University of North Carolina Asheville
Journal of Undergraduate Research
Asheville, North Carolina
Spring 2026

Investigating Potential Radar Coverage Gaps in Western North Carolina During Tropical Storm Helene and Its Predecessor Rainfall Event

Zachary T. Moss

Department of Atmospheric Sciences
The University of North Carolina Asheville
One University Heights
Asheville, North Carolina 28804 USA

Faculty Mentor: Dr. Christopher Godfrey

Abstract

A long-recognized substantial gap in low-level radar coverage exists across portions of the state of North Carolina. These gaps are due to beam blockage caused by obstructions from terrain, long distances from the nearest radars, or a combination of both. As a consequence, precipitation estimates, precipitation type identification, and severe weather and flash flood warning capabilities have become compromised, especially during high-impact weather events. The catastrophic precipitation from Tropical Storm Helene and its predecessor rainfall event provide a unique opportunity to highlight these gaps in radar coverage in Western North Carolina. Quantitative precipitation estimates from multi-radar multi-sensor data are compared with rainfall measurements from in-situ platforms across the region through statistical comparisons. This investigation will help to address the hypothesis that radar beam blockage remains a significant barrier to quantitative precipitation estimation in the mountains.

Introduction

Weather radar plays a critical role in modern meteorology, providing real-time observations of precipitation structure, intensity, and evolution. These observations are essential for forecasting hazardous weather, issuing warnings, and producing quantitative precipitation estimates (QPEs). In the United States, the Weather Surveillance Radar–1988 Doppler (WSR–88D) network serves as the primary observational system supporting severe weather and flash flood warnings, aviation safety, and water resource management (National Weather Service 2019).

Despite the extensive national radar network, coverage limitations persist in regions with complex terrain. In mountainous areas such as Western North Carolina (WNC), radar coverage is often degraded due to terrain-induced beam blockage, increasing beam width with distance from radar sites, or a combination of both. These limitations can negatively impact precipitation estimates, precipitation type identification, and warning capabilities during high-impact weather events (NWS 2019, 2020).

Previous assessments of radar coverage across the United States have produced mixed conclusions. A National Weather Service (NWS) study evaluating hazardous weather warnings and radar coverage suggested that no significant gaps exist at the national scale (NWS 2019 & 2020), yet local and regional analyses continue to highlight deficiencies in mountainous and complex terrain environments such as WNC (Westrick et al. 1999). These discrepancies underscore the importance of region-specific evaluations of radar performance.

The catastrophic rainfall associated with Tropical Storm Helene and its predecessor rainfall event provides a unique opportunity to assess these limitations. During this event, widespread heavy precipitation and flooding occurred across WNC, offering a case study to evaluate the performance of radar-derived QPE relative to in-situ observations.

This study investigates potential radar coverage gaps in WNC by comparing Multi-Radar Multi-Sensor (MRMS) QPEs with rainfall measurements from in-situ observation networks. Specifically, this study seeks to answer the following research question: To what extent do radar coverage limitations contribute to biases in QPEs in WNC during high-impact rainfall events?

Data and Methods

This study evaluates radar-derived QPEs in WNC during the passage of Tropical Storm Helene and its predecessor rainfall event. The analysis focuses on the period from 0000 UTC 25 September 2024 to 0000 UTC 28 September 2024, encompassing the full duration of the multi-day precipitation event.

Data Sources

Radar-derived precipitation estimates were obtained from the MRMS system, which integrates observations from multiple radar platforms and other data sources to produce high-resolution QPE fields (NOAA Multi-Radar/Multi-Sensor System). MRMS data provide near-real-time precipitation estimates across the contiguous United States and are widely used for hydrometeorological applications (Zhang et al. 2016).

