2.3 AN EXAMINATION OF FROZEN PRECIPITATION IMPACTS ON MRMS Q3 DURING WINTER PRECIPITATION EVENTS

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1. INTRODUCTION

Accurate surface precipitation measurements from rain gauges are critical to short-fused operational applications and long-term seasonal and climatological assessments. Direct surface measurements are also vital for modeling and verification of hydro-meteorological prediction as well as for the calibration of remote sensing quantitative precipitation estimates (QPE). While rain gauge measurements are widely considered as "ground truth," gauges not vetted by a quality control (QC) procedure can impact the verification and calibration of radar-derived precipitation estimation (Steiner et al. 1999).

Challenges regarding rain gauge measurement accuracy have been well documented; however, additional difficulties arise when rain gauges are also tasked to measure non-liquid precipitation. While certain gauge types have some skill in measuring solid, winter precipitation, the instrumentation can be subject to blockage of the gauge orifice or accumulation on the side of the orifice walls (Goodison et al. 1998). Unmeasured accumulations collected on the orifice of weighing gauges are not recorded until falling into the weighing bucket, usually after an increase of the ambient air temperature (Goodison et al. 1998). Increased evaporative loss of melted precipitation and enhanced sublimation of newly fallen snow from heating elements and high ambient temperatures have also been observed (Metcalfe and Goodison 1992, 1993).

Gauges capable of measuring the liquid equivalent of solid precipitation are also subject to error with measurement accuracy and efficiency. Errors of automated gauges generally ranged from 20% to 50% due to undercatch in windy conditions (Rasmussen et al. 2012). Collection efficiency in windy conditions are also dependent upon snow crystal types and mass, degrees of riming and aggregation, varying turbulence intensity, blowing snow, and oscillatory motions of the weighing mechanism (Goodison et al. 1998; Rasmussen et al. 2012).

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Real-time multi-sensor QPE systems are dependent upon the use of automated gauge networks for bias correction and verification of in-situ measurements. The Multi-Radar Multi-Sensor (MRMS) QPE system (hereinafter denoted as Q3) utilizes a series of radars and automated rain gauge networks across the contiguous United States and southern Canada to generate high spatio-temporal QPE mosaics (Zhang et al. 2011). Q3 ingests and quality controls (QC) thousands of hourly gauge observations for use in gauge-derived and gauge bias-corrected QPE products. The impacts of winter precipitation types on the ability for gauges to properly measure precipitation can degrade QPE outputs; thus, a greater understanding is needed on how to mitigate adverse impacts of frozen precipitation with automated QPE generation. This study examines the impacts of winter precipitation on the hourly automated real-time rain gauge observations ingested by Q3. This includes an understanding of the quantity of gauges impacted throughout a winter season both during and after significant winter events.

2. DATA AND METHODOLOGY

Hourly gauge data ingested by Q3 from 0000 UTC 1 October 2013 to 0000 UTC 1 April 2014 from a total of 11,921 gauge sites were examined across the entire MRMS domain (Fig. 1). Automated real-time hourly gauge data were obtained from the National Centers for Environmental Prediction (NCEP), the National Operational Hydrologic Remote Sensing Center (NOHRSC), and the Oklahoma Climate Survey (OCS) Mesonet. This totaled approximately 4.08×10^7 non-missing hourly gauge observations. Statistical analysis of the gauge observations were computed for each hour and at each gauge site over the entire study period and compared to each collocated 1 km^2 Q3 radar-only QPE (hereinafter referred to as Q3RAD) grid cell (Zhang et al. 2011). Comparisons between non-missing gauge and Q3RAD hourly values were assigned one of the four following classifications:

- Both reporting no precipitation (G, R = 0),
- Both reporting precipitation (G, R > 0),
- Gauge reporting precipitation but Q3RAD does not (G > 0, R = 0), or
- Q3RAD reporting precipitation but the gauge does not (G = 0, R > 0).

