Extreme Rainfall Estimation Using Radar for Tropical Storm Allison

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Abstract

Tropical Storm Allison dropped more than 30 inches of rain over metropolitan Houston in June 2001, causing unprecedented flooding and more than $5 billion dollars of damage. Over parts of the city and Harris County, rainfall rates exceeded 3 inches per hour for eight consecutive hours.

Rainfall distributions from rain gages are typically estimated by assuming a spatial geometry tied to point rain gage observations using, for example, Thiessen polygons, inverse distance squared weighting, or statistical Kriging techniques. Unfortunately, the spatial distributions inferred by these approaches have little connection with how rain actually falls. Since the release of the WSR-88D (NEXRAD) radar in the early 1990s, many hydrologists and engineers have begun using gage-adjusted radar rainfall estimates for hydrologic and water resource modeling.

However, due to the extreme nature of the event, traditional radar rainfall estimation methods using uniform bias adjustment techniques severely underestimated the rainfall rates in the heaviest regions of the storm. NEXRAIN created a gage-adjusted radar rainfall dataset using over 150 rain gages and incorporated a spatial adjustment technique developed by Edward Brandes at the National Severe Storms Lab in the mid-1970s.

The radar-rainfall data set used in this project was a mosaic of several WSR-88D radars that cover the Houston area. Slight performance characteristics between the radars caused visible discontinuities at the edges of the individual coverage areas. In addition, an area of underestimation due to the use of higher scan elevations in the immediate vicinity of the Houston radar was noted. A GIS approach was used to reduce or eliminate these spatial discontinuities.

Use of these two techniques greatly improved gage-adjusted radar rainfall estimates of the extreme rainfall while preserving the spatial signature of the radar rainfall distribution.

Introduction

Tropical Storm Allison dropped more than 30 inches of rain over metropolitan Houston in June 2001, causing unprecedented flooding and more than $5 billion dollars of damage and 22 deaths (National Weather Service, 2001). In terms of damages, the storm was the worst tropical storm in U.S. history. The vast majority of the damages occurred in and around Harris County, Texas, where rainfall rates exceeded 3.0 inches per hour (7.6 cm/hr) for eight consecutive hours. Figure 1 shows an example of the devastation: massive flooding at the confluence of Buffalo and White Oak Bayous near downtown Houston on the morning of June 9, 2001.

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Figure 1: Confluence of Buffalo and White Oak Bayous at Main Street near Downtown Houston, morning of June 9, 2001 (photo courtesy of Steve Fitzgerald, Harris County Flood Control District)

To analyze this intense storm, NEXRAIN Corporation used a radar rainfall data set that was a mosaic of several WSR-88D radars that cover the Houston area. Slight performance characteristics between the radars caused visible discontinuities at the edges of the individual coverage areas. In addition, an area of underestimation due to the use of higher scan elevations in the immediate vicinity of the Houston radar was noted. A GIS approach was used to reduce or eliminate these spatial discontinuities.

Due to the extreme nature of the event, traditional radar rainfall estimation methods using uniform bias adjustment techniques severely underestimated the rainfall rates in the heaviest regions of the storm. A gage-adjusted radar rainfall dataset was created using 156 local rain gages and incorporating a spatial adjustment technique developed at the National Severe Storms Lab in the mid-1970s (Brandes, 1975). The use of these two techniques greatly improved the rainfall estimates in area, capturing areas of extreme rainfall while preserving the spatial signature of the radar rainfall distributions.

Gage and Radar Estimated Rainfall Estimates

Traditionally, rainfall distributions are estimated by assuming a spatial geometry tied to point rain gage observations using, for example, Thiessen polygons, inverse distance squared weighting, or statistical Kriging techniques. Unfortunately, the spatial distributions inferred by these approaches have little connection with how rain actually falls. From a modeling perspective, these techniques too often place the wrong rain at the wrong place at the wrong time.

In recent years, improvements in technology have made radar a viable tool to improve the estimation of rainfall between the gages. Radar provides a high resolution view of the variability of rain falling over a region. Unfortunately, radar by itself has not proven to be a consistent estimator of the actual rainfall amounts.

The strength of a rain gage network is its ability to consistently estimate rain falling on a number of discrete points. Its weakness is the network's inability to estimate rain falling between the gages. On the other hand, radar's strength is its ability to see between the gages but radar lacks the consistency in estimating rainfall at a specific point.

