearly stationary, long wave trough that channeled deep, tropical moisture into southern Texas from a faraway Pacific hurricane ("Madeline") located off the tip of Baja, Mexico (see Fig. 2.2O). During the period October 17-19, this combination of circumstances produced phenomenal local rainfall accumulations in excess of 30" in the region (NOAA/NWS, 1998-2). Such occurrences are hardly rare in the area, with single-event rainfall totals in excess of 30 inches having been recorded at least nine times in the past century[1]. Indeed, the region presently holds the continental U.S. record for 24-hour rainfall - i.e., 43 inches, on 25-26 July, 1979 in Alvin, Texas (about 20 miles south of Houston) (Smith et al, 2000).

When the WSR-88D Precipitation Processing System (PPS) algorithm (Fulton et al, 1998) was originally run in real time at the WFOs in the vicinity of the heaviest precipitation, rainfall totals were significantly underestimated. For example, during the October event, the radars at New Braunfels (KEWX) and Ft. Hood - Granger (KGRK) underestimated rainfall amounts by about a factor of two, even after switching to the NEXRAD (Rosenfeld) Tropical Z-R relationship part way into the event, prompting speculation that even that tropical relationship may be inadequate for such situations[2]. These results were very similar to those found during another extreme rainfall event of tropical origin in October '94 (Smith et al, 2000). Concern about the performance of the WSR-88D algorithm during these "super tropical" events prompted the Hydrologist In Charge of the West Gulf RFC (Dave Morris) to suggest to the Director of the National Weather Service (Jack Kelly) that the matter warranted research on a time-critical basis[3].

2.2 Data Availability

In order to follow up on these preliminary findings and assess the performance of the WSR-88D algorithm during situations characterized by prolonged availability of deep, tropical moisture, the PPS was rerun from Archive II playback and compared against rain gage data as "ground truth" while specific parameters pertinent to rainfall rate and accumulation were varied. Unfortunately, Archive II data records were either sporadic or completely unavailable from the sites that would have best captured the locales of the heaviest accumulation. These included New Braunfels (between San Antonio and Austin), Ft. Hood - Granger (near Waco) and Laughlin AFB (KDFX) (near Del Rio) for both events! This somewhat compromised the potential for achieving optimum benefit from the study. Consistent data records were available, however, from sites which either captured a good portion of the precipitation from one of the events (though perhaps not the specific regions with the heaviest accumulation), or captured the heaviest accumulation from afar. These included Houston (KHGX) for both incidents, San Angelo (KSJT) for the August event and Corpus Christi (KCRP) for the October event (see Fig. 2.0).

Rain Gage data were obtained directly from the West Gulf RFC. These included automated, hourly reports and 24-hour "co-op" reports. Both the automated reports ending at "clock-hourly" times and the co-op reports covering 12 UTC - 12 UTC periods were used (independently) in the analyses, as explained below.

2.3 Methodology

2.3.1 Variation of PPS Parameters

From those radars where Archive II data were available, comparative runs from replay were performed while primarily varying the parameters of the Reflectivity-to-Rainfall Rate relationship (i.e., $Z = aR^b$, where Z is reflectivity power in mm^6/m^3; R is rainfall rate in mm/hr; a is the "multiplicative coefficient"; and b is the "power coefficient"). Particularly, the sanctioned WSR-88D Default or Convective (i.e., $Z = 300R^{1.4}$) and Rosenfeld Tropical (i.e., $Z = 250R^{1.2}$) versions were used in each case. Most simulations were performed with the Maximum Precipitation Rate or "Hail Cap" threshold maintained at the default WSR-88D value of 103.8 mm/hr (~4"/hr). This rate corresponds to an equivalent reflectivity of 53 dBZ (where $dBZ = 10 \log_{10}Z$) based upon the Default Z-R relationship and predicated on the assumption that derived precipitation rates higher than this are likely due to the impingement of the radar beam upon hail. With the Tropical Z-R relationship, however, the same rainfall rate corresponds to only ~48 dBZ. If one were, instead, to base the "Hail Cap" on the reflectivity value of 53 dBZ rather than the rain rate of 4"/hr, the upper-threshold rainfall rate would jump to 262.0 mm/hr (~10.3"/hr). On the assumption that only "warm rain" processes were occurring, one simulation was performed for each of the August and October events with the Z-R relationship set to the Tropical version and with the Hail Cap raised to the value consistent with it at 53 dBZ.