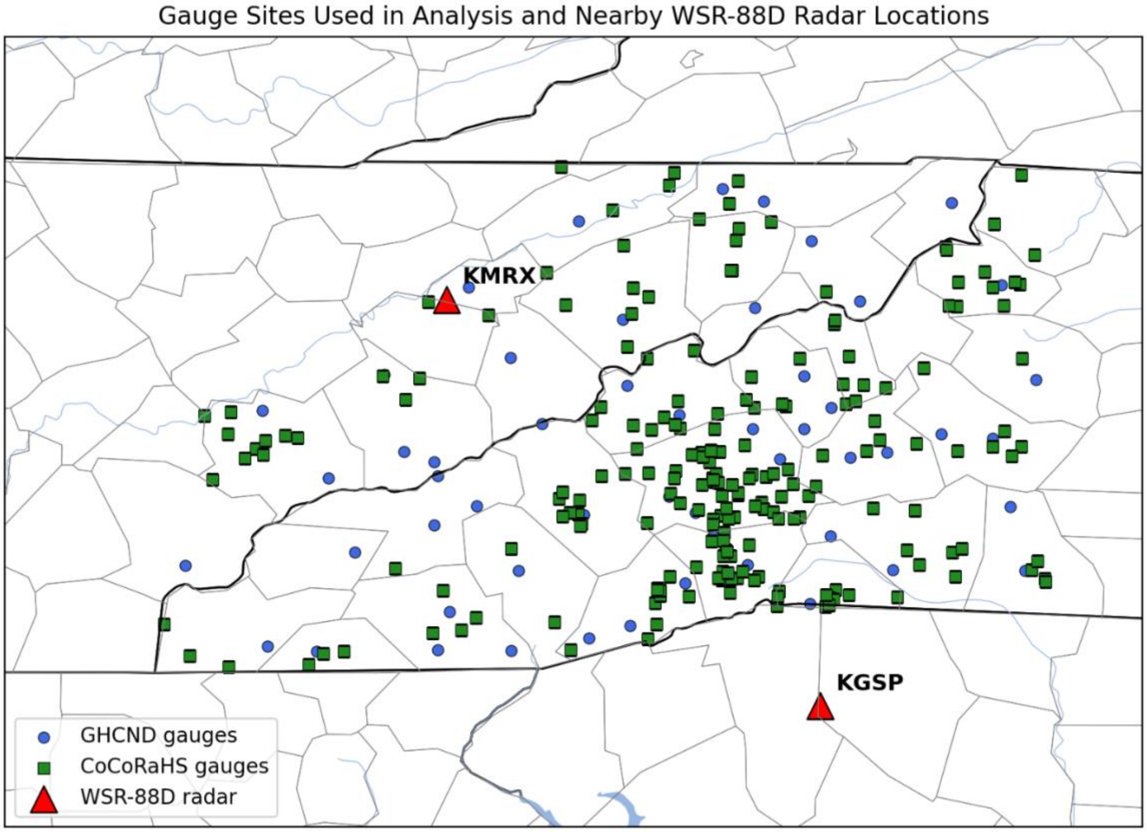

Figure 1. Gauge observation sites used in the MRMS comparison across WNC, separated by GHCN–D and CoCoRaHS networks. Nearby WSR-88D radar sites KGSP and KMRX are shown for geographic context.

In-situ precipitation measurements were collected from multiple observational sites across WNC and surrounding regions to provide a basis for comparison with MRMS estimates. These datasets include observations from the Community Collaborative Rain, Hail, and Snow (CoCoRaHS) network and the Global Historical Climatology Network–Daily (GHCN–D), both of which were accessed through the NOAA National Centers for Environmental Information GHCN–D archive. These networks provide point-based precipitation measurements with varying temporal resolutions, ranging from sub-hourly to daily accumulations (Menne et al. 2012).

All precipitation measurements were converted to consistent units (millimeters) and aggregated to represent total accumulated precipitation over the study period. Station metadata, including latitude, longitude, and elevation, were retained for spatial analysis.

Data Processing and Merging

To enable direct comparison between MRMS QPE and in-situ observations, precipitation datasets from each observational network were combined into a unified dataset. Each station was assigned a network identifier, and duplicate or overlapping observations were removed where necessary.