By merging rain data from a gage network and rain data derived from radar, hydrologists can take advantage of the strengths of each measurement system while minimizing their respective weaknesses. Essentially, a radar image is used as an areal template for the spatial distribution of rainfall. The rain gage data are used to scale the areal template. The net result is a gage-adjusted radar rainfall data set that combines the spatial distribution characteristics of the radar image with the scaling information from the gages.

Because of the difference in scale of the measuring devices – a rain gage is about 120,000,000 times smaller than a radar pixel – a direct comparison between the two is not always possible. The radar is estimating the average rainfall over the radar pixel, while the rain gage is measuring the rainfall over the gage orifice. Depending on the gage's location within the radar pixel, the rain gage estimate might be higher or lower due to intrapixel variation in rainfall. However, over a large number of gages, one would expect that the average gage rainfall is equal to the average gage-adjusted radar rainfall estimates.

Methodology

Radar rainfall data were extracted from NEXRAIN's archive of 15-minute radar rainfall with a nominal resolution of 2 km x 2 km. Each radar image is a composite prepared using data from all National Weather Service WSR-88D radars covering the study area. Occasionally, visible discontinuities exist between radar coverages because the National Weather Service radars may have slightly different calibrations or performance characteristics. A radar might also measure ground-based objects instead of rainfall, creating anomalously high rainfall estimates known as ground clutter. Using a smoothing procedure developed in ArcView, the locations of ground clutter are suppressed and the discontinuities between radar coverages are eliminated.

Typically, radar rainfall estimates are made using a uniform bias technique. Data from 156 gages - 127 from the Harris County Office of Emergency Management (HCOEM) and 29 from the City of Houston (COH) - were collected and aggregated into 15 minute time-steps to match the timing of the radar rainfall data. Gage data that were inconsistent with nearby gages or were inconsistent with radar rainfall estimates were not used in the analysis. For each of the rain gages used in this study, a time series of gage data and a time series of radar data at the pixel over each of the rain gages were collected. The average gage and radar data (from the radar pixels over the rain gages) were calculated. A gage/radar (G/R) ratio was computed by dividing the average gage rainfall by the average radar rainfall during each time step. The G/R ratios were then multiplied by the raw radar dataset for each time period during the study to determine the gage-adjusted radar rainfall data. This process was repeated for each storm period during the study period.

During Tropical Storm Allison, rainfall rates over Greens Bayou in eastern Harris County exceeded six inches per hour and HCOEM Gage 1600 had over 25 inches (64 cm) of rain over an eight hour period. At high rainfall intensities such as these, the radar is not always able to determine the difference between rainfall and hail and a "reflectively cap" is used (Austin 1987). The reflectively cap will truncate all rainfall intensities above a default threshold to the default rainfall intensity. While the process eliminates overestimation of rainfall during hail events, it can cause underestimation of rainfall during extremely intense rainfalls when high reflectivity values represent "real" rainfall and not hail. Because of this truncation, the uniform adjustment procedure is not always able to characterize intense rainfall cells.

To correct for these potential errors, the authors used a spatial adjustment procedure based upon a theory developed in 1975 (Brandes 1975) and was originally created for adjusting radar data from the WSR-57, a predecessor to the current WSR-88D radar, using rain gages. This process uses gages in the vicinity of a pixel to adjust the rainfall estimate at that pixel. Gages that are closer to the pixel are given more influence than gages that are located further away, up to a default radius. Gages beyond the default radius do not have any influence over the adjustments for the rainfall estimate at that pixel. The process is repeated for each pixel during each time period during the storm event.

The NEXRAIN-Brandes Method warps the radar surface by creating a field of spatially varying adjustment coefficients based upon the local gage and radar data, but does not force the radar estimate to match the gage estimate at each gage location. Figure 2 shows an example of these weights. At a given pixel, a gage that is located 5 km from the center of pixel would be given a relative weight of 0.6, while a gage located 10 km from the center of pixel would be given a relative weight of about 0.15, or about ¼ of the influence of the closer gage. In Figure 2, gages beyond 15 km from a given pixel have no influence of that pixel. This method works well for adjusting radar rainfall estimates over large areas. This method is also able to accurately characterize high intensity rainfall cells.