In some instances, additional runs were performed from an experimental Z-R relationship based upon the Tropical version, as well. These relationships were dubbed "Best Z-R" because they were formulated, from hindsight, after the Bias (   ) was determined (see below), with the intent of achieving a 1:1 correspondence, in the mean, between rain gage and radar accumulations. Using a strategy of maintaining the power coefficient (b) but modifying the multiplicative coefficient (a), the revised version of the 'a' coefficient (a_{rev}) was determined from:

$$a_{rev} = \quad ^{-b}\, a$$

where ‘a’ and ‘b’ are the WSR-88D Tropical values (i.e., 250; 1.2). The “Best Z-R” relationship for a particular case would thus consist of a_{rev} and the Tropical version of ‘b’.

2.3.2 Gage-Radar Comparisons and Verification

The simulations were performed for varying, multi-hourly periods corresponding roughly to the subjectively-defined “heart” of each event. In each instance, two types of analyses were undertaken: one in which radar estimates at sample bins co-located with rain gages were compared against the Hourly (automated) gage reports; the other, likewise, against the 24-hour (Co-op) reports. For the Hourly analysis, all qualifying Gage-Radar Pairs (“G-R Pairs”) found at each of the individual “clock hours” during the multi-hour simulation were lumped together, equivalently, into one pool. For the 24-hour analysis, G-R Pairs were determined for standard, 12 UTC - 12 UTC reporting periods. For most simulations, one 24-hour analysis was performed; in a couple of instances, the duration of the significant precipitation event was sufficient to enable two such analyses to be undertaken.

The performance of each simulation was measured in terms of the multiplicative, mean-field ‘Bias’ ( ), computed very simply from:

$$= \quad Gi \, / \quad Ri$$

where the only qualification for a G-R Pair was that both had to register non-zero precipitation. No compensation for range was attempted, nor was any consideration given to stratifying the reports based on the freezing level, and only the most rudimentary quality control was performed (i.e., just a few visibly erroneous gage values were removed).

The manner in which the Multi-Hour G-R analyses were perfomed (see above) gives some inference into the performance of all the hourly-based WSR-88D accumulation products, including the graphical products (i.e., One Hour Precip (OHP); Three Hour Precip (THP); User-Selectable Precip (USP)) and the 256-level Hourly Digital Precipitation Array (DPA) product used as the basis for many operational procedures at Weather Forecast Offices (WFOs) and River Forecast Centers (RFCs). The 24-hour analyses give a better suggestion of the long-term Bias and are indicative of the performance of the Storm Total Precipitation (STP) product[4].

In addition to the Bias, several other statistical measures of the performance of the PPS algorithm were determined for each simulation, including the No. of G-R Pairs, the Mean Gage and Mean Radar Accumulation values, the Standard Deviation and Variance of each, their Covariance and Cross Correlation Coefficient, and the RMS Error.

2.4 Test Cases

The August event was assessed from the Houston (KHGX) and San Angelo (KSJT) radars. The Houston simulations covered the early portion of the event, as bands of the tropical storm moved onto the Southeast Texas coast from the Gulf. The San Angelo simulations covered the event for a later period, as the storm continued to move inland from east to west.

The October event was assessed from the Houston (KHGX) and Corpus Christi (KCRP) radars for approximately the same time period, as Archive II data from further west, which would have captured the earlier evolution of events, were unavailable.

2.4.1 Houston Simulations, August 21-24 1998 Event

Simulations from KHGX for the August event were performed with the Default and Tropical Z-R relationships (only) from approximately 8/21 12 UTC - 8/23 00 UTC. Since the rainfall moved inland from the Gulf of Mexico and did not occur over reporting gages for about the first six hours of the rerun, the effective period during which the One-hour G-R pairs were evaluated was ~8/21 18 UTC - 8/23 00 UTC (~30 hours). 24-hour analyses were performed ostensibly for ~8/21 12 UTC - 8/22 12 UTC, although the gage and radar accumulations really covered only the final ~18 hours of this period.