MRMS precipitation values, which have a spatial resolution of 1 km, were matched to station locations using nearest-neighbor selection based on geographic coordinates and station identifiers. This approach ensured that each station observation was paired with the closest corresponding MRMS grid point. The resulting merged dataset contained, for each station, the 72-hour observed precipitation total, the corresponding 72-hour MRMS-derived precipitation estimate, and associated station metadata.

Statistical Analysis

To assess the performance of MRMS QPE relative to in-situ observations, several statistical metrics were calculated. The bias was defined as the difference between MRMS-derived precipitation and observed precipitation:

$$Bias = P_{MRMS} - P_{obs}$$

where P_{MRMS} is the MRMS precipitation estimate and P_{obs} is the observed precipitation at each station. Stations were further classified based on bias sign (overestimation vs. underestimation) to identify any systematic tendencies in radar-derived QPE.

Results and Discussion

The comparison between MRMS-derived QPEs and in-situ gauge observations revealed systematic differences across WNC during the 72-hour study period. Overall, MRMS estimates exhibited substantial variability in both magnitude and spatial distribution when compared to observed precipitation totals.

The scatterplot (Fig. 2) illustrates the relationship between MRMS-derived precipitation and gauge observations. While a general positive relationship is evident, significant scatter around the one-to-one line indicates notable discrepancies between the two datasets. In particular, MRMS frequently underestimated precipitation at higher observed totals, as many data points fell below the one-to-one line for larger gauge values. This pattern suggests that MRMS struggled to capture the most intense precipitation accumulations during the event.

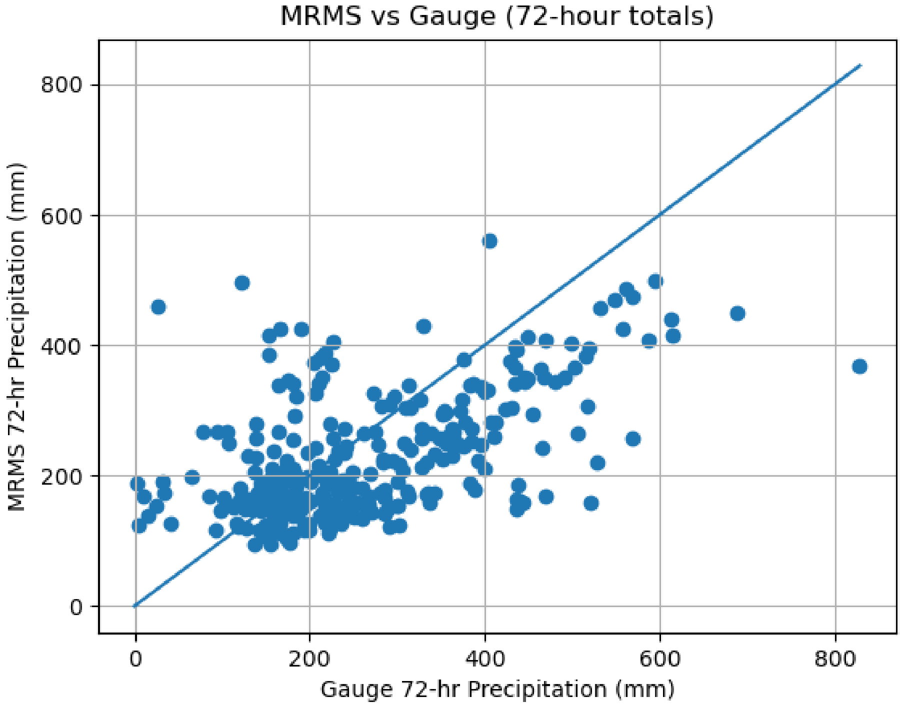

Figure 2. Scatterplot comparing MRMS-derived 72-hour rainfall totals (mm) with corresponding gauge observations across WNC during the passage of Tropical Storm Helene and its predecessor rainfall event (0000 UTC 25 September 2024 to 0000 UTC 28 September 2024). The solid line represents the 1:1 relationship. Points above the line indicate overestimation by MRMS, while points below the line indicate underestimation.

