The R(A) QPE algorithm utilizes 0.5° tilt reflectivity (Z) and the span of differential phase (PhiDP) along a radar radial to calculate specific attenuation fields used to estimate precipitation below the melting layer. Key to the calculation of specific attenuation fields is the path integrated attenuation (PIA) along a radar radial estimated via the following equation:

$$\text{PIA} = \alpha^*(\text{PhiDP Span})$$

where the parameter α is estimated via the slope of Zdr to Z or is assigned a value if 1) the algorithm determines that stratiform rain predominates or 2) the number of pairs of Zdr/Z is less than 10,000. Estimating or assigning a value for α is quite important as it is approximately linearly dependent on Specific Attenuation for S band radars (Ryzhkov et al., 2014). This means a twofold increase in α can result in a twofold increase in the estimated rain rate. The R(A) QPE algorithm from MRMS build V 12.0 assumed α was

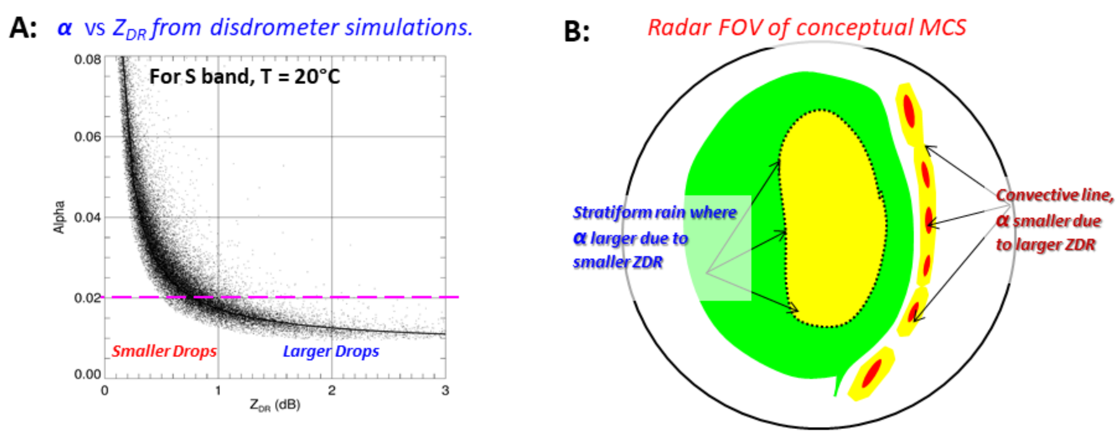

Figure 9: Plot of the parameter α vs Zdr as seen from disdrometer simulations derived from over 45,000 DSDs collected in Oklahoma (A) and the expected reflectivity structure of a conceptual Mesoscale Convective System as viewed by a radar PPI (B).

spatially constant within the radar field of view; in reality this quite often is not the case. An example of this (Figure 9 A and B) would be a mesoscale convective system (MCS, figure 1 XB) that has a well-developed stratiform rain region behind a leading convective line. An α estimated from a slope fit would utilize Zdr and Z data across the radar field of view (FOV) where the radar beam was below the melting layer (ML). Therefore a net α (dashed purple line, Figure 9 A) could be too high for the leading convective line (larger drops/Zdr, smaller α required) or too low for the trailing stratiform rain (smaller drops/Zdr, larger α required). This can cause significant QPE variability with a R(A) quantitative precipitation estimate (QPE) wet (dry) bias in some convective (stratiform) precipitation systems. Further, there also existed a R(A) QPE dry bias for light stratiform and for tropical rainfall as the precipitation rates were often significantly higher than those rates estimated from specific attenuation fields using a net α. This results in significant variability, as measured by the Interquartile Range (IQR) in the R(A) QPE accumulations particularly for the higher rainfall totals. To mitigate this increased variability, a rain rate adjustment was added to the R(A) QPE algorithm. The rate adjustment, defined as the ratio of $\alpha(Z)$ to αo, is multiplied against the specific attenuation rain rate equation as in the below:

$$R(A)\ adj. = 4120.0 * A^{1.03} * (\alpha(Z) / \alpha o)$$

where $\alpha(Z)$ is calculated from the best fit curve to the upper 20% of the α vs Z distribution as simulated from disdrometer data (Figure 10) and αo is the net α value for the radar FOV. Rain rate adjustments are made when a mix of deep convective and stratiform rain is present and only for $40 \leq Z \leq 50$ dBZs where the alpha distribution is the least variable. When precipitation is primarily stratiform in character rain rate adjustments are only made for $25 \leq Z \leq 35$ dBZs to reduce underestimates in tropical and light stratiform rainfall. The

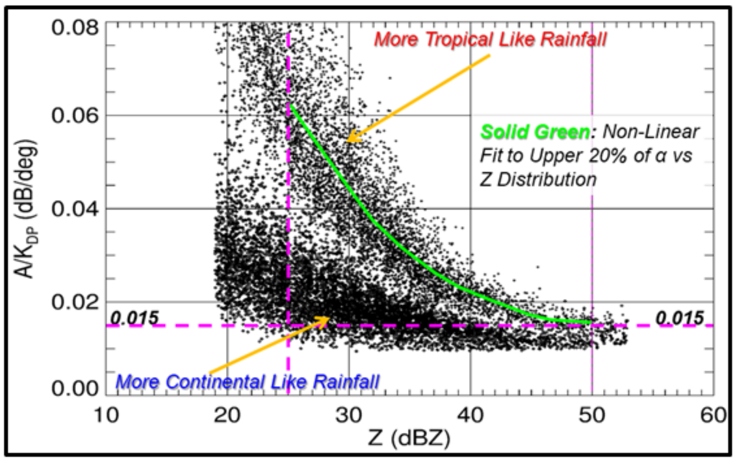

Figure 10: Plot of the upper and lower 20% of the α vs Z distribution as seen from disdrometer simulations derived from over 45,000 DSDs collected in Oklahoma. The solid green line represents a polynomial fit to the upper 20% of the distribution.

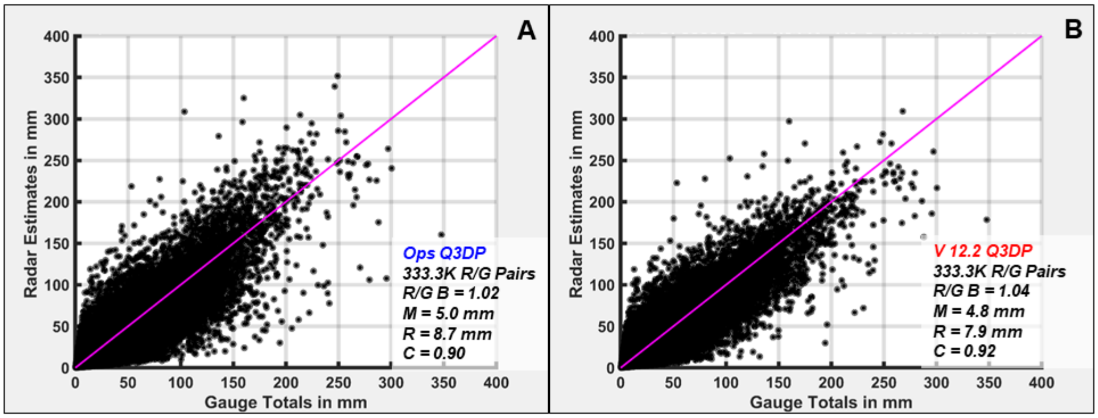

Figure 11: 24-hr accumulations of Ops (A) and V12.2 Q3DP (B) QPE vs. gauge scatterplots for 333.3 K matched radar to gauge pairs collected between 15 March - 31 October 2021. 'R/G' refers to radar to gauge pairs, 'R/G B' refers to radar to gauge bias ratio, 'M' refers to mean absolute error, 'R' refers to root mean square error, and 'C' refers to correlation coefficient.