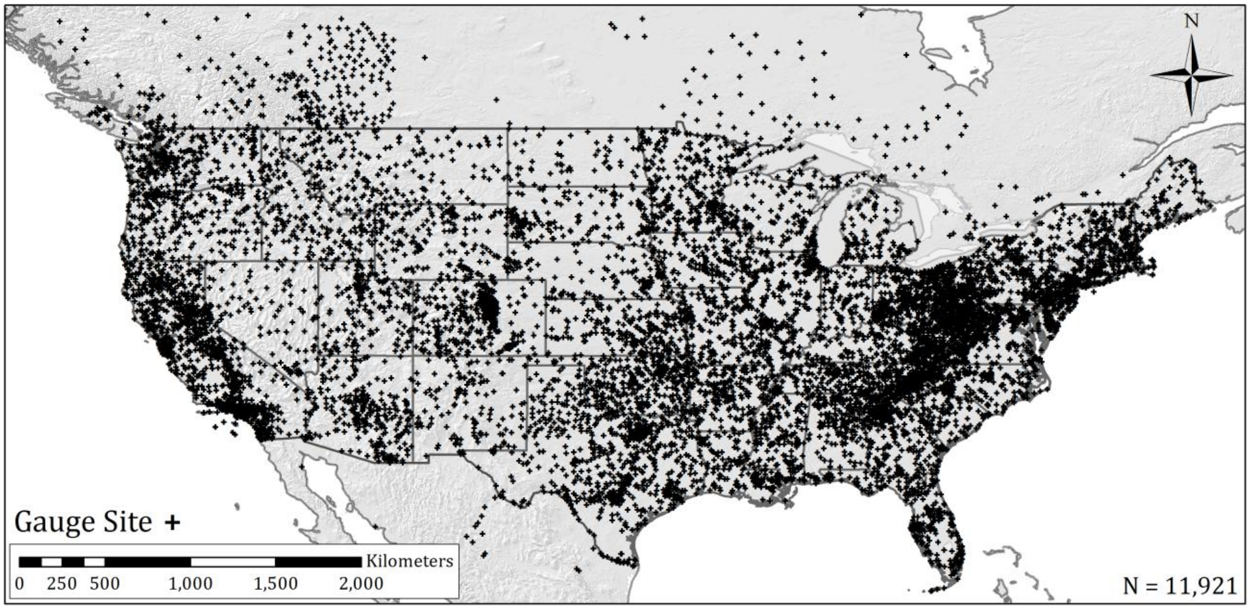

Figure 1. Location of all gauge sites ingested by Q3 during the study period.

Gauge and Q3RAD comparisons were assessed against the Rapid Refresh (RAP) model surface wet-bulb temperature (T_{wb}) and a Radar Quality Index (RQI) derived by beam blockage coverage and melting layer impacts (Zhang et al. 2012). Approximately 89.3% of all observations were classified as G, R = 0 and were excluded from the study. RAP model surface T_{wb} analysis utilized a threshold of 0°C to delineate environments that were predominantly conducive for solid, winter precipitation types. Spatial evaluation over the entire temporal period utilized sites with data that was available at least 90% of the time with an average RQI value of at least 0.1 to ensure quality results and consistent radar coverage. Observations where the gauge became blocked or frozen by solid precipitation were statistically examined up to six hour prior to becoming "stuck" to assess gauge performance during periods of potential partial impacts or transitioning surface precipitation types. Gauge observations were compared to collocated Q3RAD estimates from six hours prior to becoming stuck (T = -6) to one hour prior (T = -1). Both the gauge and collocated Q3RAD grid point had to record non-zero values from T = -6 to T = -1 and then meet the G = 0, R > 0 criteria along with a RAP surface T_{wb} ≤ 0°C at the hour the gauge became stuck (T = 0).