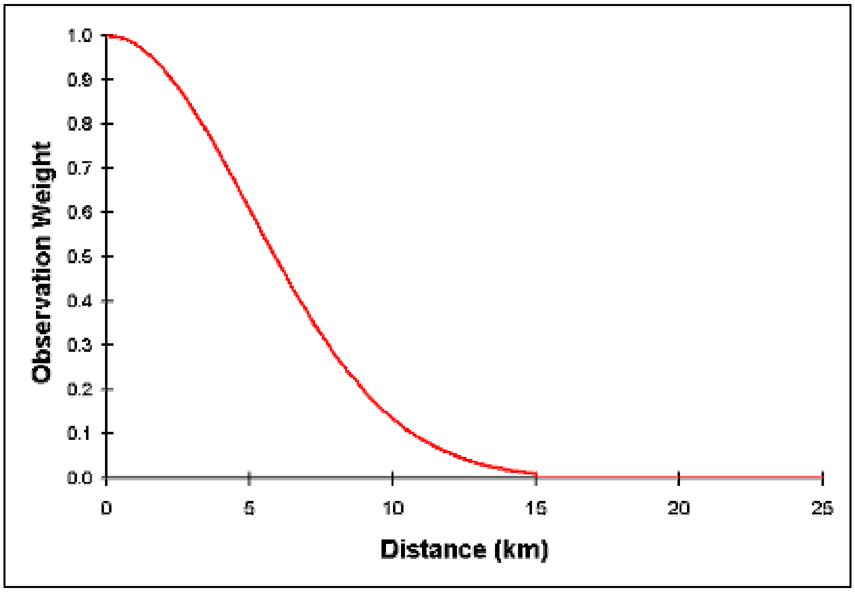

Figure 2: Relative weights used in radar rainfall adjustment based on distance from radar pixel to rain gage

Results

Figure 3 shows the result of the gage-adjusted radar rainfall adjustment procedure for the study period using the NEXRAIN-Brandes Method. The *Gages* line shows the average accumulated rainfall for the 156 gages with valid rainfall data and the *Radar* line shows the average accumulated rainfall from the radar pixels over the valid rain gages. The *Adj_Radar* line shows the average gage-adjusted radar rainfall estimates for the pixels at the rain gages using the NEXRAIN-Brandes Method. In Figure 3, the *Adj_Radar* line nearly matches the *Gages* line, indicating a good match between the rain gage and the gage-adjusted radar rainfall datasets during the eight day study period.

