Initial Assessment of the Dual-polarization Quantitative Precipitation Estimate Algorithm's Performance for Three Dual-Polarization WSR-88Ds

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INTRODUCTION: The Radar Operations Center (ROC) Applications Branch has completed a preliminary performance assessment of the Dual Polarization (DP) Quantitative Precipitation Estimate (QPE) for the Norman, OK (KOUN), Vance AFB, OK (KVNX) and Wichita, KS (KICT) Weather Surveillance Radars-1988-Doppler (WSR-88D). KOUN is the prototype DP WSR-88D radar upgraded to DP in June 2009. KVNX and KICT are operational DP WSR-88Ds upgraded in February and July 2011, respectively. The purpose of the assessment is to document the DP QPE and legacy Precipitation Processing System (PPS) algorithms performance, as compared to rain gauge rainfall totals, for these three radars for the data collected for 2011.

DATA AND METHODOLOGY: ROC Applications staff collected Level II radar data for a variety of weather events. The events included severe storms, storms embedded in light to moderate rain and heavy rainfall events. For KOUN ten cases were analyzed with six of them collected during April through June, 2011; the other four were collected during September and November, 2011. For the KVNX radar fourteen cases were analyzed with ten collected during April through August, 2011. Similar to KOUN, the other four KVNX cases were collected during September and November, 2011. However, for KICT the cases analyzed were different with only two collected during July and August, 2011; the rest were collected between September and December, 2011. Therefore, the KICT data set has more cases with cooler temperatures, less deep convection/higher incidence of stratiform rain and lower melting levels than those analyzed for KOUN and KVNX.

For each of the collected weather events, Level II radar data was processed using standard Radar Processing Generator (RPG) "playback" software. The RPG software was used to calculate the DP QPE and PPS storm total accumulation fields for each volume scan of data within the surveillance range of the radar for each weather event. There is a difference in resolution between the resulting DP QPE (0.25 km by 1 degree) and PPS (2.0 km by 1 degree) storm total accumulation fields, the result of which is a 'smoother' PPS data field. The impact of this is some increase in 'noise' in the DP QPE storm total accumulations fields, but not enough to prevent making an initial assessment of the algorithm performance. A software script, designed to execute within the RPG software, was used to determine the accumulated DP QPE and PPS radar rainfall estimates for specific latitude/longitude coordinates corresponding to the locations of selected rain gauges.

Rain gauge data was paired with the corresponding DP QPE and PPS radar estimates for the gauge location. This assumes that gauge data represented "truth." However, there are well known uncertainties associated with using gauge data. For example, rainfall totals from gauges may be underestimated due to clogging, wind effects, or mechanical errors (e.g., Sieck et al. 2007; Vasiloff et al. 2009). Inaccurate gauge reports from automated sites may also result from telemetry or other kinds of communications problems (e.g., Kim et al. 2006). Additionally, spatial sampling differences can result in uncertainties in comparing radar and gauge data (Wilson and Brandes 1979; Villarini and Krajewski 2009; Villarini and Krajewski 2010). For Florida rainfall, Habib and Krajewski (2002) estimated that 40-80% of R-G uncertainties were due to spatial differences. These examples highlight the limitations for using gauge data as "truth." In order to minimize gauge quality errors, Oklahoma Climatological Survey (OCS) Mesonet rain gauges were used for the two Oklahoma radars as these gauges are well maintained and data is quality controlled (Shafer, et al. 2000; Fiebrich et al 2006; McPherson et al. 2007). For the KICT radar, predominantly Hydro-meteorological Automated Data System (HADS) gauges were used although there were a few OCS gauges used along the Oklahoma border. The research community has noted that HADS gauges tend to have more errors than seen in the OCS network (personal communication, Vasiloff, 2011). Nonetheless, HADS gauges make up a sizable proportion of the gauges found across the U.S and were used in this assessment. Regardless of the type of gauge, ROC staff members performed standard quality control checks (e.g. compared totals to nearby gauges, looked at gauge trends, comparison to radar, etc) to remove any erroneous gauge data. Rain gauge data were downloaded from the OCS and the Meteorological Assimilation Data Ingest Site (MADIS) websites.