3. ANALYSIS OF WINTER PRECIPITATION IMPACTS

3.1 *Gauge Observation Analysis*

Analysis of all available gauge and Q3RAD values over the entire temporal period determined that G = 0, R > 0 events were more prevalent than G, R > 0 events. Figure 2 displays the distribution of gauge versus Q3RAD comparisons when separating the observations based on a RAP model surface T_{wb} threshold of 0°C and when at least one sensor reported a non-zero precipitation accumulation. The findings yielded two sets of proportionalities. The percent of G, R > 0 events reduced from 46.9% to 10.6% when the surface T_{wb} was supportive for solid, winter precipitation. In contrast, the amount of G = 0, R > 0 observations nearly doubled from 33.9% in above-freezing surface T_{wb} conditions to 62.5% in surface T_{wb} ≤ 0°C regimes. The significant reduction of G, R > 0 events along with the increase of G = 0, R > 0 observations when the surface T_{wb} is at or below freezing highlights the difficulties of rain gauges measuring winter precipitation types.

The average number of gauge sites classified as G = 0, R > 0 in regions where the surface T_{wb} ≤ 0°C was 270 per hour over the study period (Figure 3). There were 11 events totaling 102 hours where at least 1000 gauge sites were G = 0, R > 0. The majority of G = 0, R > 0 events were when hourly Q3RAD was less than 0.05 in (1.27 mm); however, there were 291 hours when there were at least 100 observations of G = 0, R ≥ 0.05 in (1.27 mm), with a maximum of 515 observations at 0300 UTC 13 February 2014. Three of the more significant winter events had at least one hour where 40.0% or more of the gauge sites had Q3RAD ≥ 0.05 in (1.27 mm). Stuck gauges during moderate to heavy solid, winter precipitation rates would produce a zero gauge observation while hourly Q3RAD values exceeded 0.50 in (12.7 mm).

Figure 4 shows the number of hours at each gauge site with 90% data availability when G = 0, R > 0, the surface T_{wb} ≤ 0°C, and the average RQI ≥ 0.1 (i.e., radar coverage was present). The Pacific coastal region and the southern United States had less than 40 hours of stuck observations, with some sites having zero stuck observations. In contrast, areas from the intermountain western United States across the northern Plains to

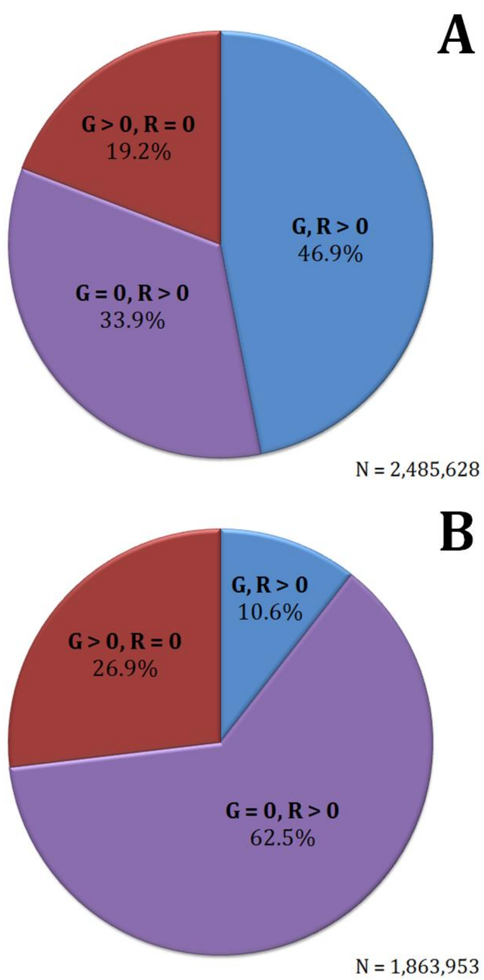

Figure 2. Percentage of each hourly comparison classification type between gauges and Q3RAD for when A) RAP model surface T_{wb} > 0°C and B) surface T_{wb} ≤ 0°C.

New England had over 200 hours of stuck observations. Some areas reported over 400 hours of G = 0, R > 0 observations. Variations in the number of G = 0, R > 0 hours in the western United States were a result of intermittent radar coverage based on RQI.