A synopsis of the evolution of the event can be seen in Figure 2.3A.H, which shows level 1 Base Reflectivity images every 6 hours. An overview of some of the key results for the Default Z-R test run, in the form of a multi-panel image, is shown in Figure 2.4.A.H. (In this and other overview figures, the left column contains results for the Hourly G-R analysis through the duration of the event; the right column contains results for the 24-hour G-R analysis for the standard 12 UTC - 12 UTC period shown. The first row in each column displays a WSR-88D accumulation image with geography and rain gage data for the analogous period overlaid: on the left-hand side, the accumulation image is an OHP product for an hour which typifies the event; on the right-hand side, the accumulation image is an STP product for the standard, 24-hour period. The second row in each column displays a scatter diagram of Gage (X-axis) vs. Radar (Y-axis) values. The third row shows the Bias and related fields (i.e., No. G-R Pairs; Avg. Gage value; Avg. Radar value) as a function of range in the form of bar diagrams. (Note that the scales and values shown on the left and right ordinates differ in the one and 24-hour representations.) The fourth row shows tables summarizing key statistics for each of the one and 24-hour G-R analyses. All accumulation values in all panels are in mm.) A similar overview of the key results for the Tropical Z-R test run is shown in Figure 2.5A.H.

2.4.2 San Angelo Simulations, August 21-24 1998 Event

Inland rainfall on the second and third days was long lasting as well as excessive, peaking in an area south of the KSJT radar toward Del Rio, near the Mexican border. One-hour analyses were performed for the ~60 hour period 8/22 12 UTC - 8/25 00 UTC; 24-hour assessments were performed for each of the periods ending 8/23 12 UTC and 8/24 12 UTC. In addition to the Default and Tropical Z-R relationships, a simulation was performed with the Hail Cap raised (and Z-R parameters set to Tropical values, as described in Section 2.3.1).

Analogously to the Houston cases, Fig. 2.3A.S provides an overview of the event by showing Base Reflectivity images every 6 hours, Fig. 2.4A.S provides an overview of key results in the form of a multi-panel display for the Default Z-R run and Fig. 2.5A.S does likewise for the Tropical Z-R run. Additionally, results are shown for the run with the raised Hail Cap in Fig.

2.6A.S (also in the form of a multi-panel display, but here showing only the accumulation images with gage data overlaid and the summary-statistics tables for the Hourly and 24-hour G-R analyses). Of the two 24-hour periods, only the results for the first one (i.e., ending 8/23 12 UTC) are shown, in the right-hand column.

2.4.3 Houston Simulations, October 17-19 1998 Event

The Houston simulations for the October event were performed for the ~36 hour period 10/17 12 UTC - 10/19 00 UTC; 24-hour analyses for the period ending 10/18 12 UTC. Again, runs were performed with the Z-R parameters set to the Default and Tropical values and also with the Hail Cap raised. Furthermore, a simulation was performed with an experimental "Best" Z-R after assessment of the results of the run with the Tropical Z-R relationship, as described in Section 2.3.1.

Once more, Base Reflectivity images are shown every 6 hours (Fig. 2.3O.H) and overviews of key results are shown in multi-panel format for the Default Z-R, Tropical Z-R, Hail Cap-raised, and "Best Z-R" simulations in Figs. 2.4O.H to 2.7O.H, respectively.

2.4.4 Corpus Christi Simulations, October 17-19 1998 Event

The KCRP radar captured the October event for a similar time period as the KHGX radar (though from further away), thus offering an opportunity for corroboration. One-hour analyses were performed for the ~32 hour period 10/17 12 UTC - 10/18 20 UTC; 24-hour analyses for the period ending 10/18 12 UTC. Runs were performed with the Z-R parameters set to the Default and Tropical values, only.

Base Reflectivity images every six hours, and multi-panel overviews of key results for the Default and Tropical Z-R runs are shown in Figures 2.3O.C to 2.5O.C, respectively.

2.5 Evaluation of Results

2.5.1 Default Z-R Simulations

The results of the various simulations with the Default Z-R relationship (and the Hail Cap maintained at its default value) are shown in Figs. 2.4A.H, 2.4A.S, 2.4O.H and 2.4O.C for HGX (August event), SJT (August), HGX (October) and CRP (October), respectively. As anticipated, rainfall estimates are significantly underestimated in all instances, with Bias values ranging from 2.09 to 3.06 in the four G-R analyses of the August event and ranging even higher, from 2.87 to 3.55, in the four analyses of the October event. RMS errors are seen to be consistently high compared to the mean gage and mean radar values, indicative of the substantial differences between them. Correlation Coefficients are in all instances higher in the 24-hour analyses than in the one-hour analyses, reflective of the longer term over which they are determined and perhaps indicating that more confidence can be placed in the 24-hour results. Indeed, in the one-hour G-R analyses, instances of measurable gage values matched with null radar values in the G-R Pairs tables were commonly observed (not shown). It is also noted that in all but one of the test cases, the hourly-report evaluations yielded higher biases than the 24-hour evaluations (often significantly higher).