The paired radar estimate/gauge data are henceforth called radar/gauge (R/G) pairs and the comparison of the radar estimates to the gauge values was used to assess algorithm performance. A total of 809 R/G pairs for KOUN, 612 R/G pairs for KVNX, and 807 R/G pairs for KICT were examined. We used the following statistical measures to evaluate performance:

Bias Error: *defined as* **(Radar Rain Estimate - Gauge Rain Total)** *measures the tendency for DP QPE or PPS to under or over-estimate rainfall.*

Root Mean Square Error (RMSE) = $\{\text{Sum (Bias Error)}^2 / N\}^{0.5}$ *where N is the number of R/G pairs; RMSE measures the variability or the "scatter" in errors. The lower the RMSE, the more accurate the radar estimates.*

Both of these statistical measures were defined in the same way as Ryzhkov et al. (2005). Additionally, we compared the differences between the DP QPE and PPS bias and RMSE values for four categories stratified by increasingly higher gauge totals: 1) All R/G pairs contained within the dataset; 2) R/G pairs with gauge totals > 0.5"; 3) R/G pairs with gauge totals > 1"; 4) R/G pairs with gauge totals > 2". The purpose for this stratification was to examine the changes in bias and RMSE values when increasingly higher gauge rainfall totals are considered.

Rainfall bias and RMSE errors for these data have a non-gaussian distribution and so parametric tests are not justified. Instead, we use a matched-pairs Fisher's permutation test (Efron and Tibhirani 1993) utilizing 4000 permutations. This test is non-parametric and does not rely on any assumptions about the underlying data ditsribution but instead uses properties inherent in the empirical data distribution. A p-value of 0.05 (95% confidence level) was used in to define statistical significance.

Data Category	**Mean DP QPE Bias (in)**	**Mean PPS Bias (in)**	**DP QPE RMSE (in)**	**PPS RMSE (in)**	**Significant Difference Between DP & PPS?**
All R/G Pairs, 809 obs	**0.07"**	**0.01"**	**0.37"**	**0.45"**	**Bias = YES** **RMSE = YES**
R/G Pairs for Gauge Amts >0.5" 344 obs	**0.06"**	**-0.06"**	**0.52"**	**0.65"**	**Bias = YES** **RMSE = YES**
R/G Pairs for Gauge Amts > 1.0" 178 obs	**0.01"**	**-0.13"**	**0.60"**	**0.79"**	**Bias = YES** **RMSE = YES**
R/G Pairs for Gauge Amts > 2.0" 49 obs	**-0.02"**	**-0.21"**	**0.84"**	**1.21"**	**Bias = YES** **RMSE = YES**

Table 1: *Comparison of DP QPE & PPS Bias and RMSE Errors for KOUN data.*

KOUN RESULTS: Table 1 summarizes the DP QPE and PPS comparison results for KOUN. Note that DP QPE and PPS bias errors were significantly different with a slightly higher bias for DP QPE for all measurements. For rainfall amounts greater than an inch, DP QPE bias was near zero; for PPS, the bias shifted to the negative indicating a propensity to underestimate for the higher rainfall amounts. This initially was surprising as examination of individual cases indicate the PPS bias is slightly positive from April to June. This is due to PPS tending to overestimate rainfall when high reflectivity (over 50 dBZ) is present, often caused by the presence of hail. However, subsequent examination of individual cases in September and November indicated the