3.2 *Quality of Observations Before Becoming "Stuck"*

Gauge observations showed diminishing quality in the hours prior to becoming stuck. Analysis of 4086 gauge observations that reported precipitation for at least six hours prior to becoming stuck found a notable change in behavior within the last three hours before becoming completely stuck. Statistical evaluation showed a slight underestimation by Q3RAD with an average mean bias ratio of approximately 0.95 from T = -6 to T = -4 and a correlation coefficient (CC) above 0.500 (Figure 5A-C). By T = -3, the mean bias ratio increased to 1.010 while the CC decreased to 0.454 (Figure 5D). These trends continued to T = -1 with a mean bias ratio of 1.686 and a CC of 0.192 (Figure 5F).

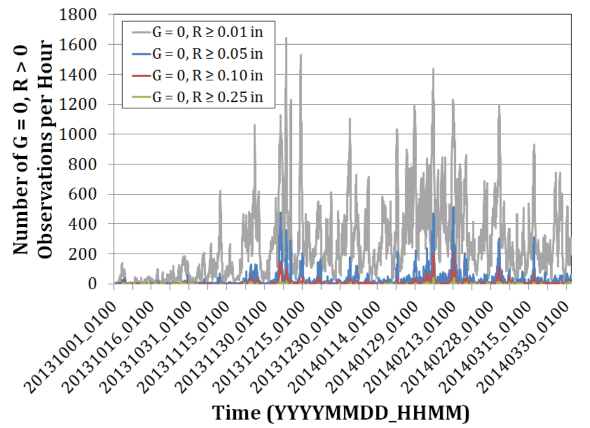

Figure 3. Number of G = 0, R > 0 observations per hour when RAP model surface T_{wb} ≤ 0°C for Q3RAD values of at least 0.01 in. (gray), 0.05 in. (blue), 0.10 in. (red), and 0.25 in. (green).

The mean bias ratio would suggest a significant overestimation by Q3RAD; however, these statistical values more likely show the resulting partial impacts of frozen precipitation on the gauge instrumentation.

3.3 *Post-Event Thaw*

There is a second, yet equally, important impact from those gauges that had become partially or completely stuck during winter precipitation events. Thawing from increased surface ambient temperatures resulted in gauges reporting false non-zero precipitation after having collected solid, winter precipitation (i.e., G > 0, R = 0). While the average number of gauge sites when G > 0, R = 0 was 224 per hour, the number of G > 0, R = 0 observations peaked during maximum daytime heating between 1700 and 2100 UTC (not shown). In contrast, the average number of false precipitation reports were at a minimum during the overnight hours from 0200 to 0800 UTC.

The identification of thawing impacts became increasingly complex when coinciding with additional precipitation. An example of this occurred over the mid-Atlantic region on 13-14 February 2014 (Figure 6). Winter precipitation was observed across the domain shown except for southern Delaware and southern New Jersey. Gauges across New Jersey, northern Delaware, and far southeast Pennsylvania (Region 1) along with the area around the District of Columbia (Region 2) had become partially or completely stuck by 1000 UTC 13 February (Figure 6A). As the precipitation moved northward out of the region, thawing commenced with above freezing ambient surface temperatures (Figure 6B). Additional precipitation then occurred during the thawing process, with primarily rain (snow) being observed over Region 1 (Region 2) by 0000 UTC 14 February based on surface observations (Figure 7C).