In the depictions of Bias and related fields vs. Range (in the form of bar diagrams), a consistent pattern of biases (yellow bars) rising at farther ranges (due to radar values (turquoise bars) falling) is not particularly observed. Generally speaking, radar and rain gage values (blue bars) are seen to change in a similar manner as a function of range. In two of the four test cases (i.e., KSJT/August and KCRP/October), the heaviest rainfalls occurred far away from the radar, causing radar as well as gage values to increase with distance. In the two KHGX cases, where rainfall was more evenly distributed with distance, gage values generally decreased from 140 km on out, offsetting a general decrease at the same ranges in the radar values. Furthermore, biases were not generally observed to be at a minimum (radar values at a maximum) at mid ranges, as commonly cited in case studies of continental-convective rainfall events (Smith and Krajewski, 1995). These findings would suggest that freezing level effects were not an issue in these two South Texas extreme rainfall events, and that warm rain processes predominated.

2.5.2 Tropical Z-R Simulations

The results of the various simulations with the Tropical Z-R relationship (and the Hail Cap maintained at its default value) are shown in Figs. 2.5A.H, 2.5A.S, 2.5O.H and 2.5O.C. In all the one-hour and 24-hour precip products, radar accumulations are noticeably enhanced compared to the analogous Default Z-R images. The biases are considerably reduced in all instances but are still greater than unity, indicating continued underestimation by the NEXRAD algorithm. Bias values now range from 1.13 to 1.59 in the four G-R analyses of the August event and from 1.38 to 1.81 in the analyses of the October event.

RMS errors are consistently reduced compared to the Default Z-R simulations as well. This is particularly true in the 24-hour evaluations, where RMS errors are lowered by 22.7% to 37.2%. In the Hourly evaluations, the RMS error actually increases slightly in one instance (+2.0%) and in the other three instances, it is down from 5.6% to 25.6%. The more modest reductions here are likely due to a phenomenon observed in the Hourly G-R tables: due to the enhanced rainfall rates of the Tropical Z-R formulation, many more radar sample bins are able to register measurable precipitation at the effective precision of the PPS algorithm (i.e., ~1 mm/hr) and thus qualify as members of G-R Pairs. Of the four test cases, the number of qualifying one-hourly G-R reports rises from 9.6% to 14.8%. Since the added G-R Pairs are in light precipitation regions, however, they cause the Mean Gage values to be reduced slightly, and they diminish the amount by which the Mean Radar values are increased, compared to the analogous Default Z-R runs. In the 24-hour evaluations, this phenomenon was not observed to the same degree, due to the longer accumulation period. Only an average of one G-R pair was added per simulation (up 2.3%). Correlation coefficients, on the other hand, improved more in the one-hour analyses than in the 24-hour analyses when going from the Default to the Tropical Z-R relationships.

2.5.3 Raised Hail Cap Simulations

To further explore the impact of converting to a Tropical parameterization of the PPS algorithm, two of the four case studies (i.e., August/STJ and October/HGX) were rerun with the Z-R parameters retained at their Tropical settings (as in Section 2.5.2) but with the 'Hail Cap' threshold raised to the value consistent with the rainfall rate at 53 dBZ at those settings (i.e., 262.0 mm/hr, as explained in Section 2.3.1). The results are shown in Figures 2.6A.S and 2.6O.H, respectively[5]. Compared to the runs with the Tropical Z-R settings but the Default Hail Cap (i.e., Figs. 2.5A.S and 2.5O.H), the results are essentially similar except in the vicinity of precipitation cores. In the August/SJT comparisons, the differences are almost indiscernible in the one and 24-hour accumulation images. Biases are reduced, but infinitesimally (i.e., only when measured to the third decimal point). In the October/HGX comparisons, accumulations in the core regions are, on close examination, seen to be enhanced. Biases are reduced very slightly, from 1.81 to 1.79 in the one-hour G-R analysis and from 1.62 to 1.57 in the 24-hour analysis. RMS errors are also reduced slightly, from 11.48 to 11.43 in the one-hour analysis and from 73.09 to 71.65 in the 24-hour analysis. However, these statistics and the visual results at the resolution of the (16-level) accumulation products somewhat belie the impact of raising the Hail Cap. In the 24-hour October/HGX STP products, the maximum accumulation rises from 331 to 414 mm. This could have significant implications for the potential for flooding in small, localized basin regions that happen to be affected.