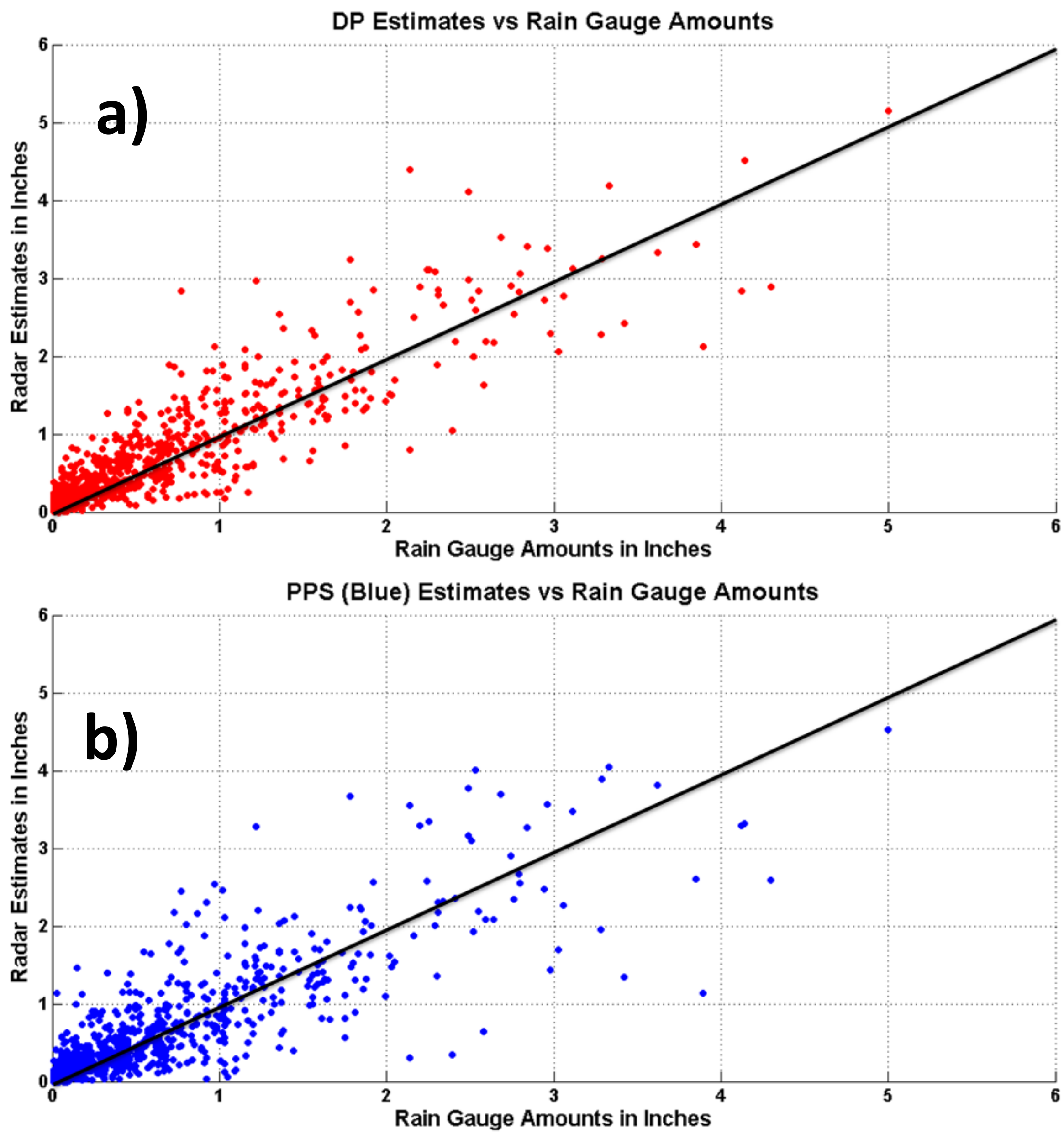

***Figure 1**: Scatter plots of **a)** DP rain estimates and **b)** PPS rain estimates vs. observed gauge measurements for all 809 gauge/radar pairs from KOUN. Note the less scatter with the DP radar estimates when compared to those from PPS.*

PPS bias had distinctly negative for these latter season rain events influencing the statistics. The more negative PPS bias appears to be related to the lower melting level and the increased presence of stratiform rain with these later events.

KOUN DP RMSE values are significantly lower than PPS values for all categories, with the amount of improvement over PPS increasing for the higher rain gauge totals.   Figure 1 shows a comparison between the DP and PPS radar rain estimates vs. the corresponding rain gauge totals. The scatter plots show that DP QPE estimates are closer to the gauge values with significantly less variability. This is reflected in the statistics in Table 1. Figure 2 shows KOUN bias values

