Comparison of X-band radar rainfall estimates in the Atlanta to Athens region

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1. Introduction

To improve public response, flash flood warnings (FFW) and flash flood statements (FFS) have evolved to impact-based warnings (IBW), which are primarily based on radar rainfall estimates. The flash flooding source information tag and the flash flooding causative event tag are two of three categories used to describe floods and provide supplemental information on the potential damage impact. Both tags rely on rainfall rate from radar to provide additional information about the status of flash floods. The number of FFWs may be greater in urban areas, compared to ex-urban areas, because of urban heat islands (UHI), which are urbanized areas with limited greenspace and high concentrations of infrastructure that emit and absorb heat from the sun. This makes the temperature of the urban area significantly greater than its surroundings and creates a layer of unstable air. This creates a large temperature gradient in the daytime, which, given specific conditions in the atmosphere, could intensify weather conditions. As the climate system warms, more intense weather events are expected to occur in urban areas (McLeod et al., 2017). If there is heavy rainfall, urban areas, such as the Atlanta metropolitan area, are more likely to experience flash floods due to impermeable infrastructure (Bedient et al., 2003; McLeod et al., 2017; Yoon & Nakakita, 2017). However, detecting heavy rainfall events like this can be challenging in the Atlanta to Athens regions, as there are blockages and gaps in radar coverage, which can lead to poor rainfall estimates.

In this study, rainfall data from a recently acquired Furuno WR-2100 X-band radar will be compared to both S-band rainfall estimates and local rain gauge data from weather events in the Athens to Atlanta region. The radar is owned by Georgia Tech (GT), University of Georgia (UGA), and the Georgia Tech Research Institute (GTRI) and is used to examine heavy rain events and winter and severe weather in the region between Atlanta and Athens. This region includes blockages in coverage created by existing radars, so the X-band radar will serve as a "gap" filling instrument. Data from heavy rain events and severe weather events will be analyzed using multidimensional data from different azimuthal scans every minute and compared to rain gauge data and S-band radar data. Different methods of estimating rainfall will be conducted using a Z-R relationship and interpolation methods. Information from this study will help the research team better understand the full capability of the new X-band radar, specifically the accuracy of its rainfall estimates, and it could be used to help warning coordinators optimize their flood warning systems when the radar is used in operations.

2. Review of Literature

2.1 X-band radar capabilities

To detect heavy precipitation, S-band radars like those used by the National Weather Service are typically used for long-range detection of heavy weather, since S-band radars have longer wavelength and larger antennae than X-band radars. However, as with all radars, there are tradeoffs with S-band radars, such as their relatively low resolution and the distance between the radar beam and the surface of the Earth increasing rapidly from the radar due to the curvature of the Earth. To help alleviate some of these issues, as well as beam blockages specific to the area east of Atlanta, GTRI, GT, and UGA acquired an X-band radar. X-band radars are used mostly for target identification and discrimination due to their higher spatial resolution. X-band radar has been proven to be more reliable for local operations. The accuracy of X-band radar decreases beyond 60 km, and at closer ranges, X-band and S-band radar have similar accuracy with rainfall estimations; however, X-band radar does not require calibration on more complicated terrain and is less expensive than S-band and C-band radar, which makes it useful in areas with a limited rain gauge network (Anagnostou et al., 2014; Diss et al., 2009; Yoon & Lim, 2022). Bias between X-band and S-band radar may also depend on storm classifications, since S-band radar attenuates significantly less in heavy weather than X-band radar (Diss et al., 2009). X-band has a higher spatial resolution than S-band and C-band radar, so the resolution of smaller objects further away from the radar are comparably more resolute (Prat & Barros, 2009).

2.2 Z-R Relationships and problems with comparing rain gauge data to radar rainfall data

In this project, we will compare the estimated radar rainfall to local rain gauges. There are challenges in doing this comparison, as X-band radar outputs data with high spatial resolution in three dimensions. This can lead to much uncertainty when comparing radar to rain gauge data for various reasons.

The first step in the comparison is to calculate the radar rain rate. One way to do this is by using the empirical Z-R relationship between reflectivity and rainrate, $Z= AR^b$ (i.e. the most commonly used Z-R relationship, $Z=200R^{1.6}$), where R is rainfall rate in mm/hr, Z is the radar reflectivity factor (mm^6/m^3), and A and b are empirical constants (Marshall & Palmer, 1948). Studies have suggested employing a dynamic approach to Z-R relationships, since the relationship is reliant on microphysical interactions and drop size distributions and different Z-R relationships can be derived using different tools (e.g. disdrometers, radars, rain gauges) (Borga et al., 2022; Collier, 2009; Marshall & Palmer, 1948; Prat & Barros, 2009). Changing the a and b parameters of the Z-R equation according to rain gauge data can produce errors since rain gauges are point measurements and radar measurements are three-dimensional projections of volume onto a two-dimensional surface (mm^6/m^3) (Gires et al., 2014).

Because rain gauges provide point measurements at a location on the surface of the Earth and radars provide scans from volume coverage patterns, it is difficult to compare the data with measurements alone. The height above the radar at which reflectivity data is collected is most important for these approximations (Pattani, 2010). To collect rain gauge data directly beneath the radar path, previous methods have included locating the rain gauge location with the radar dataset and extracting the cells that correspond to the location of the weather station (Pappa et al., 2021). Because the radar outputs radar reflectivity values every 2 minutes and the typical rain gauge is a 10 minute point measurement in the same paper, the average value was taken of five two minute datasets that correspond to the same time period of the rain gauge datasets. This method was generally effective, but radar rates overestimated rainfall totals in comparison to rain gauges. Different a and b parameters for the Z-R equation were better suited for different events. For instance, $a = 200$ and $b = 1.6$ provided better estimates for seaside regions while $a = 431$ and $b = 1.25$ provided better estimates for stations near the radar or places in high elevations.

2.3 Existing techniques to calculate and compare rainfall

Pattani (2010) provided another method of comparing radar rainfall values with rain gauges. A generalized reduced gradient solver (GRG) built into MATLAB was used to derive the a and b parameters for the Z-R relationship rather than testing different existing parameters (Marshall & Palmer, 1948). National Climate Data Center (NCDC) radar archives from the National Oceanic and Atmospheric Administration (NOAA) were used rather than an independent X-band radar. Because the rain gauge totals were provided in 15 minute intervals, the radar reflectivity was integrated into 15 minute intervals of rainfall data using NOAA's Weather and Climate Toolkit ArcGIS R^3 tool. This method may not be applicable to this project due to the incompatibility of the Furuno radar output.