The inherent issue with having additional precipitation simultaneously occur during the thawing of

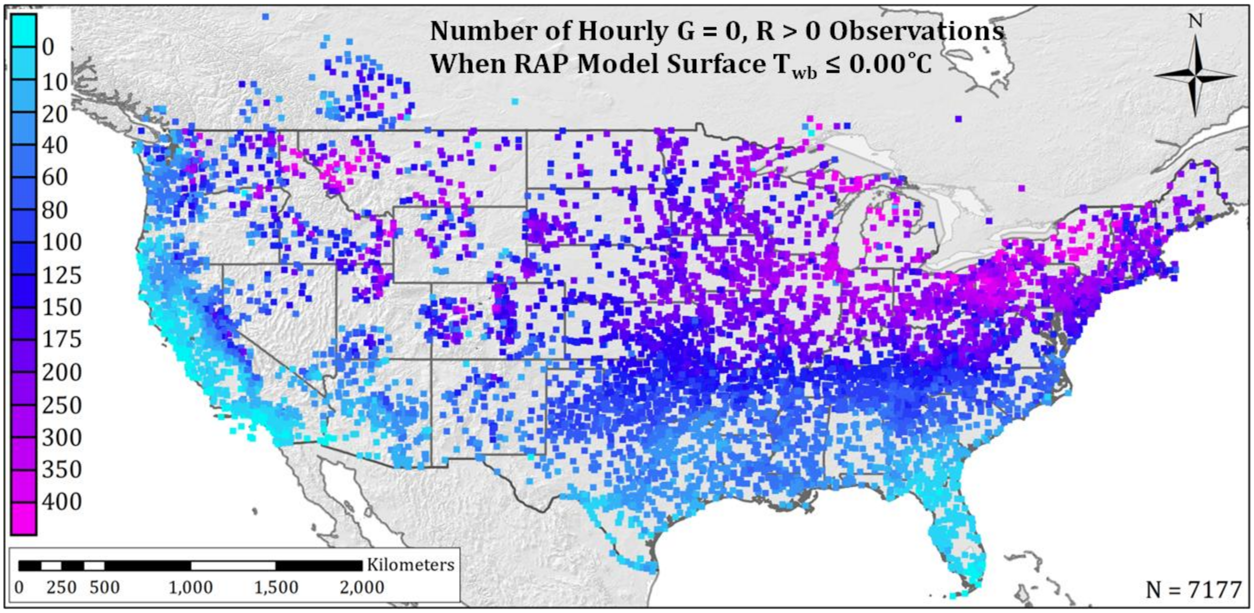

Figure 4. Number of hourly observations where G = 0, R > 0 when T_{wb} ≤ 0°C at each gauge site over the MRMS domain. Gauge sites shown had at least 90% data availability with an average RQI ≥ 0.1.