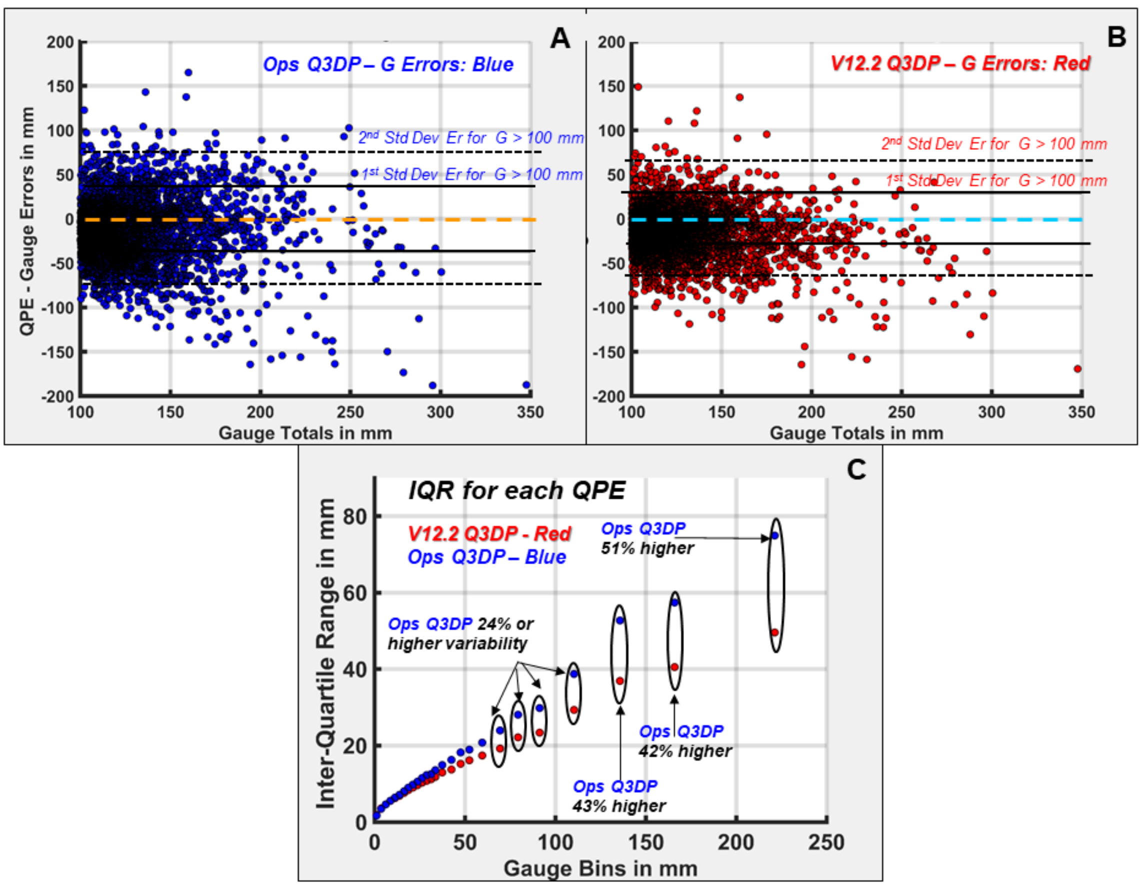

Figure 12: QPE minus gauge errors as a function of gauge total for Ops Q3DP(A) and the new V12.2 Q3DP (B) as well as Interquartile range for both QPEs (C) for 333.3 K matched radar to gauge pairs collected between 15 March - 31 October 2021.