The Cressman interpolation is a function that can be used to interpolate station data to grid data. It is a correction method that can be applied to different kinds of variables (Cressman, 1959). The Cressman interpolation technique has been used by researchers who have also used

RainMap, the software that will be used with the Furuno radar to examine rainfall rates in the Atlanta-Athens region. It is an interpolation function that acts as a correction method that can be applied to different kinds of variables. For instance, it was used on the divergence equation to reduce error and compare it to another dynamical equation (Cressman, 1959). It can also be used as an interpolation function to interpolate station data to grid data for maps in GIS. In terms of precipitation data, the Cressman interpolation can be used to define the space of a precipitation field from climate models, but the method seems to overestimate spatial values by overestimating the number of cells associated with rainfall (Hewitson & Crane, 2005).

The installation manual of the Furuno WR2100 X-band radar provides an alternative method for estimating rainfall intensity R that relies on specific differential phase Kdp and horizontal reflectivity Zh derived from a Cressman interpolation. The following equation measures uses Kdp as an input with parameters a,b,c, and el (elevation), which are 19.6, 0.825, and 1.2, respectively:

$$Rain(Kdp) = c \cdot (a + 2.64 \cdot 10^{-2} \cdot el + 1.73 \cdot 10^{-3} \cdot el^{2} + 1.09 \cdot 10^{-4} \cdot el^{3}) \cdot Kdp^{b}$$

This method will likely be one of the methods used to estimate precipitation from radar since it is specified in the manual.

Specific differential phase techniques, as used in Yoon and Nakakita 2017, can also be used to calculate rainfall. The R-Kdp relationship can be used in conjunction with the Z-R relationship to produce more accurate estimations of rainfall accumulations. It was found that a B value of 23.7 and a β value of 0.87 are able to accurately forecast floods with a flow nomograph by forecasting rainfall intensity (Yoon & Nakakita, 2017). Their research also shows that using forecasted values of radar rainfall with this method is more accurate than using observed values of radar rainfall; however, there is much uncertainty with this method, as it cannot accurately predict the temporal resolution of rainfall, which is necessary for forecasting.

3. Methods and Materials

3.1 Extracting data from the Furuno WR-2100 X-band radar

The Furuno weather radar was installed at the Georgia Tech Research Institute facility in Smyrna, GA. The radar is controlled remotely through the Signal Processing Unit (SPU), a PXI windows computer running LabVIEW, which receives commands from the Display Processing Unit (DPU) that runs the software RainMap. The SPU sends data to the DPU and converts it into SCN data files.RainMap can use these SCN files to display dual polarization radar of differential reflectivity. The files may be converted to netCDF files through a SCN2 converter tool. This tool is not necessary to convert the SCN files, but it organizes the files by the tilt of the four azimuth angles that the radar scans which can then be converted to netCDF files. RainMap also allows the user to input geospatial data layers and create a physical map of the area of interest.

3.2 Projection algorithm

In order to compare the rain rates from the X-band radar to the rain gauges within the vicinity of the radar, an algorithm must be created in order to identify the latitudes and longitudes associated with each point of rain rate and other atmospheric measurements. Once the locations within the area were assigned a latitude and longitude based on its distance from the radar, an area-averaging technique was applied to acquire averaged rain rates (Figure 1). Each elevation angle has 1267 different azimuth angles at 936 ranges, and each point has a latitude and longitude. With the radar as the origin, 140 blocks of 500-by-500 resolution squares in units of meters were area-averaged into 147 latitude bins ([33.14, 34.6]) and 247 longitude bins ([-85.78, -83.32]) (Figure 2). Because the rain rates from the weather stations are taken in 15 minute intervals, the rain rates are averaged every 15 minutes by taking the mean of 6 netCDF files, since the time step between each file is 3 minutes and the first file begins at t = 0, or 20:00Z (Figure 3).

3.3 Comparison technique

Ten weather stations within the range of the area-averaged bins were selected from Weather Underground. These stations are owned and operated by the general public, and all of the selected stations provide weather information in 15 minute intervals. For the purposes of this project, the precipitation rates (in inches per hour) were collected into a spreadsheet and organized by the AMS definition of rain was used in order to identify times of heavy precipitation (higher potential for flash floods). Light rain is between a trace and 0.10 inches per hour; moderate between 0.11-0.30 inches per hour; and heavy over 0.30 inches per hour. The average difference between the rain rates determined by the weather stations and their corresponding locations on the radar were also calculated in the spreadsheet to determine whether or not the radar is under- or overestimating the rain rate.

4. Discussion of the Results

4.1 January 12, 2023 analysis

The first measurements taken with the radar are from a weather event associated with a sub 1000 hPa surface cyclone that led to 0.6 inches of rain in the Atlanta area and north of the radar (Figure 3). To compare the rain rate between local rain gauges and the X-band radar, 10 stations were selected from Weather Underground. One reason for this is to verify the radar rain rate averages from the previous methods of pulling data from the netCDF files and determine how closely the averages follow the general trend from other weather stations. Another is to determine whether or not the radar accurately reports rain rates using the traditional Z-R relationship. The locations of the weather stations range from 33.14° N, 85.78° W to 34.60° N, 83.32° W. The event of interest took place on January 12, 2023 from around 20:00Z to 23:00Z, when a squall line moved through the Atlanta region (Figure 4). Long-lived squall lines are capable of producing heavy rain and therefore high rain rates, which made this event particularly of interest.

Data from the event was only sampled for 90 minutes between 20:00Z to 21:30Z. Rain rates officially exhibited a distinct peak around 21:00Z, as observed on all weather stations (Figure 5). There are six sweep angles that represent the elevation angles of the radar. The range is from 0-10° in increments of 2°, and due to the curvature of Earth's surface, the lower angles are more representative of precipitation closer to the surface while the higher angles are likely sampling rates within a cloud structure in the squall line. The rain rates from the first and second sweeps were compared with the rain rates from the radar.

The rain rates are divided into three categories of precipitation levels in accordance with the AMS definition of rain (Figure 5). This is because the comparison depends mostly on the 15 minute intervals of the event where rain was heaviest. Because there is an assumption that the rain rates will be consistent with the weather station reports, times when there is little to no rain will mean that the estimations will be similar to the reports, and this does not verify the reliability of the radar. Rain intensities are as previously defined (section 3.3).