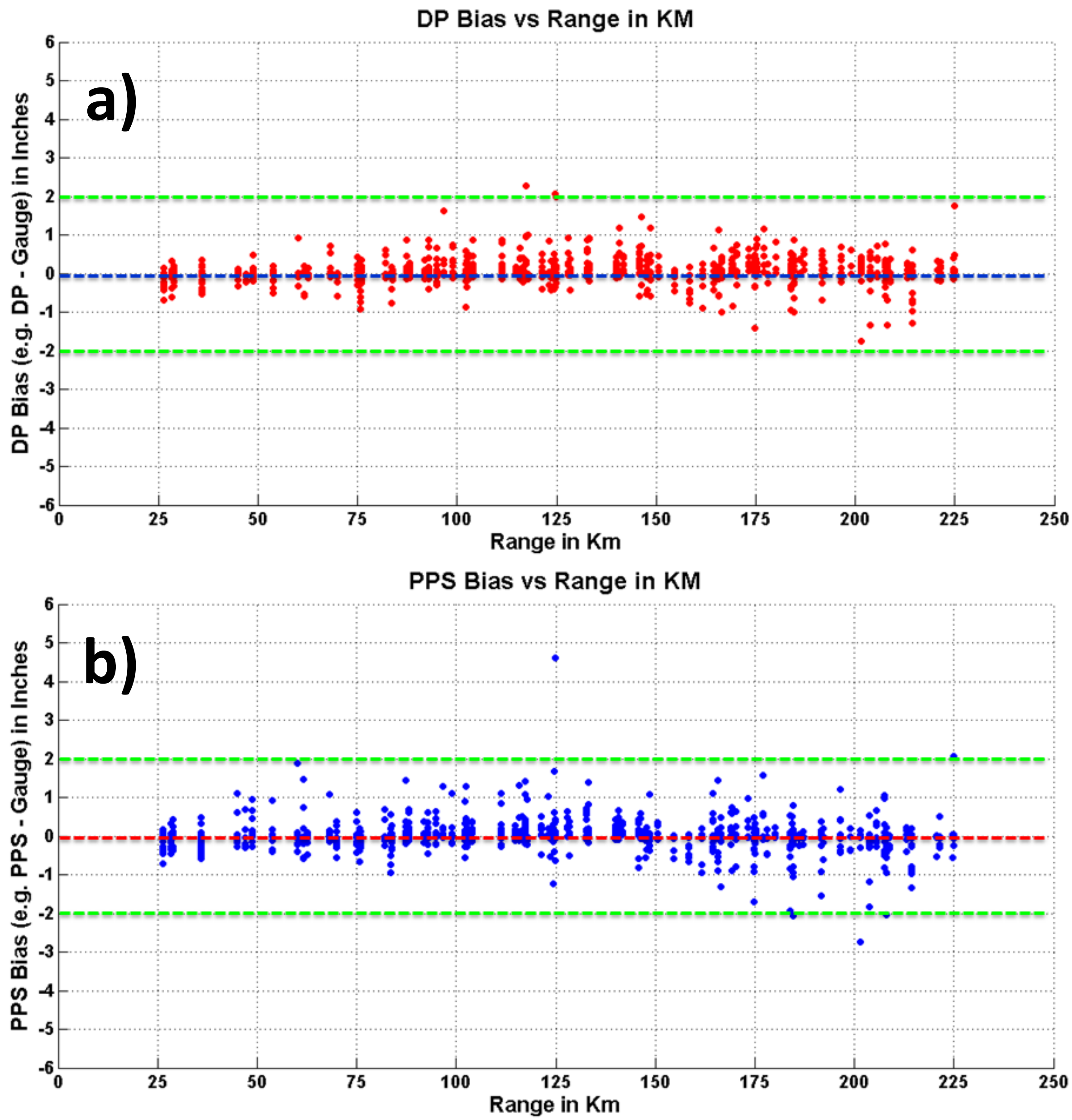

***Figure 2**:   Scatter plots **a)** DP Bias and **b)** PPS Bias Errors as a function of range for all 809 radar/gauge pairs from KOUN.   Note less scatter is observed at all distances with the DP radar estimates compared to PPS estimates. However, as a trend, scatter for both radar estimates increases with distance from the radar.*

as a function of distance from the radar. Again, less variability is present with the DP bias values. There is a slight tendency for DP to overestimate rainfall totals past 75 km. For both PPS and DP, there is more variability present in bias errors at distances greater than 150 km. There are two factors likely affecting this. First, the height of the center of the radar beam above the ground is quite high at these distances from the radar. What the radar detects at heights high above the ground, in terms of echoes and hence the potential for rainfall, does not always correlate with rainfall received by the surface rain gauge.

For precipitation detected at 8 to 10 kft above the ground, evaporation and advection by the wind likely will reduce the amount of liquid measured by gauges. The second factor likely contributing to the variability in the DP QPE rain estimates reflect some of the challenges the algorithm has in the melting layer that will be discussed later in this paper.

