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Rainfall Estimation from X-band Polarimetric Radar and Disdrometer Observation Measurements Compared to NEXRAD Measurements: An Application of Rainfall Estimates

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ABSTRACT

This paper presents the comparison of rainfall estimation from X-band dual-polarization radar observations and NEXRAD observations to that of rain gauge observations. Data collected from three separate studies are used for X-band and rain gauge observations. NEXRAD observations were collected through the NCEI archived data base. Focus on the K_{dp} parameter for X-band radars was important for higher accuracy of rainfall estimations. The Unidata IDV was used to evaluate the rainfall estimates of NEXRAD observations. The rainfall estimation models were then evaluated versus gauge data using significance testing. It is shown that the X-band radar has a lower p-value thus indicating that the X-band radar is better in predicting rainfall accumulations. Average rain intensity (ARI) was then calculated approximately every 30 minutes to show that the NEXRAD radar is able to show periods of increase rain rate. The results show that the methodology works well at interpreting rain rates and rainfall estimations by X-band and partially by NEXRAD for the events analyzed herein.

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1. Introduction

Improving rainfall estimates from radar measurements has been one of the priorities of radar meteorology. The use of radar polarization parameters in the linear polarimetric basis is generally accepted to improve quantitative estimates of rainfall rate (Matrosov 2002). There are many different tools to collect rainfall estimations. Next-Generation Weather Radar (NEXRAD), X-band, C-band, S-band, rain gauges, and disdrometers are all tools that can be used to determine rainfall estimates.

Most research done in the field of radar polarimetry applied to rainfall estimates have been performed by radar wavelengths at S band and C band. Longer radar wavelengths are the obvious choice for measurements in moderate to heavy rain because of low attenuation and backscatter phase shifts effects (Matrosov 2002). X-band radars have advantages over longer wavelengths that make them a convenient tool and an appropriate choice for some practical applications. For a given transmitter power and antenna size, shorter wavelengths offer greatly increased sensitivity for detecting weak targets (Matrosov 2002).

Fig. 1. Aerial photography of the experimental domain overlaid by the XPOL and nearest NEXRAD (KDVN) sampling grids, and of the dual-gauge and disdrometer locations. Photo courtesy of Anagnostou (2003).

Next-Generation Weather Radar (NEXRAD) consists of a network of Weather Surveillance Radar-1988 Doppler (WSR-88D) radars. Reflectivity observations from each WSR-88D are used to generate many operational products, including estimates of precipitation developed with the NEXRAD precipitation processing system (Young 2000). The precipitation estimates based by these radars are used in NWS Forecast Offices by meteorologists and hydrologists for guidance in forecasts and warnings. NEXRAD is combined with gauge data to make multisensory precipitation estimates.

2. Background

The best way to get accurate data in X-band rainfall rates is to compare them with gauge and disdrometer data. In Matrosov (2002), 15 observed rain events were quantitatively compared by rainfall accumulations from different radar estimators and the high-resolution rain gauges. From this study we chose two cases which were presented with both X-band and rain gauge storm accumulations of rainfall (Table 1).

In addition, Anagnostou et al. (2003) used high-resolution X-band polarimetric radar (XPOL) data and the IIHR gauge/disdrometer network located in Iowa City, Iowa. He then proposed a rainfall estimation technique that was based on algorithms that coupled along-the-ray profiles of $Z_{aH}(r)$, $Z_{aV}(v)$, and $\Phi_{DP}(r)$, where $Z_{aH}(r)$ and $Z_{aV}(v)$ are the attenuated radar reflectivity in the signal phase at horizontal (*H*) and vertical (*V*) polarization for the XPOL measurements, $\Phi_{DP}(r)$ is the differential phase shift between *H* and *V* polarization (degrees), and *r* symbolizes the range bin along the ray. An experimental study by Matrosov in 2002 provided a quantitative error analysis of the various rain estimators based on field data (Anagnostou

2003). This study is based on a field experiment which collected data from an X-band polarimetric radar, XPOL, over a densely instrumented site with three disdrometers and several tipping-bucket dual-gauge (0.25 mm) platforms located between 5 and 10 km from XPOL (Anagnostou et al. 2003). The observed rainfall events occurred for the months of October and November 2001 and ranged in intensity from moderate stratiform precipitation to high-intensity (>50 mm h^{-1}) convective rain cells. From this study we chose one event on October 22-23 (Table 1) where each rain gauge cluster is indicated as A, B, or C (Figure 1).