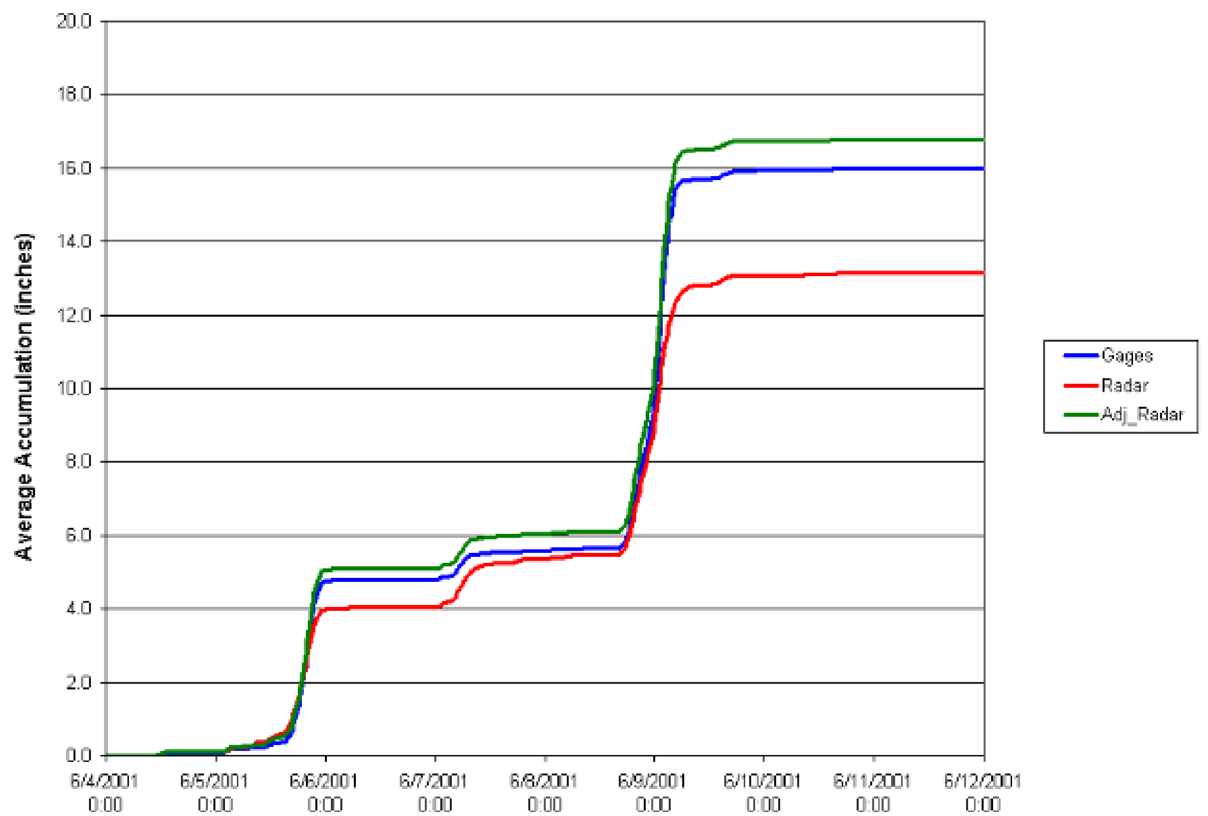

Figure 3: Average gage, radar, and gage-adjusted radar rainfall accumulation plot for Tropical Storm Allison

Figure 4 shows a scatterplot comparing the total rainfall measured at each of the 156 operating gages against the total gage-adjusted radar rainfall estimates using the NEXRAIN-Brandes Method. A perfect fit, where the gage-adjusted radar rainfall total equals the rain gage rainfall total at each gage, would lie along the 45-degree line. Due to difference in scale of the measuring devices (an eight inch (20.3 cm) diameter rain gage, typically, versus a 2 km x 2 km radar pixel), it is not expected that these match up perfectly. However, the gage-adjusted radar rainfall data are expected to cluster around the 45-degree line. The totals on the scatterplot only represent the total rainfall at each gage that was used during the analysis. In other words, gage and radar rainfall totals are not included in time periods where the gage was not operational.