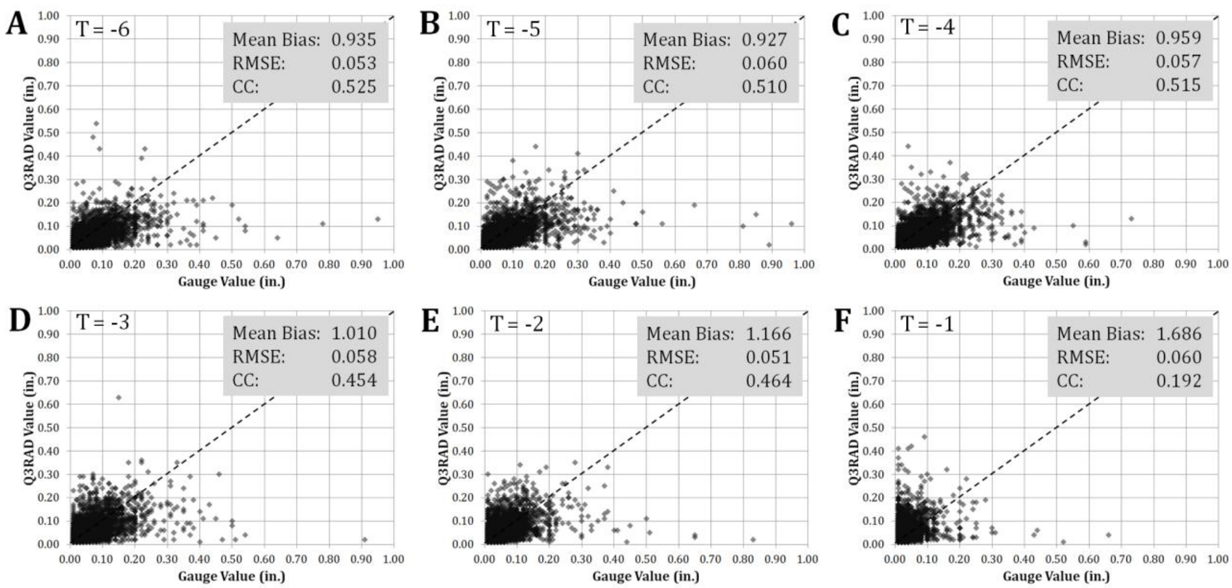

Figure 5. Scatter plot of Q3RAD QPE versus gauge observations from A) T = -6 to F) T = -1. The dashed line represents the one-to-one line between gauge and Q3RAD values. Statistical evaluation of each hour prior to becoming stuck are located in the top-right corner of each graph. Mean bias ratio is calculated as R/G.

frozen precipitation is that the gauge observation quality becomes compromised. The scatter plot of the gauge versus Q3RAD values within Region 1 denoted what would appear as an underestimation of the Q3RAD product with a mean bias ratio of 0.808 (Figure 7A). However, a more likely theory is that the unstuck automated gauges were accumulating the melt from previous precipitation and the current rainfall. In contrast, the scatter plot and resulting mean bias ratio of 2.755 for Region 2 would assume a significant Q3RAD overestimation (Figure 7B); however, gauge behavior in Region 2 better resembled continued thawing with little to no new accumulating solid, winter precipitation being sampled.

4. DISCUSSION ON GAUGE QUALITY

An estimated 60.4% of all hourly gauge observations occurred when the RAP surface T_{wb} ≤ 0°C, with 313 hours having over 90% of observations with surface T_{wb} ≤ 0°C (not shown). Each gauge site had a surface T_{wb} ≤ 0°C for an average of 2066 hours with an area from New England through the Great Lakes region to the Sierra Nevada Mountains had over 3000 hours of