X-band radar has been traditionally limited in its applicability for quantitative precipitation estimations (QPE). This is due to a relatively high attenuation rate of radar signals in rain. The use of polarimetry provides a new tool for correcting attenuation effects, which in turn greatly increases the utility of X-band radars for QPE. In Matrosov (2004), there were five significant landfalling storms at Fort Ross (FRS), California, near the mouth of the Russian River, in an area that has poor coverage by the NWS WSR-88Ds. These storms were observed by the NOAA X-band radar. Also, during this study there were three high-resolution (0.01 in.) tipping-bucket rain gauges used for validating rainfall retrievals. These were located at the Salt Point State Park, Goat Rock, and Bodegy Bay. They recorded the number of 0.01-in. tips every 2 min. The accumulations collected in this study by the X-band radar were then compared to the three high-resolution (0.01 in.) tipping-bucket gauges. Collecting rainfall accumulations for given time intervals especially over the entire course of a storm present very important hydrological information (Matrosov 2004). From this study we chose two events (Table 1). It was shown in Matrosov (2004) that the estimates of storm accumulation from a nearby NEXRAD (KMUX) were much lower than actually observed for these events. This can be mainly attributed to the much higher altitude of NEXRAD scans (compared to the X-band scans) over the area of interest in this study. The NOAA X-band transportable polarimetric radar has shown that it is capable of providing high-resolution and accurate estimates of rainfall parameters. While Lim et al. (2013) presented new methods for rainfall estimation from X-band dual-polarization radar observations. Dual-polarization radars have become an important tool for meteorological applications. This has occurred over the last decade and it is important for tools such as quantitative precipitation estimations (QPE) and hydrometeor classification. However, various methods for hydrometeor classification have been proposed during the last decade but these methods were mainly for C and S band weather radars. The proposed hydrometeor classification described in Lim et al. (2013) is a robust technique that can be applied to S band, C band, and even higher frequencies such as X and K_u bands. Also, the rainfall estimation included a comparison of both instantaneous and cumulative rainfall using the conventional, filtered specific differential phase (K_{dp}) and the proposed method with surface rain gauge and disdrometer data (Lim et al. 2013). Data collected from the Hydrometeorology Testbed (HMT) in the orographic terrain of California are used to demonstrate the methodology. The study this paper presents is a further enhancement to a class of applications in improving the robustness of the rainfall estimation process. This works well especially for complex terrain applications due to reduced ground clutter contamination at K_{dp} retrieval (Lim et al. 2013).

Throughout these studies a common theme seems to be multi-parameter estimates that include the K_{dp} parameter. To better the results of this paper we used this estimator for our X-band rain accumulations which can be seen in Table 1. The multi-parameter estimator gave the best agreement with the rain gauge. The other important outlook in this study is the look at NEXRAD radar. Young's (2000) paper examined issues associated with the evaluation of NEXRAD multisensory estimates through a case study involving a 5.5-yr record of products. This study was evaluated in its area of interest because of the history of NEXRAD research in the southern plains, the availability of gauge observations, and the long period of record for NEXRAD multisensory estimates (May 1993 through September 1998) (Young 2002). In Young (2000), the two methodologies used showed considerable differences in precipitation occurrence and conditional means. This was due in large part to differences associated with light precipitation. One method indicated precipitation more often than the other, which was consistent with the gauge detection that drives the analysis. Although the paper's evaluation had identified some deficiencies in the NEXRAD multisensory products, it does not mean the products fail to produce quality precipitation estimates.

Flooding, flash flood warning systems and the efficient management of water resources call for improved quantitative measurements of precipitation at temporal scales of minutes and spatial scales of a few square kilometers (Anagnostou 2003). Since it is important to keep an eye out for flooding, then it is important to make sure that we are using the best rainfall estimation tools. In this paper we will look at NEXRAD radar, X-band radar, and rain gauges at the differences each had in different cases chosen. We want to know which radar is best in determining rain accumulations to better our forecasts.