KVNX RESULTS: Table 2 summarizes the DP QPE and PPS comparison results for KVNX. For KVNX, DP QPE RMSE values were significantly lower than for PPS. The degree of improvement DP QPE provided increased for the R/G pairs with gauge totals over an inch of rainfall. Figure 3 shows scatter plots of the DP QPE and PPS radar estimates compared to the

Data Category	**Mean DP QPE Bias (in)**	**Mean PPS Bias (in)**	**DP QPE RMSE (in)**	**PPS RMSE (in)**	**Significant Difference Between DP & PPS?**
All R/G Pairs, 612 obs	**0.16”**	**0.13”**	**0.42”**	**0.47”**	**Bias = YES** **RMSE = YES**
R/G Pairs for Gauge Amts >0.5” 306 obs	**0.17”**	**0.12”**	**0.51”**	**0.60”**	**Bias = YES** **RMSE = YES**
R/G Pairs for Gauge Amts > 1.0” 160 obs	**0.14”**	**0.07”**	**0.57”**	**0.70”**	**Bias = NO** **RMSE = YES**
R/G Pairs for Gauge Amts > 2.0” 35 obs	**0.05”**	**0.11”**	**0.67”**	**0.88”**	**Bias = NO** **RMSE = YES**

Table 2: *Comparison of DP QPE & PPS Bias and RMSE Errors for KVNX data.*

gauge totals. As seen with KOUN, the KVNX DP QPE estimates are more closely related to the gauge totals and do not have as much variability.