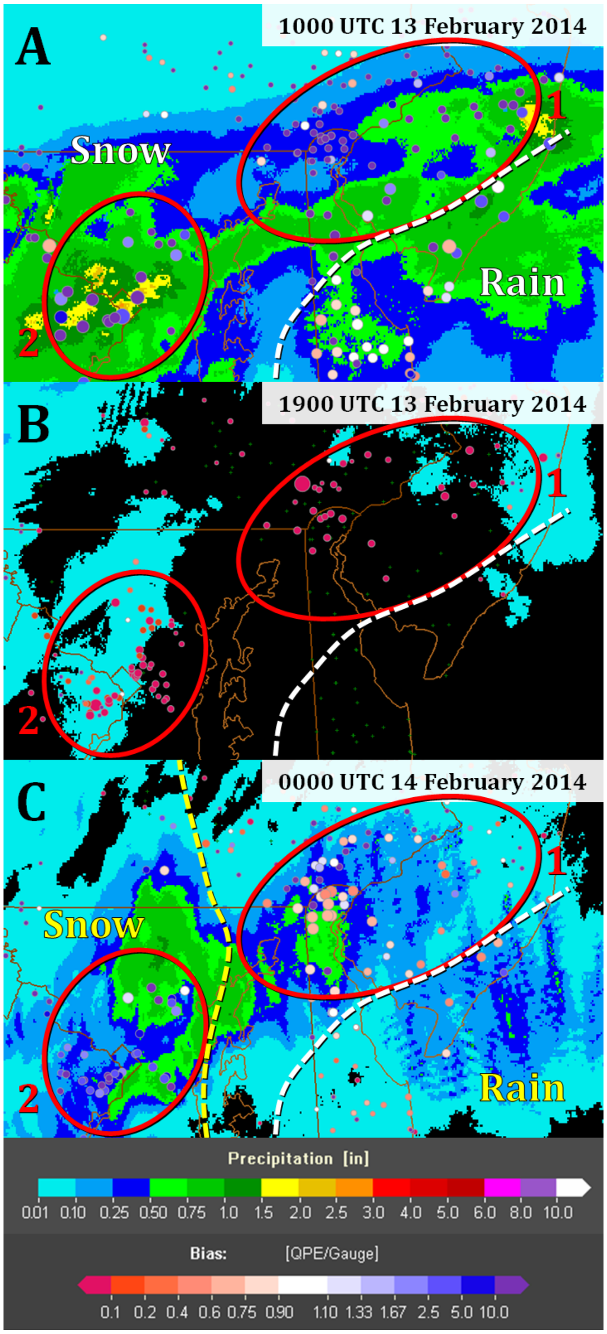

Figure 6. Precipitation and thawing event sequence from A) 1000 UTC 13 February 2014, B) 1900 UTC 13 February 2014, and C) 0000 UTC 14 February 2014. Q3RAD QPE shown in color fill and gauge totals and biases shown in colored bubble plot. Areas of snow and rain that occurred during A) and C) are delineated by white and yellow dashed lines, respectively. Regions denoted by red circles used in the statistical analysis shown in Figure 7. Color bars are shown at the bottom of the figure.

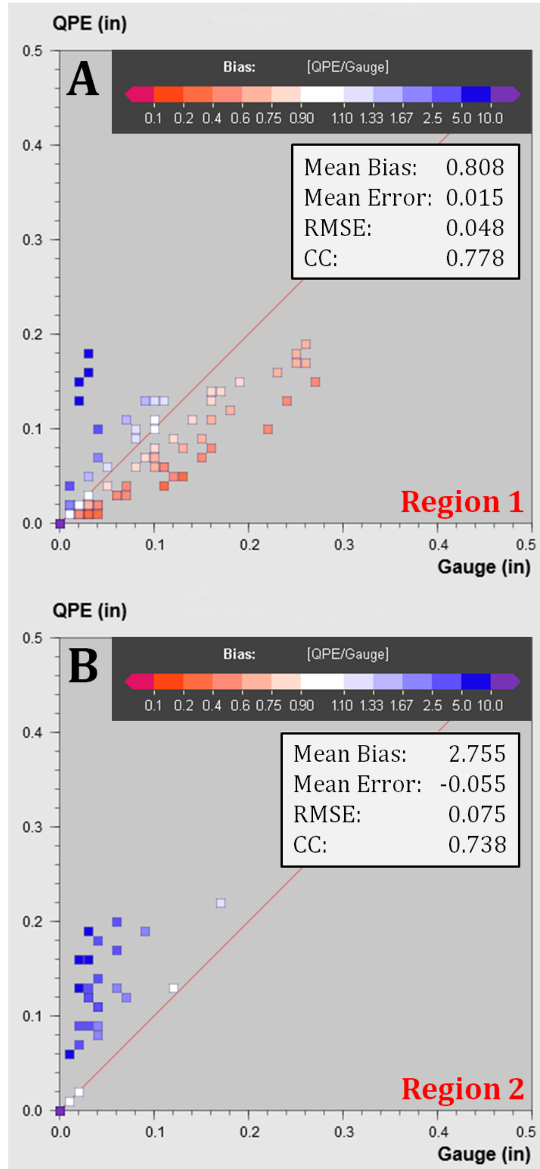

Figure 7. Scatter plot of Q3RAD QPE versus gauge observations for A) Region 1 and B) Region 2 denoted in Figure 6. The color of each comparison in the scatter plot represents the bias ratio (Q3RAD/gauge). Bluish colors indicate an overestimation by Q3RAD, and reddish colors indicate an underestimation by Q3RAD.