3. Methods

a. Setup

The locations used for this research include: Fort Ross, California (FRS), Young (2000); Wallops Island, Virginia, Matrosov (2002); and Iowa City, Iowa, Anagnostou (2003). NEXRAD radars used included KMUX (San Francisco, CA), KAKQ (Wakefield, VA), and KDVN (Davenport, IA) respectively to the locations mentioned. This research was mainly dependent on Young (2000), Matrosov (2002), and Anagnostou (2003) in using the data presented in these papers. The data necessary for this research included dates, times, and accumulations of rain during an event. The reason for this was to get accurate and detailed estimates of X-band radar and rain gauge data. Each location mentioned above is unique. The Wallops Island, VA location is on the East Coast United States, the Fort Ross, CA location is on the West Coast United States, and the Iowa City, IA location is in the middle United States. Fort Ross, CA deals with incoming Pacific Ocean storms. Wallops Island, VA is caught between the Atlantic Ocean and Chesapeake Bay. Iowa City, IA is in the rolling plains which are interrupted by main rivers. Each location has one thing in common which is flooding.

b. NEXRAD Data

Rainfall estimates were collected from the NCEI archived data. Level-III NEXRAD data was used to get these rainfall estimates. The Next Generation Weather Radar (NEXRAD) system currently comprises 160 sites throughout the United States and select overseas locations. The

Table 1. Dates, times, and accumulations (at the principal verification site) of rain cases observed during the experiments at Wallops, VA, Iowa City, IA, and Fort Ross, CA.

			Rain Gauge (mm)	X-band (mm)	NEXRAD (mm)
Location	Date	Time (UTC)	Sum	Sum	Sum
KAKQ	Feb-25-2001	1720-2020	7.4	7.2	0
	Mar-21-2001	0800-1700	63	47	35.56
KDVN	Oct-22-23-2001 (A)	2230-0330	30.5	32.5	20.42
	Oct-22-23-2001 (B)	2230-0330	34.75	34.25	16.03
	Oct-22-23-2001 (C)	2230-0330	16.5	13.75	21.95
KMUX	Feb-17-18-2004	1000-0312	26	22	7.62
	Feb-2-2004	1000-2000	25	24.75	0

maximum range NEXRAD radar can reach is 230 kilometers. Level-III data is made up of derived products from Level-II data. Level-II data include the original three meteorological base data quantities: reflectivity, mean radial velocity, and spectrum width, as well as the dual-polarization base data. Level-III is comprised of over 75 products. The ones of interest to this research include Storm Total Precipitation (NTP) and Base Reflectivity (N0R).

c. Unidata IDV

The Integrated Data Viewer (IDV) from Unidata is a Java^{TM}-based software framework for analyzing and visualizing

Table 2. Latitude-Longitude Coordinate of interest in relation to NEXRAD radar.

<table>
<tr><td>Location</td><td colspan="2">Latitude</td><td>Longitude</td></tr>
<tr><td>Fort Ross, CA (KMUX)</td><td colspan="2">38.52</td><td>-123.23</td></tr>
<tr><td>Wallops Island, VA (KAKQ)</td><td colspan="2">37.88</td><td>-75.43</td></tr>
<tr><td rowspan="3">Iowa City, Iowa (KDVN)</td><td>Cluster A</td><td>41.637150</td><td>-91.55793</td></tr>
<tr><td>Cluster B</td><td>41.639187</td><td>-91.54776</td></tr>
<tr><td>Cluster C</td><td>41.634699</td><td>-91.54485</td></tr>
</table>

geosciences data. The IDV was used in determining the NEXRAD rainfall estimates from the storm events discussed in Young (2000), Matrosov (2002), and Anagnostou (2003). No smoothing of the data was done in determining the rainfall estimates of NEXRAD Level-III data. To ensure best estimates of NEXRAD rainfall estimates, coordinates of the locations of interest were used (Table 2).

d. Procedure and Analysis

The NEXRAD data was received from the NCEI archived data. It was then read by the Unidata IDV. To get the most accurate estimate it was useful to zoom in to get an individual resolution cell for the value to be estimated. This helped to read an accurate estimate of accumulated rainfall during the storm periods (Table 1). The location indicator was used to show locations of interest (Table 2). By clicking on the area of interest it was possible to get the most accurate value of accumulated precipitation in the area.