Spatial patterns of bias further highlight these discrepancies (Fig. 3). Bias values, defined as MRMS minus observed precipitation, show widespread underestimation by MRMS. The strongest negative biases are concentrated in portions of central and southern WNC, where several stations exhibit large underestimates exceeding 200–400 mm. Many of the stations exhibiting stronger negative bias were also located at relatively higher elevations (Fig. 3), further supporting the hypothesis that terrain influences radar-derived precipitation estimates in WNC.

In contrast, some localized regions display positive bias, indicating overestimation by MRMS; however, these occurrences are less spatially coherent and generally smaller in magnitude (99 stations exhibited overestimation) compared to the widespread underestimation (212 stations exhibited underestimation). This asymmetry between underestimation and overestimation suggests that terrain-induced limitations more often reduce radar-derived precipitation estimates than inflate them.

The observed discrepancies between MRMS and gauge measurements are consistent with known limitations of radar coverage in mountainous regions (Westrick et al. 1999). As radar beams propagate away from the radar site, beam height increases with distance and can overshoot lower-level precipitation, particularly in regions with complex topography. Additionally, terrain features can partially or fully block the radar beam, further degrading the quality of radar observations. Because Tropical Storm Helene was an extreme precipitation event, the magnitude of the observed biases may not be representative of most rainfall events in WNC. However, high-impact events provide an important opportunity to evaluate radar performance under conditions where accurate precipitation estimation is most critical.