2.5.4 'Best Z-R' Simulation

Using the formula and the strategy discussed in Section 2.3.1 (above) for determining a "Best Z-R" based on the Tropical relationship, 'a_{rev}' was determined after the fact for each of the Tropical Z-R simulations (i.e., based on 'a' = 250; 'b' = 1.2). For the October/HGX case, the results were as follows: multi-hour analysis (36 hour duration): a_{rev} = 122.67; first 24-hour analysis: a_{rev} = 140.13; second 24-hour analysis: a_{rev} = 130.41. Based on these results, a mean value of 130 was selected for a_{rev} and the October/HGX simulation was rerun (i.e., with "Best Z-R" of 'a' = 130; 'b' = 1.2)[6]. Results are shown in Fig. 2.7O.H

As seen in comparison to Fig. 2.5O.H for the Tropical Z-R case, radar-estimated accumulations are significantly enhanced. Biases are now very close to unity (i.e., 1.06 for the multi-hourly G-R evaluation; 0.95 for the 24-hour evaluation). RMS errors are again reduced significantly (by 13% to 14% in the two evaluations), though correlation coefficients are virtually unchanged. One phenomenon again observed (as when switching from the "Default" to the "Tropical" Z-R relationships) was that substantially more G-R pairs qualified in the multi-hourly analysis, due to the fact that the enhanced rainfall rates of the "Best Z-R" relationship allowed several sample bins formerly registering zero to now register measurable accumulation at the timescale of an hour. With this "Best Z-R" simulation, 11.3% more hourly G-R pairs now qualified than in the run with the Tropical Z-R parameters; 27.8% more than the run with the Default parameters.

Although these results from hindsight were the best yet for this particular case, it is difficult to find one specific value of 'a_{rev}' that would have given optimal results for all the cases studied, simultaneously. For the two October/CRP analyses, a choice of a_{rev} = 170 would have been best; for August/HGX (both one and 24-hour evaluations) and for the 24-hour August/SJT evaluations, a_{rev} = 200 would have been a good, median choice; but for the one-hour August/SJT analysis, a selection of a_{rev} = 140 would have been more appropriate.

2.6 Summary and Conclusions

The performance of the WSR-88D operational PPS algorithm during two 1998 South Texas extreme rainfall events marked by sustained tropical environmental conditions was assessed by varying parameters of the "Z-R" relationship and "Hail Cap" threshold while replaying the cases from Archive II Base Reflectivity data. Evaluations were performed at two sites for each event. Accumulation estimates generated by the algorithm for one and 24-hour periods were compared, independently, against one-hour (automated) and 24-hour (co-op) gage reports for the same periods. For each event at each site, simulations were performed with the WSR-88D 'Default' and 'Tropical' settings of the Z-R parameters while the 'Hail Cap' threshold was maintained at its default value. At one site for each event, an additional run was performed with the Tropical Z-R settings and with the 'Hail Cap' threshold set to a much higher value consistent with the rainfall rate at 53 dBZ with the Tropical relationship. Finally, an attempt was made to determine a revised, "Best Z-R" relationship (based on the Tropical) that may be appropriate for these and other "super tropical" rainfall events. For one of the test cases (i.e., October 17-19 from the Houston radar), another simulation was performed based on such a relationship (and the default setting of the 'Hail Cap') in order to assess its performance, quantitatively and statistically, against the others.