Figures and Tables produced in this research were made using JMP.

4. Results and Discussion

a. KAKQ

Wallops Island, VA is in a difficult location for rainfall estimates by NEXRAD radar, which is located in

Norfolk/Richmond, VA. It is approximately 172 kilometers away from the KAKQ radar. This makes the estimation of rainfall at Wallops Island, VA difficult due to the distance it is away from the KAKQ radar. With this in mind, the estimates collected by the X-band radar and quantitatively by rain gauge/disdrometer networks in Matrosov (2002) and the KAKQ NEXRAD radar estimates collected can be seen in Table 1.

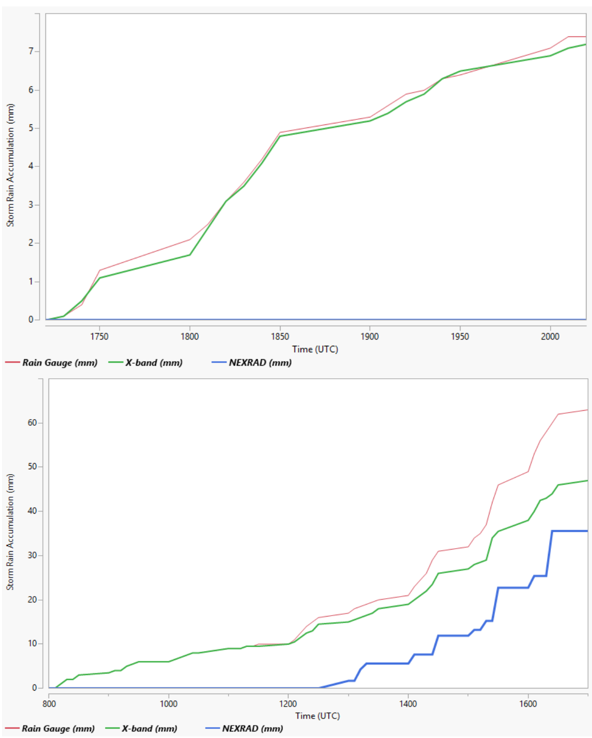

Fig. 2. Comparisons of rainfall accumulations from high-resolution rain gauge, X-band radar, and NEXRAD radar for two rain events: (a) 25 Feb 2001 and (b) 21 Mar 2001.

As seen in Figure 2, the NEXRAD radar failed to detect any precipitation accumulations for the February 25th, 2001 event. This is most likely due to the light rain that occurred. The X-band estimates were closely related to that of the rain gauge on this particular day. On the other hand, on the March 21st event there was quite the discrepancy for values from each. Both the X-band and NEXRAD radar underestimated the rainfall.

b. KDVN

Iowa City, IA is in a great location for the NEXRAD radar, which is located in Davenport, IA, to get rainfall estimates. It is approximately 80 kilometers away from the KDVN radar. It is also flat terrain which gives it minimal obstructions. Most of the