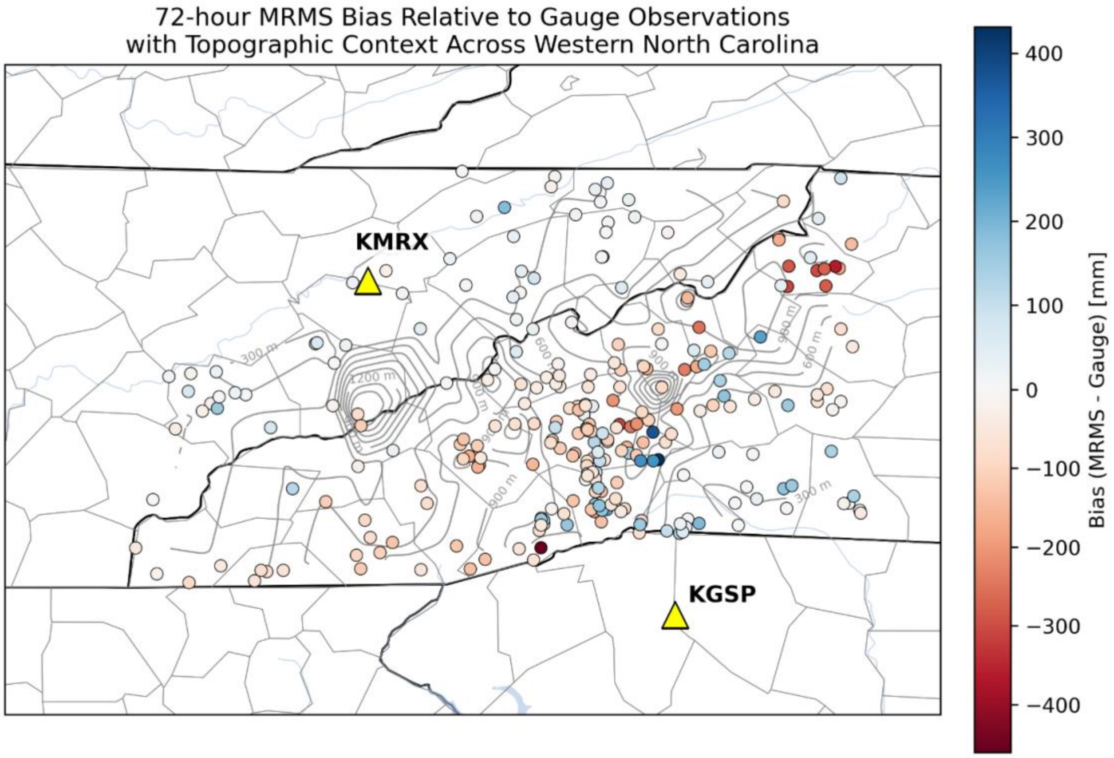

Figure 3. A spatial distribution of 72-hour precipitation bias (mm) at gauge locations across WNC during the passage of Tropical Storm Helene and its predecessor rainfall event (0000 UTC 25 September 2024 to 0000 UTC 28 September 2024). Bias is defined as MRMS-derived precipitation minus observed gauge precipitation. Positive values (blue points) indicate overestimation by MRMS, while negative values (red points) indicate underestimation. Gray contour lines represent interpolated elevation contours (m) generated from station elevation data and are included to provide topographic context across the study region. Nearby WSR-88D radar sites KGSP and KMRX are shown for geographic context.

Conclusion

This study evaluated the performance of MRMS-derived QPE in WNC during the 72-hour event associated with Tropical Storm Helene and its predecessor rainfall. Comparisons with in-situ gauge observations revealed substantial discrepancies, with MRMS frequently underestimating precipitation totals, particularly in regions of complex terrain.

The spatial distribution of bias indicates that underestimation is widespread across the region and is most pronounced in areas where radar beam blockage and increasing beam height likely limit low-level sampling of precipitation. While some localized overestimation was observed, these instances were less spatially coherent and generally smaller in magnitude. Overall, the results suggest that terrain-induced limitations play a significant role in degrading radar-derived precipitation estimates across WNC.

These findings support the hypothesis that radar coverage gaps remain a critical challenge for accurately estimating precipitation in mountainous regions. The tendency for MRMS to underestimate high precipitation totals has important implications for flood forecasting and hazard mitigation, as it may lead to an underrepresentation of extreme rainfall during high-impact events.

Future work should explore additional data sources, including numerical weather prediction output and satellite-derived precipitation estimates, to further quantify these discrepancies and assess potential improvements in radar-derived QPE accuracy. Expanding observational coverage and evaluating the potential impact of additional radar installations may also provide valuable insights for improving precipitation estimation and enhancing weather hazard preparedness in the region.

Acknowledgments

This research was conducted as part of the NC Radar Project at the University of North Carolina Asheville. The author thanks Dr. Christopher Godfrey for guidance and mentorship throughout the project. Additional appreciation is extended to collaborators and contributors who assisted with data collection and analysis. The author also appreciates the constructive feedback provided during the manuscript review process, which helped improve the clarity and presentation of the study. This work benefited from precipitation datasets provided by CoCoRaHS and GHCN–D.

References

Menne, M.J., I. Durre, B. Korzeniewski, S. McNeill, K. Thomas, X. Yin, S. Anthony, R. Ray, R.S. Vose, B.E. Gleason, and T.G. Houston, 2012: Global Historical Climatology

Network–Daily (GHCN-D), version 3. NOAA National Climatic Data Center, https://doi.org:10.7289/V5D21VHZ

National Weather Service (U.S.), 2019: Study: Gaps in NEXRAD Radar Coverage. https://repository.library.noaa.gov/view/noaa/25911

National Weather Service (U.S.), 2020: Report to Congress: Gaps in NEXRAD Radar Coverage. https://doi.org/10.25923/kmy7-7q82

NOAA Multi-Radar/Multi-Sensor System (MRMS), https://registry.opendata.aws/noaa-mrms-pds

Westrick, K. J., C. F. Mass, and B. A. Colle, 1999: The Limitations of the WSR-88D Radar Network for Quantitative Precipitation Measurement over the Coastal Western United States. Bull. Amer. Meteor. Soc., **80**, 2289–2298, https://doi.org/10.1175/1520-0477(1999)080%253C2289:TLOTWR%253E2.0.CO;2.

Zhang, J., and Coauthors, 2016: Multi-Radar Multi-Sensor (MRMS) Quantitative Precipitation Estimation: Initial Operating Capabilities. *Bulletin of the American Meteorological Society*, **97**, 621–638, https://doi.org/10.1175/BAMS-D-14-00174.1.