For the first sweep, most of the rain rates were reported after 21:00Z, which is consistent with the time at which rain rates from the weather stations were mostly reported (Figure 6). The radar tends to underestimate data in areas southeast of the Atlanta region. Another average of rain rate differences supports this observation, as highlighted in Figure 7. The highest degree of underestimation is from Atlanta, which is relatively close to the radar in Smyrna compared to the location of the lowest degree of underestimation, which is in Fayetteville. Where the weather stations consistently report moderate to heavy rain, the radar reports trace amounts or 0.00 inches per hour. Overshooting of the radar can happen when the elevation angle is high enough for the radar beam to miss the precipitation, and this can lead to underestimation. Longer ranges can also lead to the underestimation of radar rainfall rates, which is presumed to be the case with sweep 1, since the elevation angle is only 0°.

The second sweep also follows the trend shown by the weather stations, where most precipitation rates are reported after the 21:00Z mark (Figure 8). The same locations marked by the weather stations that produced significant underestimations of the radar rain rate are the same at this elevation angle (2°) (Figure 9). Compared to the first sweep, the radar in the second sweep overestimates rain rate in the areas where rain rate was previously underestimated. These are areas in south Atlanta in the metropolitan area. This may have occurred because the radar beam missed the precipitation, given the higher elevation angle. At locations too far south of the radar, the radar still underestimates the precipitation rates.

Similar studies have taken different approaches to gathering results. Most notably, when comparing rain gauges and rain rates, ground clutter and other inconsistent regions were flagged in order to collect the most accurate rain rates from radar. Also, multiple rainfall events with varying intensities were collected on over 40 stations, which is necessary for thorough statistical analysis (Pappa et al., 2011; Yoon & Lim, 2022). This study operates on the assumption that ground clutter only occurs close to the ground, hence the selection of stations several kilometers away from the radar. The stations used are privately owned, but the measurements observed are generally consistent with radar observations. Given the time constraint of this project, only one event was analyzed, and more conclusive statements rely on larger sample sizes.

Urban flood criteria is usually dependent on local rainfall information, since the impacts of rainfall intensity are dependent on geographical location, soil, and other climate defining features (Yoon & Nakakita, 2017). Despite the base of this study being in an urban location, rain intensity that leads to flash floods depends on the permeability of infrastructure, since there is no body of water directly connecting the Atlanta region. This is difficult to model. Because the impact of rain intensity is subjective to geographical location, an official definition of rain was used with the assumption that heavy rain rates are the main cause of flash floods in urban areas. The previously mentioned study also has high temporal resolution of radar data of a scan every minute instead of the X-band radar's scan every 3 minutes and then averaged over 15 minutes, but this is the extent of the capability of the radar.

If there was a shorter range of latitudes and longitudes closer to the radar for the weather stations and they were clustered directly in the path of the squall line, the results may look more consistent with what is expected from radar: closer objects to the radar at lower angles will result in more similar rain rates to the weather stations. At time periods and areas where the rain has not yet precipitated, the rain rates between radar and the weather stations are most similar because the measurements should be near zero. At locations south of the Atlanta region and at times after 21:00Z, the radar estimations and the rain gauge measurements are most dissimilar because the distance from the event is too large.

To investigate how significantly different the radar estimates are from the weather stations, a quantitative student's t-test may be employed if there are 30-40 samples (locations). This is not feasible given our time constraint because the weather stations must be manually selected, and some weather stations either did not record this event or this event is recorded in intervals other than fifteen minutes, which is necessary for the comparison to radar.

5. Conclusion

The optimization of flash flood warning systems is dependent on accurate radar rain rates. In order to formulate a cohesive conclusion on this method of extracting and comparing rain rates between radar and rain gauges, more samples are necessary for the comparison, specifically from events with varying levels of intensity, which is a factor that this project did not consider in the comparison. With a larger sample size, a statistical test may be employed to determine the statistical significance of the average difference of rain rates. With regards to the initial purpose of this project of optimizing flood warning systems, the next steps include comparing these results with other methods of parametrization (Cressman interpolation, method involving Kdp in the installation manual) rather than the traditional ZR-relationship with standard values.