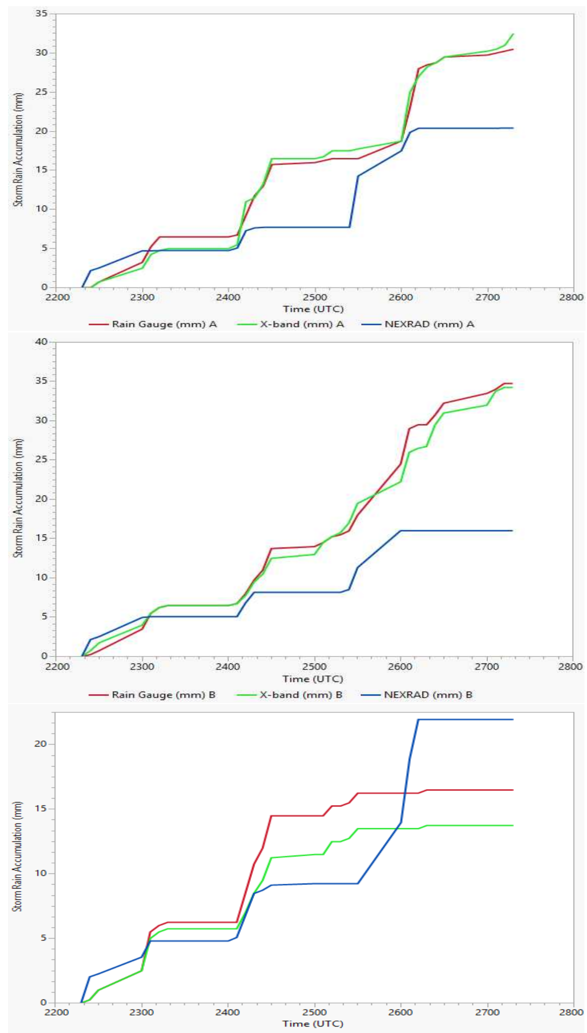

Fig. 3. Comparisons of rainfall accumulations from high-resolution rain gauge, X-band radar, and NEXRAD radar for the rain event on 22 Oct – 23 Oct 2001. Here the rain gauge clusters A, B, and C are shown respectively.

rain events presented had very light rain or had already rained prior to the times of observation. The periods of observations with no rain prior showed good estimates of accumulated precipitation. With this in mind, the estimates collected by the X-band radar and coincidently by rain gauge/disdrometer networks in Anagnostou (2003) and the KDVN NEXRAD radar estimates collected can be seen in Table 1.

As seen in Figure 3, both radars estimated rain accumulations at all three rain gauge sites on October 22, 2001, but there was differences between the measurements of all three rain gauge sites. The X-band polarimetric (XPOL) radar estimated rain accumulations better than the NEXRAD radar did. The NEXRAD radar overestimated at the rain gauge site labeled Cluster C while it underestimated rain accumulations at Cluster A and Cluster B. While these clusters are close together, it is seen that the NEXRAD radar is incapable of getting accurate measurements. As seen in Figure 1, the NEXRAD radar grid points place Cluster A and Cluster B together while Cluster C is in its own grid point. The storm on this day was moving west and this could have caused the NEXRAD to have overestimated at Cluster C due to it being closer to the NEXRAD radar by one grid point. Since the rain was moving west the NEXRAD signal would have returned quicker from the grid point Cluster C is in and have estimated more precipitation if precipitation was falling at the time of scanning but not occurring at Cluster A and B.

c. KMUX

Fort Ross, CA is in a difficult location for the NEXRAD radar, which is located in San Francisco, CA, to get rainfall estimates due to the terrain. Fort Ross is near the mouth of the Russian River, in an area that has poor

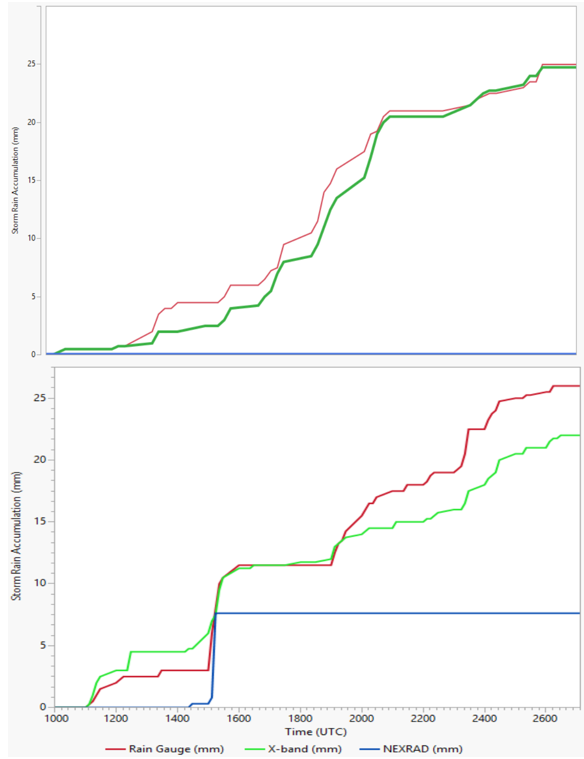

Fig. 4. Comparisons of rainfall accumulations from high-resolution rain gauge, X-band radar, and NEXRAD radar for the two rain events: (a) 2 Feb 2001 and (b) Feb 17 – Feb 18 2004.