reason only the upper 20% of the α versus Z distribution is used to adjust rain rates is because the R(A) QPE algorithm already performs well for more continental like rain (e.g. where $\alpha o < 0.020$). Figure 11 shows the 24-hr QPE vs. gauge scatterplots, collected over a 7 ½ month period during the 2021 warm season, for the current operational and the V12.2 Q3DP estimates. Overall, the statistics are fairly similar albeit V12.2 Q3DP is a little more along the one-to-one line (purple) as suggested by the higher correlation coefficient. However, the Ops Q3DP scatterplot exhibits a bulge of underestimates for gauge totals between 75 and 150 mm as well as an area of overestimates for totals > 150 mm. The V12.2 Q3DP mitigated both of these tendencies. Figure 12 shows the QPE - gauge error for Ops (A), the V12.2 (B) Q3DP and a comparison of the interquartile range for both QPEs (C). The new experimental code significantly reduces the overestimates in deep convection ($40 \le Z \le 50$ dBZs) and mitigates underestimates in light and tropical stratiform rainfall ($25 \le Z \le 35$ dBZs). While it is clear the Ops Q3DP has a better bias than V12.2 Q3DP, ~ 9 and 14 mm better for gauge totals between 150 and 200 mm and for totals > 200 mm respectively, it is at the expense of significantly higher variability both above and below the zero line (dashed orange line) as evidenced by the significantly larger 1st and 2nd standard deviations of the errors. The newer V12.2 code significantly reduces the QPE variability observed in the current Ops Q3DP, in particular that observed in some recent high-impact flash flood cases as illustrated in figure 13. Also of note is that both QPEs show a significant dry bias for gauge totals > 200 mm which will be the subject of future work.

Although not shown, both Ops and V12.2 Q3DP also exhibited a significant wet bias of as much as 1 - 1.7 mm for 24-hr totals < 15mm. Some of this wet bias is related to a limitation of the R(A) technique, that is it does not do well when the PhiDP span ≤ 3°, hence a reflectivity-to-rain rate [R(Z)] is used to estimate precipitation. Since an overall dry bias was found in coastal/tropical stratiform rain an aggressive R(Z) relation (Snow QPE: $S = 0.116*Z^{0.5}$) was used when the PhiDP span ≤ 3°. However, precipitation can fall through layers of drier air which can evaporate significant portions of the smaller droplets before reaching the ground. While this has been observed in the Northern US and the Plains regions it can be rather common over the High Plains and the Western US during the warm season. Hence, there are often QPE overestimates in these regions of the US whenever the PhiDP span ≤ 3°. As a result, we have adjusted V12.2 Q3DP parameters to allow the use of the Marshall Palmer relation ($R = 0.0365*Z^{0.625}$), which is ~ 0.5 to 1 mm lower rates for 20 and 30 dBZs respectively, whenever the PhiDP span ≤ 3°. Tests indicate this will lower some of the observed wet bias. Further, future work is investigating expanding the use of dual pol information to better distinguish between less and more efficient light stratiform rain regimes in order to further improve QPE estimates in regions where arid boundary layers are common.

Another significant change found in the V12.2 Q3DP algorithm is the use of Dual Pol information to determine the structure of the Melting Layer (ML). Precipitation estimates via specific attenuation need to be made in pure rainfall; frozen precipitation, such as hail or melting hydrometeors in the ML (e.g. Ice contamination), can cause specific attenuation fields to be too high leading to QPE overestimates. The Operational Q3DP mitigated hail contamination by avoiding regions of high reflectivity (generally Z > 50 dBZs; see Zhang et al, 2020 for details). However the current Operational Q3DP utilized model sounding data to determine the location/structure of the ML bottom via the weighted mean of the 10° and 0°C heights at the radar site and refined by the correlation coefficient (ρHV) field (Wang et al. 2019). This technique generally did not perform very well for non-isotropic melting layer structures leading to increased QPE variability. V12.2 Q3DP uses output from the dual-pol VPR (see Seamless Hybrid Scan Reflectivity Details above) to determine a more accurate melting layer structure, chiefly via the use of Z, Dual Pol Cross Correlation Coefficient (RhoHV) and model freezing level heights. This significantly improved the mitigation of ice contamination for precipitation estimated via specific attenuation. This update also changes the application areas of different rain rate methods in the synthetic QPE field. Fig. 14a and Fig. 14b show the product of SyntheticPrecipRateID before and after the update, respectively. After the change, the application of polarimetric QPE expands to a more extensive range in general (Fig. 14b).