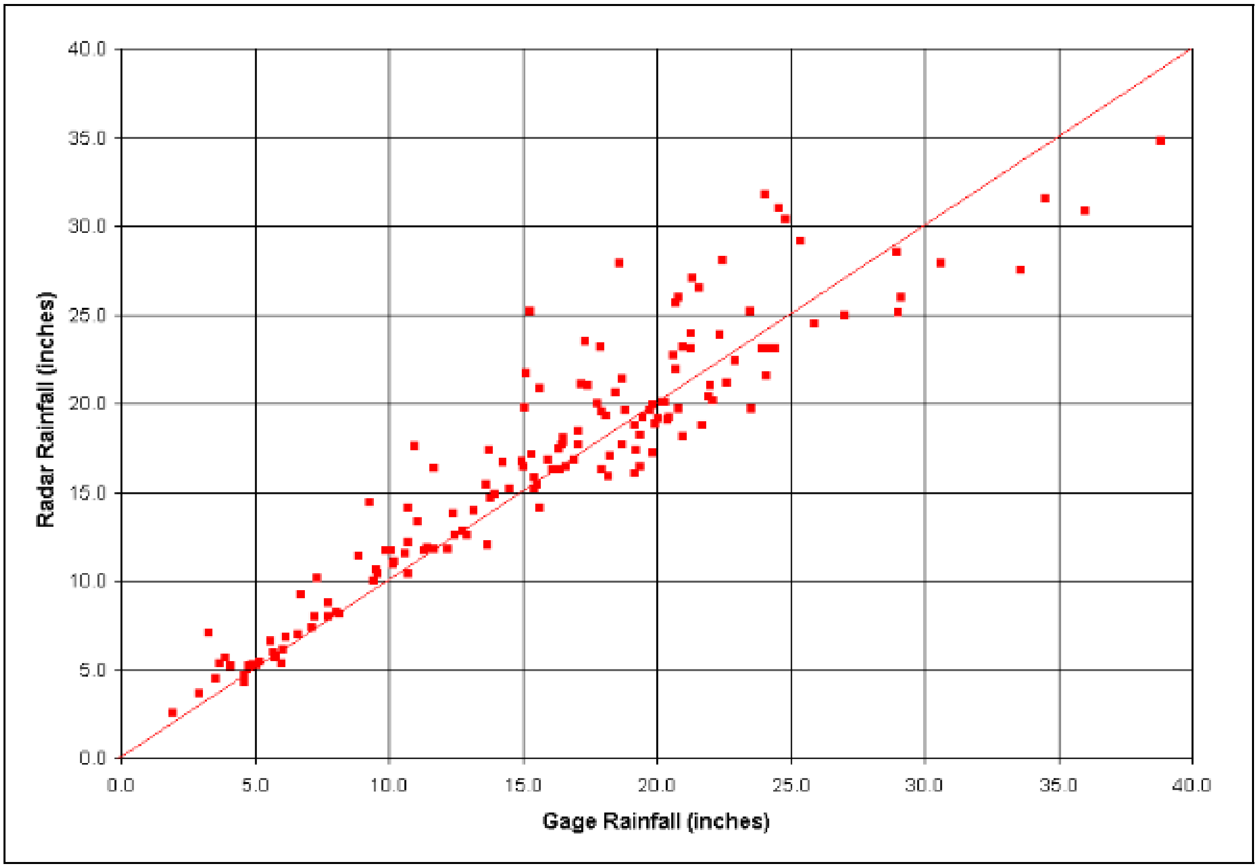

Figure 4: Scatterplot of radar and gage-adjusted radar rainfall totals versus gage rainfall for each gage

Figure 5 shows the spatial distribution across the City of Houston and Harris County. In the western portions of the study area, rainfall totals for the eight day study period were less than 2 inches (5 cm). Over Greens Bayou, gage-adjusted radar rainfall estimates were greater than 35 inches (89 cm). Over 12 hours, the maximum rainfall was greater than 25 inches (63 cm), or about 1.9 times the 12-hour, 500-year rainfall of 13.4 inches (34.0 cm) as defined by the Harris County Flood Control District. In fact, about 370 square miles (960 square kilometers) of the study area received a 12-hour rainfall in excess of defined 500-year rainfall.

At the time of the analysis, gage data from the National Weather Service were not easily obtainable, so only gages from the County and City were used in the analysis. After the analysis, some of the National Weather Service gages were used for verification of the results. During the storm event, the Port of Houston gages, operated by the National Weather Service, recorded 36.99 inches (93.95 cm), which was the highest recorded amount during Tropical Storm Allison by the NWS. An HCOEM gage located 0.51 miles (0.82 km) from the Port of Houston gage showed 25.41 inches (64.54 cm). Both gages are located in the same radar pixel and the gage-adjusted radar rainfall estimate at that pixel was 29.16 inches (74.07 cm). Table 1 shows an example of intrapixel rainfall variation and explains some of the scatter in Figure 4.