coverage by the NEXRAD radar and is vulnerable to frequent flooding (Matrosov 2004). The Fort Ross area lacks adequate coverage by the NEXRAD network, and data from these radars can result in large underestimations of rainfall accumulations. With this in mind, the estimates collected by the X-band radar in comparison to the high-resolution rain gauges in Matrosov (2004) and the KMUX NEXRAD radar estimates collected can be seen in Table 1.

As seen in Figure 4, the NEXRAD radar failed to detect any precipitation accumulations on the February 2nd, 2004 event. This is most likely due to the light rain involved with this storm system but is also a victim of the elevation of the NEXRAD radar. While on February 17th into February 18th, 2004 the NEXRAD radar estimated precipitation for Fort Ross, CA but only managed to estimate an accumulation of about one-third that of the X-band and rain gauge accumulations. In essence, the KMUX radar was not very accurate in determining the accumulations recorded for this storm in Fort Ross, CA.

d. Statistical Analysis

Presented in this study was an experiment in the comparison of the NEXRAD, X-band and rain gauge accumulations of precipitation. The outcome of this study was to see which weather radar is best for storm rain accumulation. By collecting rain estimates for X-band and rain gauge from other studies that were accurate and NEXRAD radar from archived data, it was possible to look at the comparison of each. Figure 5 shows us that the spread of points in the NEXRAD radar is much wider than that of the X-band radar to that of the rain gauge. Significance testing showed that the NEXRAD radar had a p-value of 0.0475 which is barely less than 0.05. This indicates that there is a low probability that the NEXRAD radar will get accurate rainfall estimates. The X-band radar data had a p-value of 0.0006 which is much less than 0.05. This indicates that there is high probability that the X-band radar will get accurate rainfall estimates.

In Figure 6a and 6b, all five storm events chosen show the average rain intensity (ARI) every 30 minutes. On the events where the NEXRAD radar picked up any storm rain accumulation it can be seen that it also picked up on the increase in rain rate. From Figure 3, Cluster C showed that NEXRAD was overestimating the storm rain accumulation and that can also be represented in the rain rate shown in Figure 6b. The NEXRAD in Figure 6b shows a large increase toward the end of the period where it likely caused the increase in storm rain accumulation seen in Figure 3. Two

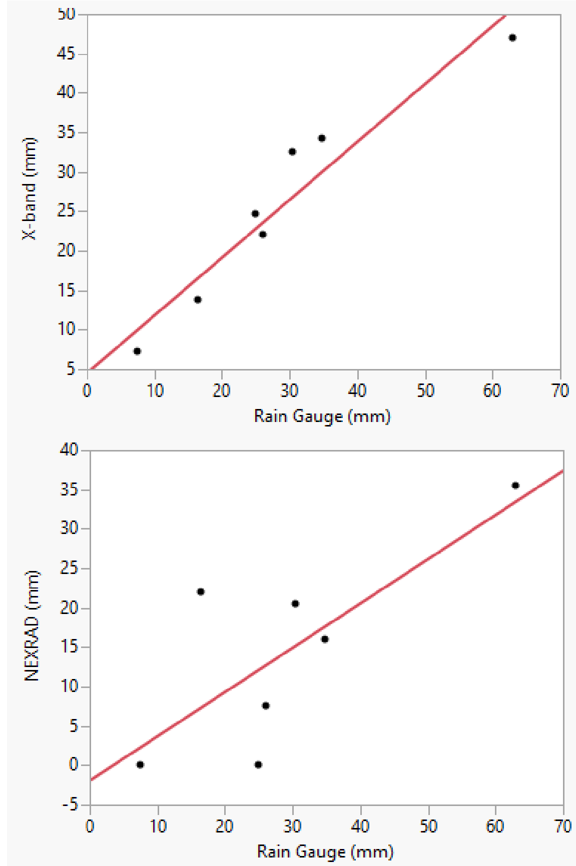

Fig. 5. Scatter plots of rain gauge vs. NEXRAD and X-band total storm rain accumulation.