The principal findings of the investigation are as follows:

- The Default Z-R relationship significantly underestimated radar accumulations in all cases, yielding biases ~(2.0 - 3.6).
- The Tropical relationship substantially improved estimates and lowered RMS errors but still underestimated accumulations in all cases, resulting in biases ~(1.1 - 1.8).
- Of the two cases, the PPS algorithm underestimated rainfall more so (i.e., biases were higher) in the October event than in the August event.
- Radar vs. gage accumulations did not show a marked tendency to decrease at far ranges nor to peak at mid ranges, hinting at the absence of freezing level effects/ presence of warm rain processes being at play during these events.
- Biases were generally higher in the analyses of the one-hour G-R pairs than the 24-hour for the same cases, indicating either a systematic difference in the reporting characteristics of the automated vs. co-op gages or between the manner in which accumulations are determined in the Hourly-based vs. Storm Total products in the PPS code.
- In runs with the Default Z-R parameters, it was frequently found that measurable, one-hour rain gage accumulations were collocated with radar sample bins registering zero hourly accumulation. When rerun with the Tropical Z-R settings, the number of radar sample bins with measurable hourly accumulation and hence,

the number of qualifying G-R pairs, increased by ~10% - 15%; when run with "Best Z-R" settings, a similar increase was again realized.

- In test runs with the Hail Cap raised and the Tropical version of the Z-R relationship (vs. the default Hail Cap and Tropical Z-R settings), the results were essentially similar except in the vicinity of precipitation cores, where some fairly significant increases were observed in some instances (e.g., max 24-hour precip rose from 331 to 414 mm in one case). Otherwise, the analogous products of the two simulations were almost indistinguishable, and little difference was seen in the statistical fields tracked (e.g., bias; RMS error; etc.)
- In the test case rerun with the retroactively-determined "Best Z-R" relationship, biases were close to unity in the analyses of both one-hourly and 24-hourly gage-radar pairs, RMS errors were reduced and the number of qualifying, one-hourly G-R Pairs was increased (compared to the analogous Tropical Z-R simulation).
- Despite the superior results obtained when running with a retroactively-determined "Best Z-R" relationship, the parameters that would have yielded the "Best" results were somewhat different in each case evaluated, and the number of cases studied was limited. Therefore, it would be difficult to suggest one alternative, "Super Tropical" Z-R relationship for possible operational use in events such as those studied here based solely on these results. On the other hand, it is noted that an alternative version of the Tropical Z-R relationship with parameters (a=200; b=1.2) would have yielded superior results to the sanctioned, WSR-88D Tropical relationship (a=250; b=1.2) in all instances evaluated.

[1] Informal count from highlights of historical South Texas floods provided by John Patton, (then) Service Hydrologist, WFO Austin/San Antonio, TX

[2] Contemporaneous communications involving staff members of West Gulf RFC, NWS Headquarters and Office of Hydrology/Hydrologic Research Lab staffs

[3] Handwritten note, Dave Morris to Jack Kelly, February 1999, a copy of which was provided to OH/HRL

[4] The hourly-based and storm total product-types are formulated independently in the PPS code, and some differences have been reported between them for similar accumulation periods.

[5] Some diagrams in Figs. 2.6A.S and 2.6O.H not shown because they are virtually indistinguishable from the analogous diagrams in Figs. 2.5A.S and 2.5O.H.

[6] A "Best Z-R" simulation with a_{rev} set to 160 (and b retained at 1.2) was also performed for the October/CRP case but is not discussed here.

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References

Fulton, R., J. Breidenbach, D.-J. Seo, D. Miller and T. O'Bannon, 1998: The WSR-88D Rainfall Algorithm. *Wea. Forecasting,* **13**, 377-395

National Oceanic and Atmospheric Administration, National Weather Service, 1998: Monthly Report of River and Flood Conditions for Hydrologic Service Area Austin/San Antonio. Report for August 1998. (Available from NWS Office of Hydrology, 1325 East-West Hwy., W/OH1, Silver Spring, MD 20910)

______, Report for October 1998.

Smith, J. A. and W. F. Krajewski, 1995: Estimation of Parameters for the NEXRAD Rainfall Algorithms. Submitted as part of the Interagency Memorandum of Understanding among the NEXRAD Program, WSR-88D Operational Support Facility, and the NWS/OH Hydrologic Research Laboratory. (Available from NWS Office of Hydrology, 1325 East-West Hwy., W/OH1, Silver Spring, MD 20910)

______, Baeck, J. E. Morrison and P. Sturdevant-Rees, 2000: Catastrophic Rainfall and Flooding in Texas. *Journal of Hydrometeorology,* **1** (2), 5-25.