6. Figures

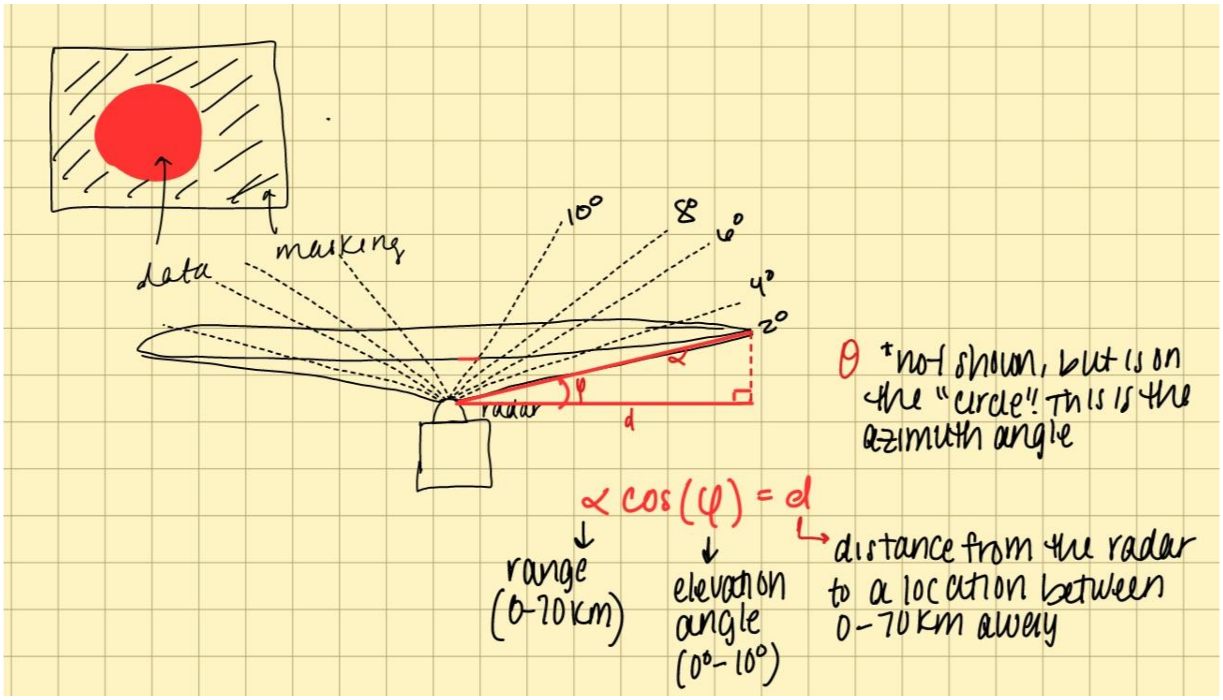


Figure 1. An exaggerated sketch of the Furuno radar and its capabilities. The radar can scan at six elevation angles (sweeps) from 0-10°, and the azimuth angles range from 0-360°. In order to find the distance between the radar and a location a range 0-75 km from the radar, the trigonometric equation above was used.

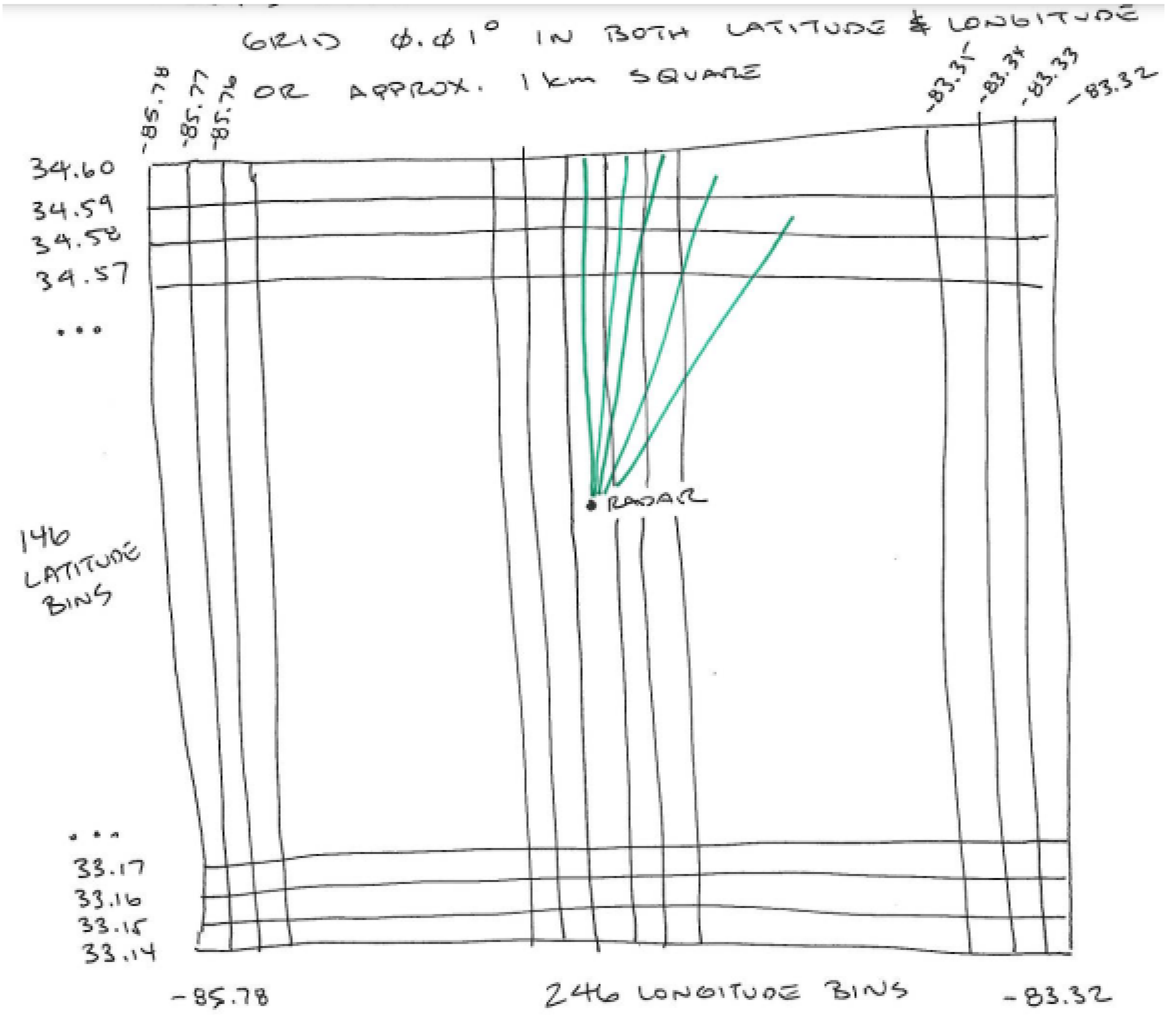


Figure 2. An exaggerated sketch of the latitude and longitude bins used to average rain rates, with each bin representing a projected area of 1 km^2.