other cases seen in Figure 6a over estimate the ARI at one or more points in time. Comparing this to the rain accumulations seen in Figure 4 and Figure 2, for the 17-18 Feb 2004 and 21 Mar 2001, it is seen that they still underestimated rain accumulations. On 17-18 Feb 2004, the NEXRAD estimated precipitation earlier in the period but failed to estimate any the rest of the period. This caused the rain accumulation in the end to be less than the rain gauge. On 21 Mar 2001, the NEXRAD estimated precipitation late in the period but failed to estimate any early in the period. This caused the rain accumulation to estimate less overall for this time period. In Figure 6b, Clusters A and B have an overall lower ARI than rain gauge and X-band. Comparing these results to Figure 3, Clusters A and B have similarities in the underestimate of rain

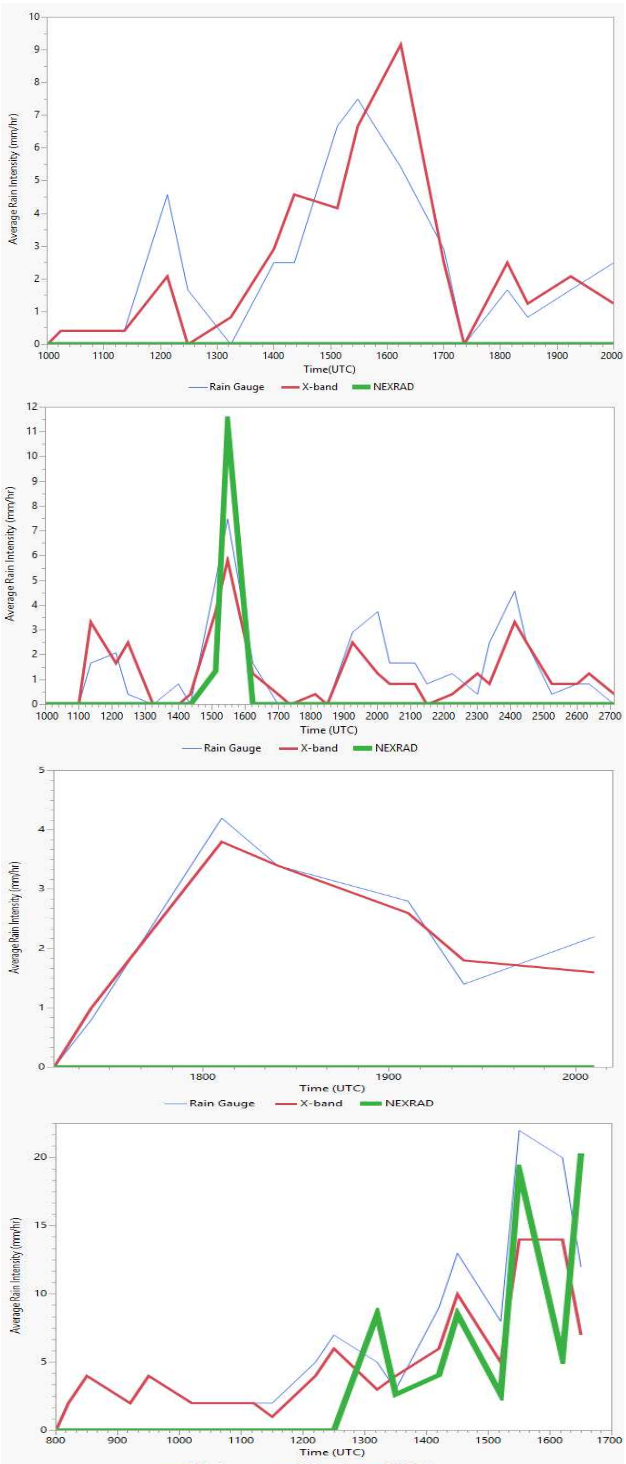

Fig. 6a. Average Rain Intensity (ARI) (mm/hr) for 4 rain events: (a) 2 Feb 2004, (b), 17 Feb – 18 Feb 2004, (c) 25 Feb 2001, and (d) 21 Mar 2001.