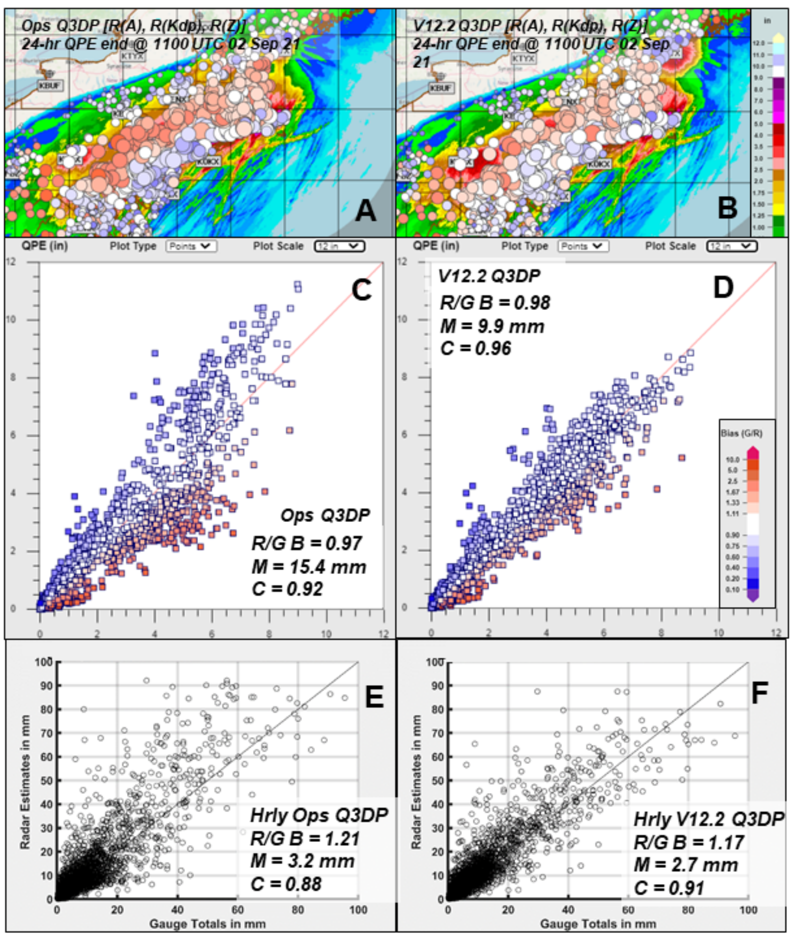

Figure 13: QPE Bubble Bias maps (A, B) 24-hr (C, D) and 1-hr (E,F) QPE vs Gauge scatter plots for data collected over the Northeast US during the 24 hour period ending 1100 UTC, 2nd

September 2021. 'R/G B' refers to radar to gauge bias ratio, 'M' refers to mean absolute error and 'C' refers to correlation coefficient.

Case study analyses of the operational Q3DP indicated examples where isolated to scattered convection were mistakenly classified as stratiform rain in the Western US. Since the Q3DP algorithm assigns a value of 0.035 to α for such a classification, there were significant overestimates observed. As organized deep convection in the Western US is less frequent and often of smaller coverage area, we decreased the Zdr/Z pairs thresholds for Z>= 42 dBZ used to determine if significant deep convection is present within the radar FOV. This allows the Q3DP algorithm to be more easily triggered to indicate deep convection is present given the climatic conditions at and west of -105.0° longitude (this is for CONUS domain only). Tests indicate this change mitigates incorrect Q3DP classifications of stratiform rain and allows a Zdr/Z slope estimate of α which better matches the precipitation environment and reduces QPE overestimates.