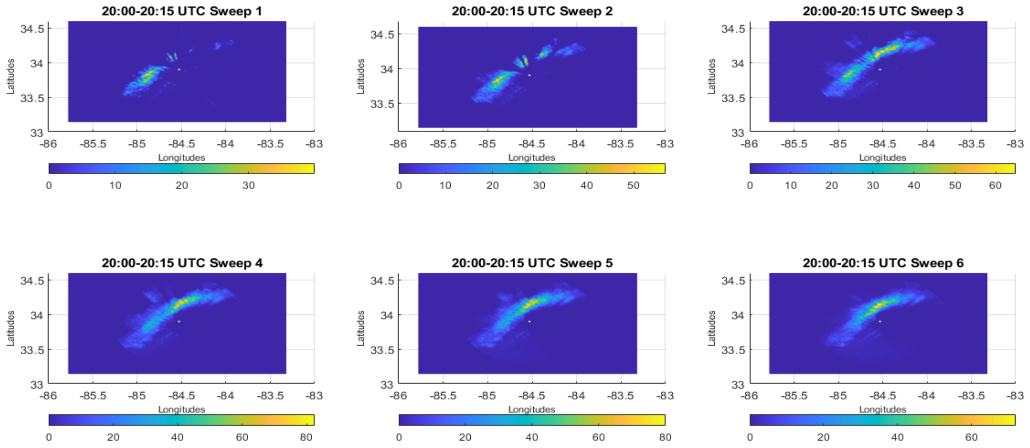
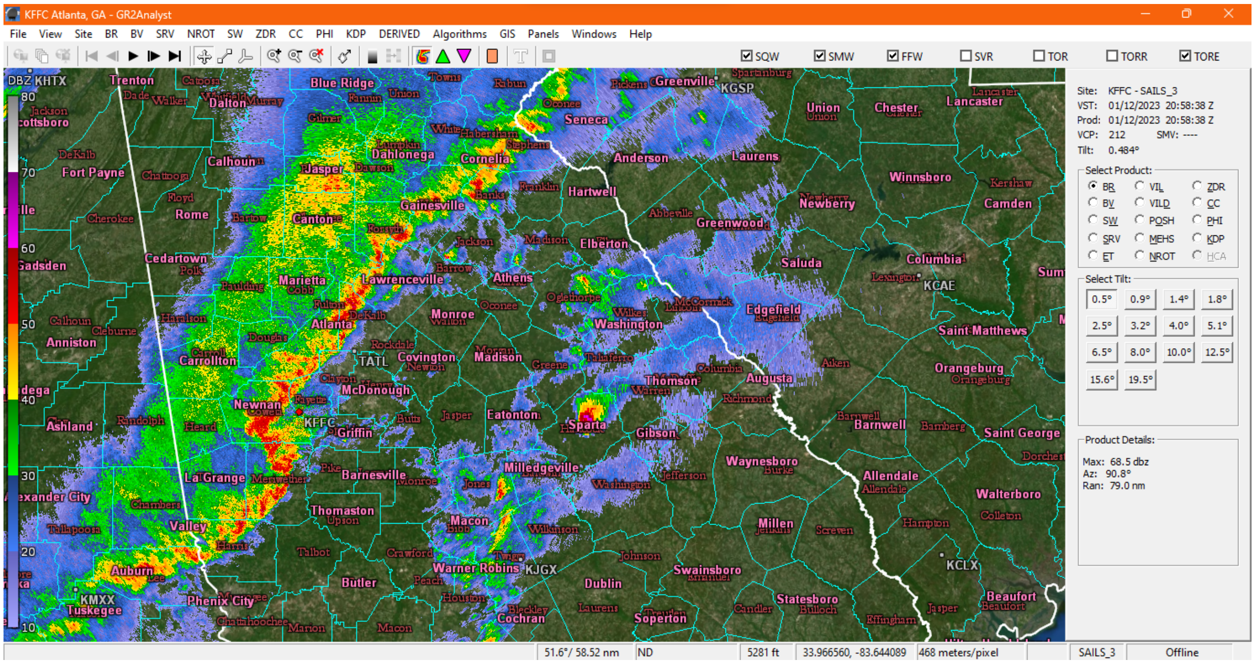


Figure 3. January 12, 2023 fifteen minute averaged radar rainfall rates measured by the X-band Furuno radar for sweeps 1 and 6, which correspond to 0° and 10° elevation angles, respectively. The white space in the center represents the location of the Furuno radar. The x and y axes are latitudes and longitudes.



Site: KFFC - SAILS_3
VST: 01/12/2023 20:58:38 Z
Prod: 01/12/2023 20:58:38 Z
VCP: 212 SMV: ----
Tilt: 0.484°

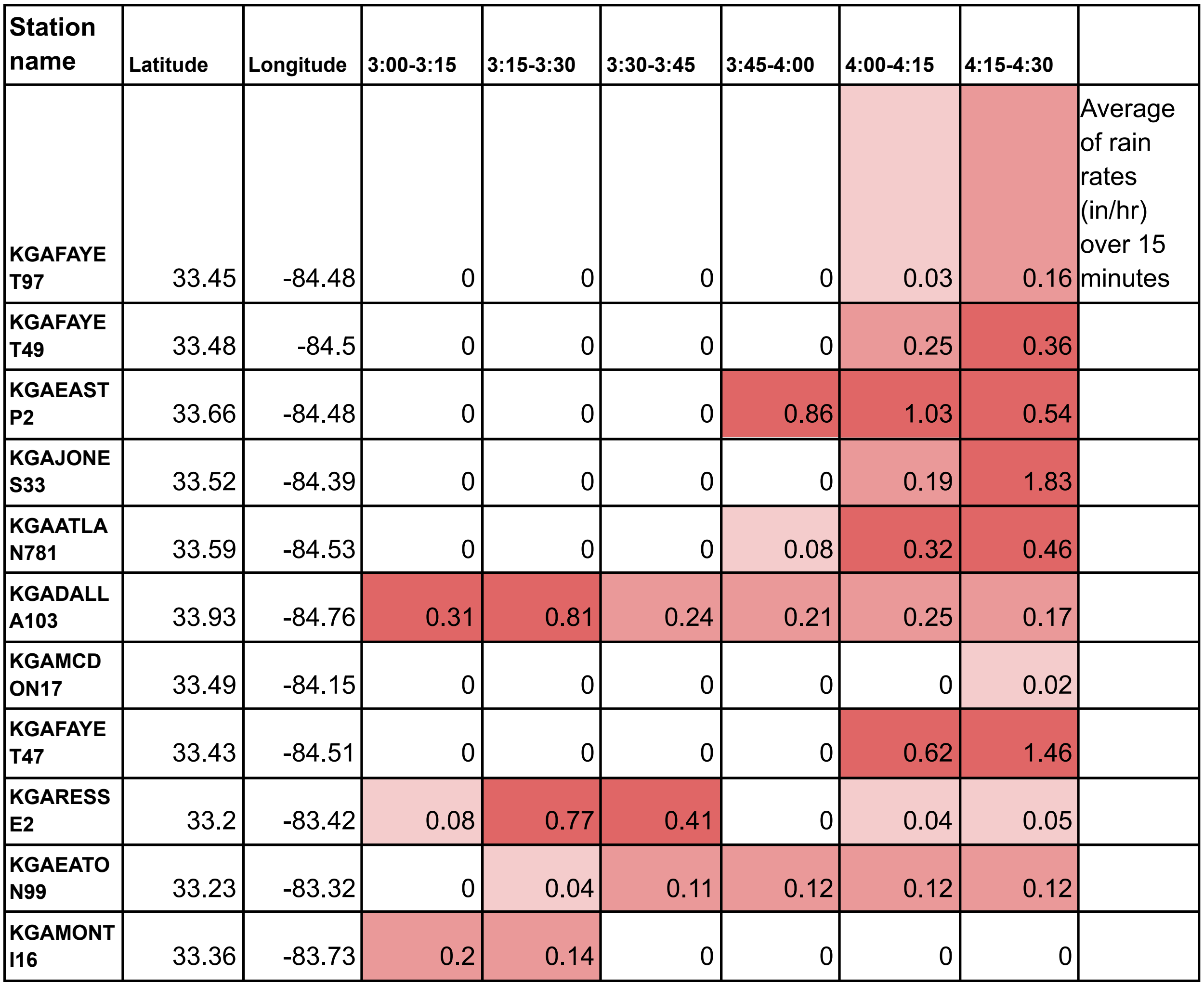
Select Product:
● BR ○ VIL ○ ZDR
○ BV ○ VILD ○ CC
○ SW ○ POSH ○ PHI
○ SRV ○ MEHS ○ KDP
○ ET ○ NROT ○ HCA