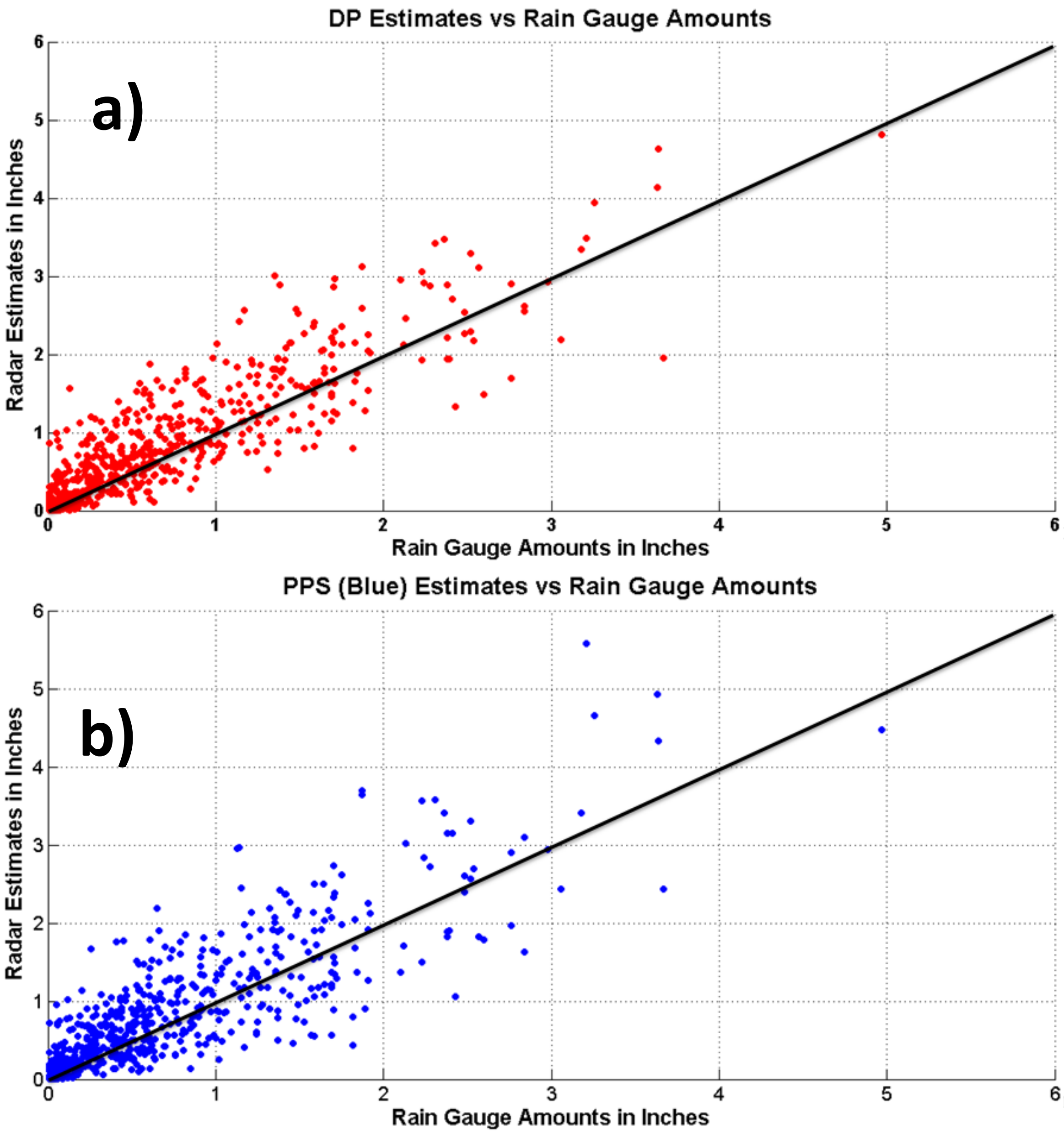

***Figure 3**: Scatter plots of **a)** DP rain estimates and **b)** PPS rain estimates vs. observed gauge measurements for all 612 gauge/radar pairs from KVNX. Note the less scatter with the DP radar estimates when compared to those from PPS.*

In contrast to KOUN, KVNX DP QPE and PPS bias values were larger for each gauge category examined. On the other hand, PPS bias decreased as R/G pairs with the higher rainfall totals were considered. This is similar to what was seen with KOUN data and is likely related to the increased stratiform rain and relatively cooler weather accompanying the KVNX rain events in September and November. The KVNX DP QPE bias values did not change over the four gauge categories. Overall, DP QPE bias values were slightly higher than PPS for the first two gauge categories where R/G pairs with lower gauge totals were included. For R/G pairs with gauge totals greater than an inch there was not a statistically significant difference between DP QPE and PPS bias.