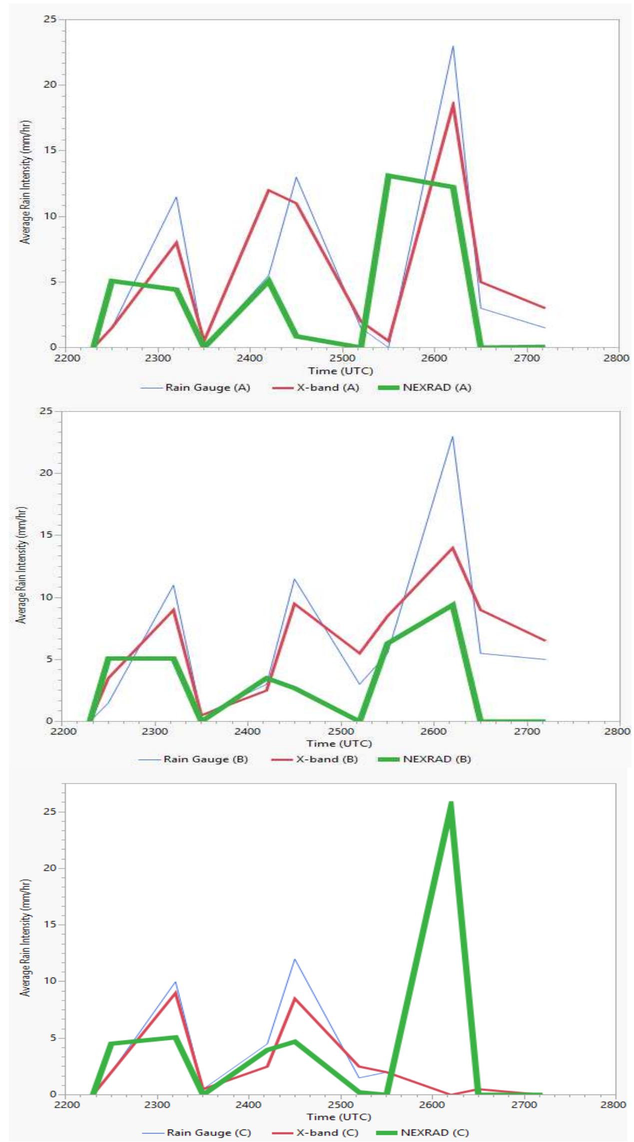

Fig. 6b. Average Rain Intensity (ARI) (mm/hr) for the rain event on 22 Oct – 23 Oct 2001 at rain gauge cluster sites: (a) Cluster A, (b) Cluster B, and (c) Cluster C.

accumulations. Overall, the comparison of ARI to storm rain accumulation points out the errors in storm accumulations. These errors being the over estimation and under estimation of rain rates by NEXRAD radar. Whereas the X-band radar closely matches the outcome that the rain gauges calculated.

5. Conclusion

Rainfall estimation using K_{dp} measurements at X-band have been shown to be relatively successful (Lim et al 2013). This paper shows that it is also more successful than the NEXRAD systems. X-band radar can provide accurate estimates of rainfall accumulations in important areas that are prone to flooding. Some areas lack adequate coverage by the weather network WSR-88Ds, and data from these radars can result in large underestimations of rainfall accumulations. Through a comprehensive study of deficiencies in WSR-88D estimates in this area is beyond the scope of this work, initial estimates show that the total storm accumulations from NEXRADs in these areas can be inaccurate which agrees with the work done by Anagnostou (2003).

Rain rates were compared to the rainfall accumulations in determining if overestimation or underestimation of rain rate caused any discrepancies in rainfall accumulation. We found that there were errors in these comparisons. Overestimation of precipitation during these events caused the rainfall accumulations to be inaccurate for NEXRAD. However, underestimation of rain rates as seen in Figure 6b for Clusters A and B show that it did indeed underestimate in the storm rain accumulation.

6. Acknowledgments

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