Further, in regions of blockage and at lower reflectivities (often 10 – 20 dBZ) the PhiDP field can be perturbed such that anomalously large R(A) rates, sometimes near 100 mm/hr are generated yet little if any rain was occurring. In one case, a simple comparison of the R(A) rate to that generated by an aggressive R(Z) relation at low reflectivities (the Snow QPE relation) indicated the former was well over 50 times higher than the latter. These anomalies are easily filtered out by using a rate comparison between the R(A) rate and that from the Snow QPE R(Z) relation; if the former is over 6 times larger than the latter for Z <= 30 dBZs then the latter rate was used instead. Hence, we have instituted this R(A)/R(Z) rain rate check into V12.2 Q3DP to avoid anomalously high R(A) QPE along radials that can sometimes occur in regions of blockage.

There were some code refinements made regarding the use of R(Kdp) for Z > 50 dBZs. The current operational code uses two R(Kdp) relations: 1) R(Kdp) = 29Kdp^0.77 (for strong convection) and 2) R(Kdp) = 44Kdp^0.822 (regularly used in NWS operations). The 1st relation is used until RhoHV > 0.97 then the 2nd relation is used. V12.2 we have added a 3rd R(Kdp) relation that was derived for more tropical like regimes [R(Kdp) = 54Kdp^0.867] and when it is used depends upon the Q3DP derived net α. If 0.020 < net α ≤ 0.025, convection that may have mixed tropical/continental rain characteristics, and RhoHV ≤ 0.97 then the 1st relation is used; if RhoHV > 0.97 then the 3rd R(Kdp) relation is used. Similarly, if 0.025 < net α ≤ 0.035, tropical like rain, and RhoHV ≤ 0.97 then the 2nd relation is used until RhoHV > 0.97 in which the 3rd R(Kdp) relation is used. These changes allow higher QPE estimates in mesoscale convective systems that are initially continental like but become very efficient with time as well for better performance in intense hurricane rain band activity where Z is significantly higher than 50 dBZs.

Besides the major changes mentioned above, the updates of the dualpol R(A) algorithm also include the following modifications. It maximizes the R(A) application in terms of beam blockage, i.e., the R(A) is applied with no blockage limitation. The updated R(A) applies the input K_{DP} directly from the QC output instead of internal derivation to save computation. In addition, the module includes updated management of the radar volume coverage pattern (VCP). It uses predefined VCP XML configuration files in the MRMS build, which alleviates future algorithm modifications from VCPs changes.

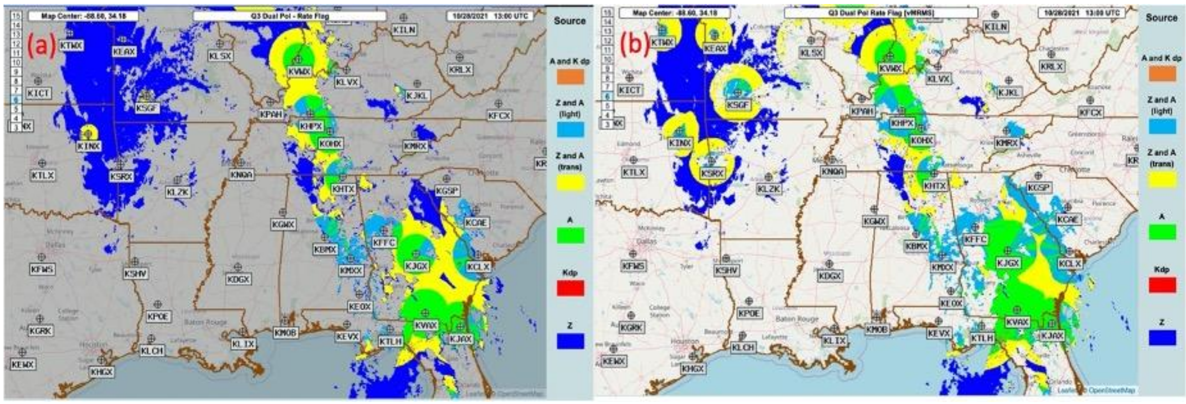

Figure 14 shows the synthetic PrecipRate ID before (a) and after (b) the new input data of two-dimensional melting layer bottom. These fields are valid at 1300 UTC on 28 Oct. 2021.

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