Select Tilt:
0.5° 0.9° 1.4° 1.8°
2.5° 3.2° 4.0° 5.1°
6.5° 8.0° 10.0° 12.5°
15.6° 19.5°

Product Details:
Max: 68.5 dbz
Az: 90.8°
Ran: 79.0 nm

51.6°/ 58.52 nm | ND | 5281 ft | 33.966560, -83.644089 | 468 meters/pixel | SAILS_3 | Offline

Figure 4. Squall line engulfing the northwest sector of Atlanta on January 12, 2023 at 21:00Z. This is a base reflectivity map generated from KFFC (Atlanta Regional Airport), where larger dBZ values are indicative of intense rainfall and high rainfall rates



Station name	Latitude	Longitude	3:00-3:15	3:15-3:30	3:30-3:45	3:45-4:00	4:00-4:15	4:15-4:30	
KGAFAYET97	33.45	-84.48	0	0	0	0	0.03	0.16	Average of rain rates (in/hr) over 15 minutes
KGAFAYET49	33.48	-84.5	0	0	0	0	0.25	0.36	
KGAEASTP2	33.66	-84.48	0	0	0	0.86	1.03	0.54	
KGAJONES33	33.52	-84.39	0	0	0	0	0.19	1.83	
KGAATLAN781	33.59	-84.53	0	0	0	0.08	0.32	0.46	
KGADALLA103	33.93	-84.76	0.31	0.81	0.24	0.21	0.25	0.17	
KGAMCDON17	33.49	-84.15	0	0	0	0	0	0.02	
KGAFAYET47	33.43	-84.51	0	0	0	0	0.62	1.46	
KGARESSE2	33.2	-83.42	0.08	0.77	0.41	0	0.04	0.05	
KGAEATON99	33.23	-83.32	0	0.04	0.11	0.12	0.12	0.12	
KGAMONTI16	33.36	-83.73	0.2	0.14	0	0	0	0	

Figure 5. Average rain rates from Weather Underground weather stations of 90 minutes of the January 12 event divided into six 15-minute intervals. The darker gradient indicates heavy precipitation (>0.30 inches per hour) while the lighter gradient indicates light precipitation (0.01-0.10 inches per hour). Values in between are indicative of moderate precipitation.

Sweep 1							
Latitude	**Longitude**	**3:00-3:15**	**3:15-3:30**	**3:30-3:45**	**3:45-4:00**	**4:00-4:15**	**4:15-4:30**
33.45	-84.48	0	0	0	0	0.005	0.02
33.48	-84.5	0	0	0	0	0.28	0.19
33.66	-84.48	0	0.01	0	0.29	0.28	0.03
33.52	-84.39	0	0	0	0	0.33	0.4
33.59	-84.53	0	0	0	0.92	1.05	0.03
33.93	-84.76	0.37	0.061	0.01	0.027	0.03	0
33.49	-84.15	0	0	0	0	0	0
33.43	-84.51	0	0	0	0	0.05	0.3
33.2	-83.42	0	0	0	0	0	0
33.23	-83.32	0	0	0	0	0	0
33.36	-83.73	0	0	0	0	0	0

Figure 6. Average rain rates from the X-band radar at an elevation angle of 0° of 90 minutes of the January 12 event divided into six 15-minute intervals. The darker gradient indicates heavy precipitation (>0.30 inches per hour) while the lighter gradient indicates light precipitation (0.01-0.10 inches per hour). Values in between are indicative of moderate precipitation.

Latitudes	Longitudes	3:00-3:15	3:15-3:30	3:30-3:45	3:45-4:00	4:00-4:15	4:15-4:30	Average difference of rain rate averages for sweep 1
33.45	-84.48	0	0	0	0	0.025	0.14	0.0825
33.48	-84.5	0	0	0	0	-0.03	0.17	0.07
33.66	-84.48	0	-0.01	0	0.57	0.75	0.51	0.455
33.52	-84.39	0	0	0	0	-0.14	1.43	0.645
33.59	-84.53	0	0	0	-0.84	-0.73	0.43	-0.38
33.93	-84.76	-0.06	0.749	0.23	0.183	0.22	0.17	0.2486666667
33.49	-84.15	0	0	0	0	0	0.02	0.02
33.43	-84.51	0	0	0	0	0.57	1.16	0.865
33.2	-83.42	0.08	0.77	0.41	0	0.04	0.05	0.27
33.23	-83.32	0	0.04	0.11	0.12	0.12	0.12	0.102
33.36	-83.73	0.2	0.14	0	0	0	0	0.17

Figure 7. Difference between the weather station and radar averages at sweep 1 for six 15-minute intervals from the January 12 event. Values less than zero (tan) indicate that the radar has overestimated the rain rate. Values more than zero (red) indicate that the radar has underestimated the rain rate. Values equal to zero (green) indicate that the radar and weather station have the same rain rate. Highlighted locations are the minimum and maximum values. Note that values of zero before 21:00Z (4:00 PM EST) may be indicative of no rain.