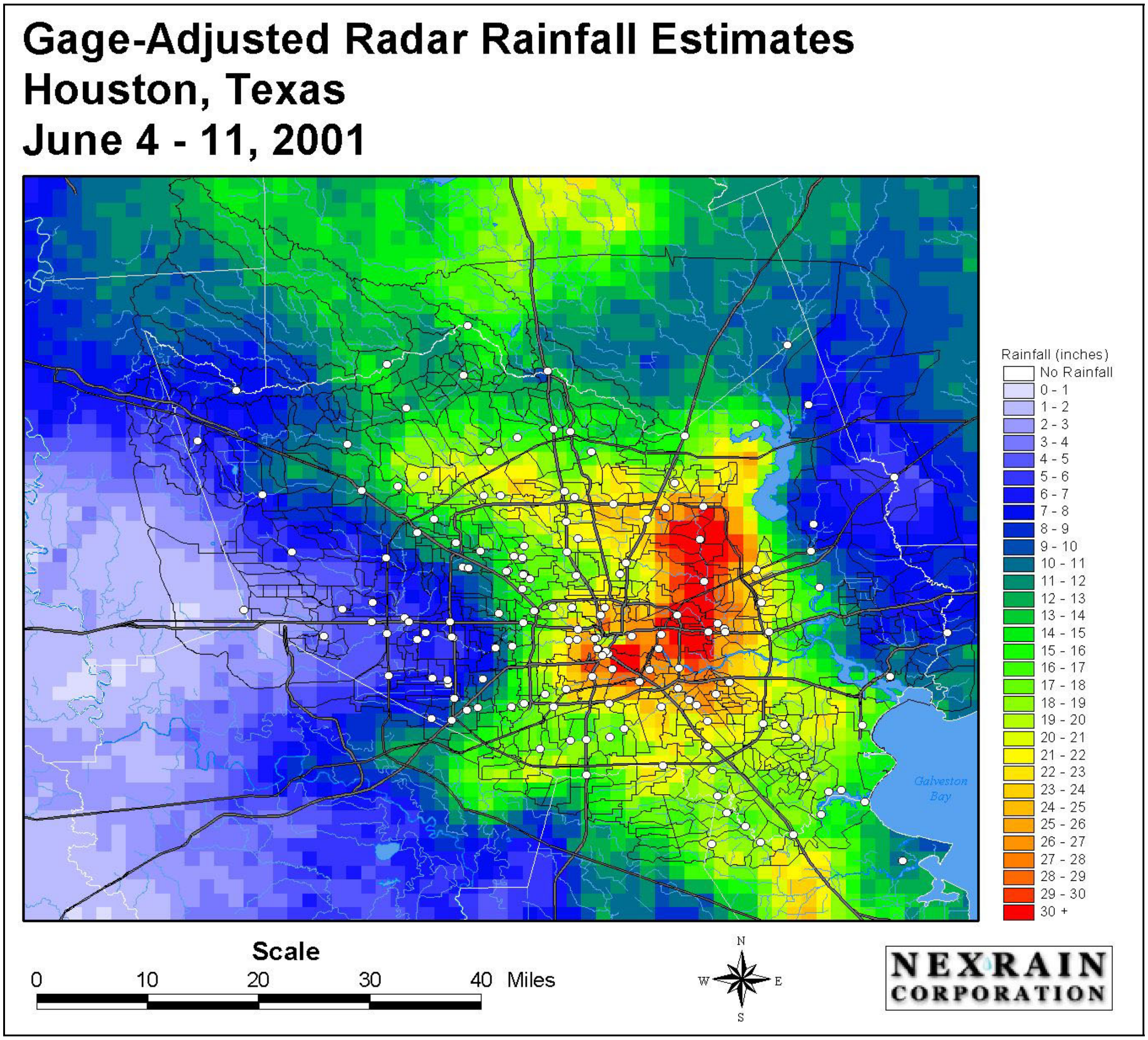

Figure 5: Gage-adjusted radar rainfall totals for Tropical Storm Allison

Table 1: Comparison of rainfall estimates measured at two rain gages inside of one radar pixel

	Rainfall	
	cm	in
Port of Houston (NWS)	93.95	36.99
HCOEM Gage 2210	64.54	25.41
Gage-Adjusted Rainfall at Radar Pixel	74.07	29.16

The maximum gage estimated rainfall used in the study was HCOEM Gage 1600, which recorded a total rainfall amount of 38.83 inches (98.63 cm). The gage-adjusted radar rainfall estimate at the pixel over HCOEM Gage 1600 was 34.80 inches (88.39 cm), which was not the radar pixel with the highest rainfall total. The pixel with the highest estimated rainfall total was the radar pixel directly to the west and showed a rainfall estimate of 35.59 inches (90.40 cm). However, HCOEM Gage 1600 is located less than 300 feet (90 m) from the pixel that estimated the largest total rainfall for the storm.

Conclusions

Using the NEXRAIN-Brandes Method to merge the data from the rain gage network with radar rainfall data, the authors were able create a gage-adjusted radar rainfall dataset that characterized the spatial signature of the storm, and was still able to estimate the intense portions of rainfall. These results would not have been possible using the standard approach of adjusting the radar rainfall estimates uniformly.

The gage-adjusted radar rainfall estimates matched well with the rain gage estimates for Tropical Storm Allison. The peak rainfall measured by the rain gages was within 300 feet (90.4 m) of the radar pixel that showed the maximum rainfall. The timing of the two measurement systems also showed a high degree of correlation.

While the NEXRAIN-Brandes Method worked well in this instance because of the intense nature of the storm, the method should be used with caution because, by nature, it affects the areal measurements of the storm by the radar.

References

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