below freezing surface T_{wb} values (not shown). Thus, surface conditions for winter precipitation types were prevalent over numerous regions of the United States and southern Canada. Given the commonality of below freezing T_{wb} in the majority of the MRMS domain along with the likelihood of diminished gauge observation quality and the loss of hundreds of gauge sites during a significant winter event, the gauge QC algorithm would need to account for this. The operational version of Q3 utilizes RAP model surface T_{wb} to mitigate winter weather impacts (Figure 8). Non-zero hourly gauge observations located in regions where surface $T_{wb} \leq 0°C$ are designated as "frozen" and are removed. Hourly

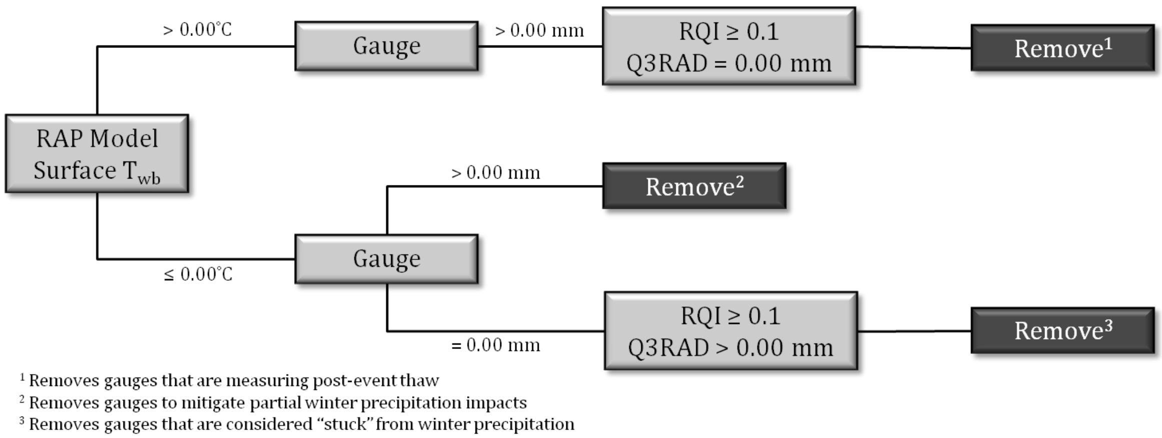

Figure 8. Section of gauge QC logic that mitigates impacts of winter precipitation on gauge observations.

gauge observations that report no precipitation while Q3RAD reports a non-zero accumulation and surface T_{wb} ≤ 0°C are also classified as "frozen" and are removed. This allowed for a better evaluation of Q3 products while reducing the impacts of frozen gauges on automated product generation. Post-event thaw impacts are removed when Q3RAD values are zero; however, there are no means of accounting for thawing when coinciding with another precipitation event. While the Q3 gauge QC algorithm can removed most impacts of winter precipitation on rain gauge observations, the loss of hundreds of gauge sites signifies that the instrumentation utilized at most gauge sites have significant deficiencies with handling winter precipitation. The loss of gauge observations during a winter event removes the ability to verify and calibrate radar-derived QPE, since no accurate "ground truth" is available, and creates challenges in finding an accurate liquid water equivalent QPE in MRMS during winter events.

5. CONCLUSIONS

Assessment of 2013-2014 cool season precipitation events found that a large quantity of gauge observations would become "stuck" in winter precipitation regimes. This study evaluated the quality of hourly gauge observations during frozen precipitation. Listed below are the key findings from this study.

- The number of gauge vs. Q3RAD comparisons where G = 0, R > 0 increase substantially in surface environments supportive of winter precipitation.
- Hundreds of gauges were reported as "stuck" per hour during winter events, with over 100 hours reporting more than 1000 stuck gauges.
- Partial frozen precipitation impacts the quality of gauge observations prior to becoming stuck.
- Post-event thaw can generate inaccurate bias correction if occurring simultaneously with precipitation.
- Q3 gauge QC algorithm removes gauge observations in regimes when RAP model surface T_{wb} ≤ 0°C to mitigate impacts of frozen precipitation on QPE products.

6. ACKNOWLEDGEMENTS

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