Sweep 2							
Latitude	**Longitude**	**3:00-3:15**	**3:15-3:30**	**3:30-3:45**	**3:45-4:00**	**4:00-4:15**	**4:15-4:30**
33.45	-84.48	0	0	0	0	0.11	0.43
33.48	-84.5	0	0	0	0	0.86	0.4
33.66	-84.48	0	0.01	0	0.86	0.86	0.06
33.52	-84.39	0	0	0	0	0.78	0.8
33.59	-84.53	0	0	0	1.29	1.36	0.07
33.93	-84.76	1.06	0.45	0.05	0.07	0.13	0.03
33.49	-84.15	0	0	0	0	0	0
33.43	-84.51	0	0	0	0	0.24	0.45
33.2	-83.42	0	0	0	0	0	0
33.23	-83.32	0	0	0	0	0	0
33.36	-83.73	0	0	0	0	0	0

Figure 8. Average rain rates from the X-band radar at an elevation angle of 2° of 90 minutes of the January 12 event divided into six 15-minute intervals. The darker gradient indicates heavy precipitation (>0.30 inches per hour) while the lighter gradient indicates light precipitation (0.01-0.10 inches per hour). Values in between are indicative of moderate precipitation.

Latitudes	Longitudes	3:00-3:15	3:15-3:30	3:30-3:45	3:45-4:00	4:00-4:15	4:15-4:30	Average difference of rain rate averages from sweep 2
33.45	-84.48	0	0	0	0	-0.08	-0.27	-0.175
33.48	-84.5	0	0	0	0	-0.61	-0.04	-0.325
33.66	-84.48	0	-0.01	0	0	0.17	0.48	0.2133333333
33.52	-84.39	0	0	0	0	-0.59	1.03	0.22
33.59	-84.53	0	0	0	-1.21	-1.04	0.39	-0.62
33.93	-84.76	-0.75	0.36	0.19	0.14	0.12	0.14	0.03333333333
33.49	-84.15	0	0	0	0	0	0.02	0.02
33.43	-84.51	0	0	0	0	0.38	1.01	0.695
33.2	-83.42	0.08	0.77	0.41	0	0.04	0.05	0.27
33.23	-83.32	0	0.04	0.11	0.12	0.12	0.12	0.102
33.36	-83.73	0.2	0.14	0	0	0	0	0.17

Figure 9. Difference between the weather station and radar averages at sweep 2 for six 15-minute intervals from the January 12 event. Values less than zero (tan) indicate that the radar has overestimated the rain rate. Values more than zero (red) indicate that the radar has underestimated the rain rate. Values equal to zero (green) indicate that the radar and weather station have the same rain rate. Highlighted locations are the minimum and maximum values. Note that values of zero before 21:00Z (4:00 PM EST) may be indicative of no rain.

Annotated Bibliography

Anagnostou, Marios & Nikolopoulos, Efthymios & Kalogiros, John & Anagnostou, Emmanouil & Marra, Francesco & Borga, Marco & Mair, E. & Bertoldi, Giacomo & Tappeiner, Ulrike. (2014). High-resolution X-band polarimetric radar observations during the HyMeX 2012 Special Observation Period in North-East Italian Alpine Region: Evaluating hydrologic impacts.

The data from C-band and S-band radar is typically the input for nowcasting systems, forecasts that provide weather conditions based on quantitative data on short timescales (usually within a few hours). C-band and S-band radar can reliably monitor rainfall fields from 50-100 km and 100-150 km, respectively, but maintenance requires the calibration of the radar with past or current rainfall events. X-band radar is less expensive, but relative to S-band and C-band radar, the radar beam attenuates at further distances from the radar. However, this means that the radar has higher spatial resolution locally, which would make it ideal for studying urban environments.

Bedient, P. B., Holder, A., Benavides, J. A., & Vieux, B. E. (2003). Radar-based flood warning system applied to tropical storm allison. *Journal of Hydrologic Engineering*, *8*(6), 308–318. https://doi.org/10.1061/(asce)1084-0699(2003)8:6(308)

Flood warning systems use real-time rainfall data from rain gauges or radar to forecast flood events, but some coastal areas have been known to flood immediately after heavy rainfall. Bedient et al. 2003 developed a successful framework from Level 2 NEXRAD data, GIS, and hydrological models to create a flood warning system, and it seems to have accurately predicted flooding events from tropical cyclones and heavy rainfall in urban areas. The use of X-band radar is once again recommended to use when comparing rain gauge and radar data.

Borga, Marco & Marra, Francesco & Gabella, Marco. (2022). Rainfall estimation by weather radar. 10.1016/B978-0-12-822544-8.00016-0.

Using a software called Rainscanner, researchers were able to observe radar rainfall rates in real-time for different weather events. The typical spatial resolution of quantitative rainfall measurement between radar and rain gauges is 1 km^2 and 5 minutes for temporal resolution. This was an optimal relationship for this paper, but this may not be applicable to this research since the temporal resolution of the rain gauges in the Atlanta-Athens region is 15 minutes.

Collier CG (2009). On the propagation of uncertainty in weather radar estimates of rainfall through hydrological models. Meteorological Applications 16:35–40. https://doi.org/10.1002/met.120

In corroboration with Prat & Ana (2009), this paper explains that the use of dynamical, time-dependent Z-R relationships would provide more accurate parameters for the

Marshall-Palmer (1948) reflectivity-rainfall rate equation. This is because the parameters depend on microphysical interactions between the drops and drop size distributions (DSD). Different Z-R relationships can be derived from the same event using different tools (e.g. radars, rain gauges, disdrometers, etc), which is why this dynamical relationship must be studied. This would be more relevant to future discourse following this research.

Cressman, G. P. (1959). An Operational Objective Analysis System, Monthly Weather Review, 87(10), 367-374. Retrieved Nov 21, 2022, from https://journals.ametsoc.org/view/journals/mwre/87/10/1520-0493_1959_087_0367_aooas_2_0_co_2.xml

The Cressman interpolation technique has been used by researchers who have also used RainMap, the software that will be used to examine radar rainfall rates in the Atlanta-Athens region. It is an interpolation function that acts as a correction method that can be applied to different kinds of variables. For instance, in this paper, it was used on the divergence equation to reduce error and compare it to another dynamical equation. It can also be used as an interpolation function to interpolate station data to grid data for maps in GIS.

Diss, S., Jacques, T., Lavabre, J., Ribstein, P., Moreau, E., Chatelet, J. (2009). Ability of a dual polarized X-band radar to estimate rainfall. Advances in Water Resources. 32. 975-985. 10.1016/j.advwatres.2009.01.004.

This paper compares X-band and S-band radar with a dual polarimetric radar while surveying four extreme weather events with flash floods. The accuracy of X-band radar decreased beyond 60 km, but at closer ranges, both radars had similar accuracy with radar rainfall estimation. X-band does not require calibration with existing rainfall records, so it is useful to use in areas with a limited rain gauge network. It is also important to note that the S-band radar was only used in areas with high precipitation, as this may have contributed to the results being similar to X-band radar (considering it reduces in spatial accuracy further away from the radar). Bias between X-band and S-band radar also depends on storm type, so it is important to categorize the storms before comparing radar and rain gauge totals. For the statistical analysis, the Nash-Sutcliffe criterion, which analyzes radar rainfall and rain gauge points near the x=y axis.

Gires A, Tchiguirinskaia I, Schertzer D, Schellart A, Berne A, Lovejoy S (2014) Influence of small scale rainfall variability on standard comparison tools between radar and rain gauge data. Atmos Res 138:125–138. https://doi.org/10.1016/j.atmosres.2013.11.008

Instead of using pre-established a and b parameters of the reflectivity-rainfall rate equation ($Z = aR^b$) based on storm type and location, Gires et al. (2014) adjusted the parameters according to the rain gauge data. This process can produce a lot of errors because rain gauges are stationary measurements and radar measurements are 3D volume projections onto a 2D surface. It is important to establish a method of converting rain gauge data spatially and temporally.

Hewitson, B. C., & Crane, R. G. (2005). Gridded Area-Averaged Daily Precipitation via Conditional Interpolation. *Journal of Climate*, *18*(1), 41–57. http://www.jstor.org/stable/26251998

This paper implements the Cressman interpolation method to define the space of a precipitation field for a climate model, but the method has been concluded to overestimate these values because it overestimates the spatial grid points of the cells associated with rainfall. Non-radar stationary measurements were also implemented into the interpolation.

McLeod, J., Shepherd, M., Konrad, C.E.. (2017). Spatio-temporal rainfall patterns around Atlanta, Georgia and possible relationships to urban land cover, Urban Climate, Volume 21, Pages 27-42, ISSN 2212-0955, https://doi.org/10.1016/j.uclim.2017.03.004.

This paper used satellite derived rainfall estimates to determine the relationship between urban land cover and extreme precipitation events. Urban heat islands, such as Atlanta, are expected to experience more intense weather events (e.g. flooding) as the climate system contributes to more intense convective outbreaks.

Marshall JS, Palmer WMK (1948) The distribution of raindrops with size. J Meteorology 5:165–166

The Z-R relationship (also called the reflectivity-rainfall rate equation) $Z = aR^b$ was derived in this paper. Radar reflectivity, Z, is measured in mm^6/m^3 and is a measure of the intensity of returned energy to radar. Rain rate, R, is measured in mm/hr and is a measure of the intensity of rainfall if rain rate was constant.

Pappa, A., Bournas, A., Lagouvardos, K., & Baltas, E. (2021). Analysis of the Z-R relationship using X-Band weather radar measurements in the area of Athens. Acta Geophysical. 69. 10.1007/s11600-021-00622-5.

This paper analyzes Z-R relationships using X-band weather radar measurements in Attica, Greece. The radar outputs radar reflectivity values every 2 minutes, but the rain gauge is a 10 minute point measurement. To fix this, Pappa et al. 2021 took the average of 5 2-minute datasets over the same time period of the rain gauge datasets. To ensure that the radar measurements and the rain gauge measurements did not vary spatially, they only used the cells that corresponded to the station's locations and extracted them to conserve memory.

Pattani, K. (2010). *Evaluation of optimal real-time reflectivity-rainfall rate (Z-R) functional relationships* (thesis).

This paper also concludes that with the use of X-band radar, radar rates generally overestimated rainfall totals compared to rain gauges despite the study of different rainfall events (based on intensity). The parameters better suited for seaside regions are a = 200, b = 1.6, and the parameters better suited for stations closer to the radar or in high elevations are a = 431, b = 1.25. A GRG solver (generalized reduced gradient optimization solver) built into MATLAB was used to derive a and b parameters for the Z-R relationship rather than testing the various existing methods because it minimizes error. However, they received their radar data from NCDC radar archives, and there is a compatible NOAA WCT ArcGIS R^3 tool that converts radar reflectivity to 15 minute intervals of rainfall to match the temporal scale of the rain gauge network. This will not be feasible for this project because the source of radar data will come from the X-band Furuno radar.

Prat, O., Barros, A. (2009). Exploring the Transient Behavior of ZR Relationships: Implications for Radar Rainfall Estimation. Journal of Applied Meteorology and Climatology. 48. 10.1175/2009JAMC2165.1.

Radar scans increase with height as the distance between the radar and atmospheric object increases due to Earth's curvature, while the rain gauge remains stationary and measures on Earth's surface. X-band has a higher spatial resolution than C-band and S-band radar, so changing the a and b parameters in relation to rain gauge data, as suggested by Gires et al. (2014), will be feasible.

Yoon, S.-S.; Lim, S.-H. (2022). Analyzing the Application of X-Band Radar for Improving Rainfall Observation and Flood Forecasting in Yeongdong, South Korea. Remote Sens. 14, 43. https://doi.org/10.3390/rs14010043

It has been concluded from the data of this paper that X-band radar is less likely to underestimate rainfall totals. Yoon & Lim (2022) also developed a flood forecasting method with a nomograph based on a specific differential phase relationship with rain rate $R(K_{DP}) = 23.7K_{DP}^{0.87}$ and accurately estimated rainfall data with the Z-R relationship $Z=200R^{1.6}$. Future discourse could estimate the accuracy of rain rate with an R-KDP relationship.

Yoon, S.-S., & Nakakita, E. (2017). Application of an X-band multiparameter radar network for rain-based urban flood forecasting. *Journal of Hydrologic Engineering*, *22*(5). https://doi.org/10.1061/(asce)he.1943-5584.0001281

Radar data can be used for flood prediction in conjunction with a nomograph, as this method has been proven accurate (Yoon & Lim 2022). KDP-R and Z-R relationships were used to accurately estimate rainfall intensity. It is important to compare rain gauges with radar rainfall in order to optimize urban flood warning systems, as urban floods can occur relatively quickly with intense rainfall. Earlier warnings (10-15 minutes ahead) are optimal for urban areas.