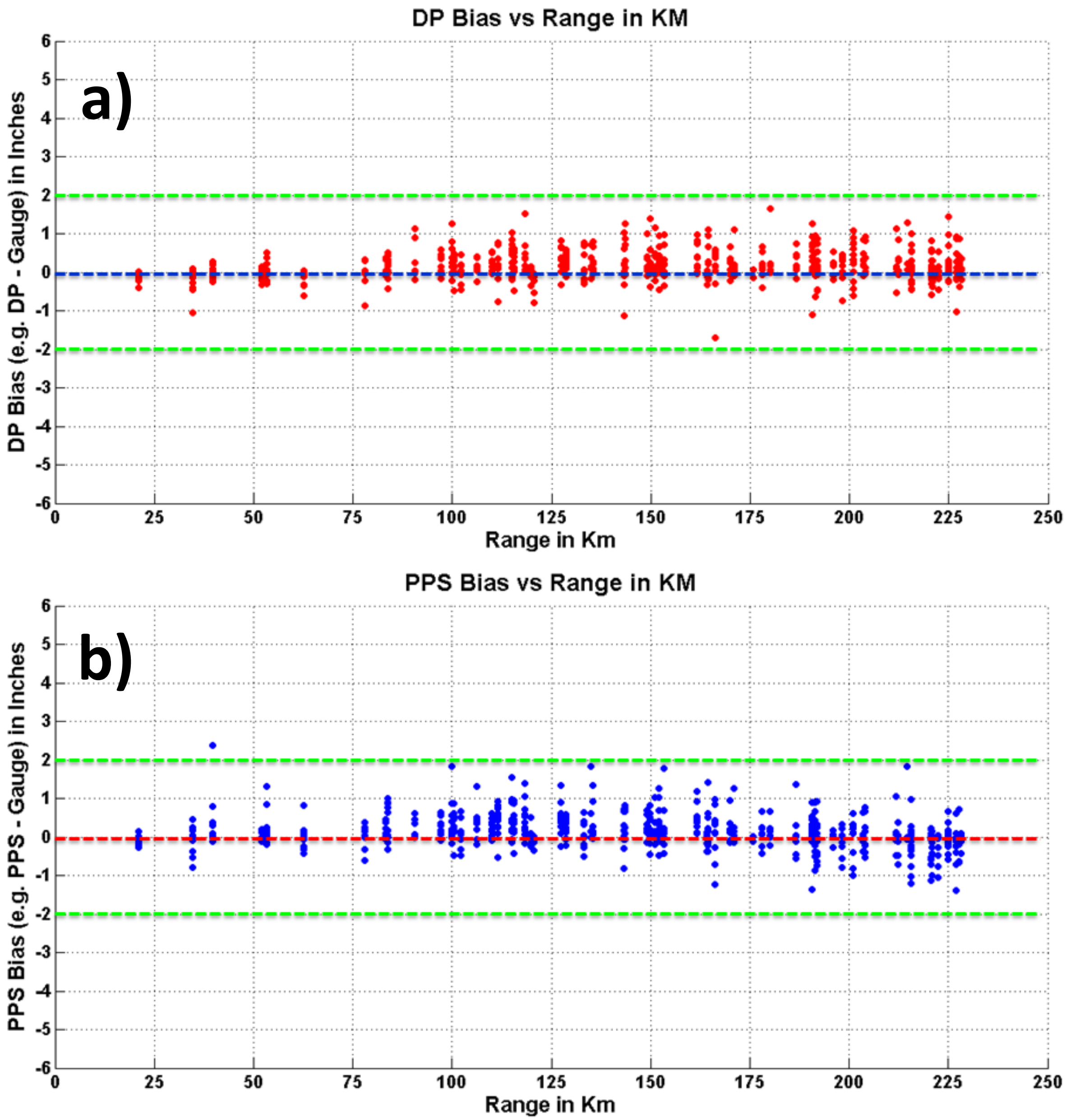

***Figure 4**: Scatter plots **a)** DP Bias and **b)** PPS Bias Errors as a function of range for all 612 radar/gauge pairs from KVNX. Note less scatter is observed at all distances with the DP radar estimates compared to PPS estimates. However, as a trend, scatter for both radar estimates increases with distance from the radar.*

Figure 4 shows the KVNX DP QPE and PPS bias values as a function of distance from the radar. KVNX DP QPE bias values were slightly higher for distances greater than 100 km from the radar, a feature a little more prevalent than seen with the KOUN DP QPE bias values. Similar to KOUN, more variability is observed in the KVNX DP QPE bias values for distances greater than 100km from the radar. On the other hand, KVNX PPS bias values show a tendency to underestimate gauge totals for distances greater than 150 km from the radar.

KICT RESULTS: The results for KICT are significantly different than those seen in KOUN and KVNX. Table 3 summarizes the DP QPE and PPS comparison results for KICT. KICT DP QPE

Data Category	Mean DP QPE Bias (in)	Mean PPS Bias (in)	DP QPE RMSE (in)	PPS RMSE (in)	Significant Difference Between DP & PPS?
All R/G Pairs, 807 obs	**0.21”**	**0.05”**	**0.64”**	**0.62”**	**Bias = YES RMSE = NO**
R/G Pairs for Gauge Amts >0.5” 451 obs	**0.19”**	**-0.06”**	**0.76”**	**0.77”**	**Bias = YES RMSE = NO**
R/G Pairs for Gauge Amts > 1.0” 270 obs	**0.08”**	**-0.19”**	**0.80”**	**0.87”**	**Bias = YES RMSE = YES**
R/G Pairs for Gauge Amts > 2.0” 65 obs	**-0.12”**	**-0.25”**	**0.93”**	**1.03”**	**Bias = YES RMSE = YES**

Table 3: *Comparison of DP QPE & PPS Bias and RMSE Errors for KICT data.*

RMSE values are *not* significantly different for the first two categories, those which include R/G pairs with lower rain amounts. For gauge categories containing R/G values with gauge totals greater than an inch there is a significant difference between DP QPE and PPS RMSE. However, the DP QPE RMSE values are only slightly better than PPS and do not offer the same degree of improvement seen for data from KOUN and KVNX. Figure 5 is a scatter plot of the KICT DP QPE and PPS radar estimates vs. the rain gauge totals. The amount of variability present is more than previously seen with the KOUN and KVNX scatter plots. This is likely due to two factors. First, in contrast to the data used for KOUN and KVNX, most of the rain gauge data used for the KICT evaluation were from HADS rain gauges. The research community has noted that HADS gauges tend to have more errors than seen in the OCS network (Personal Communication, Vasiloff, 2011). Assuming these errors are randomly distributed, such errors

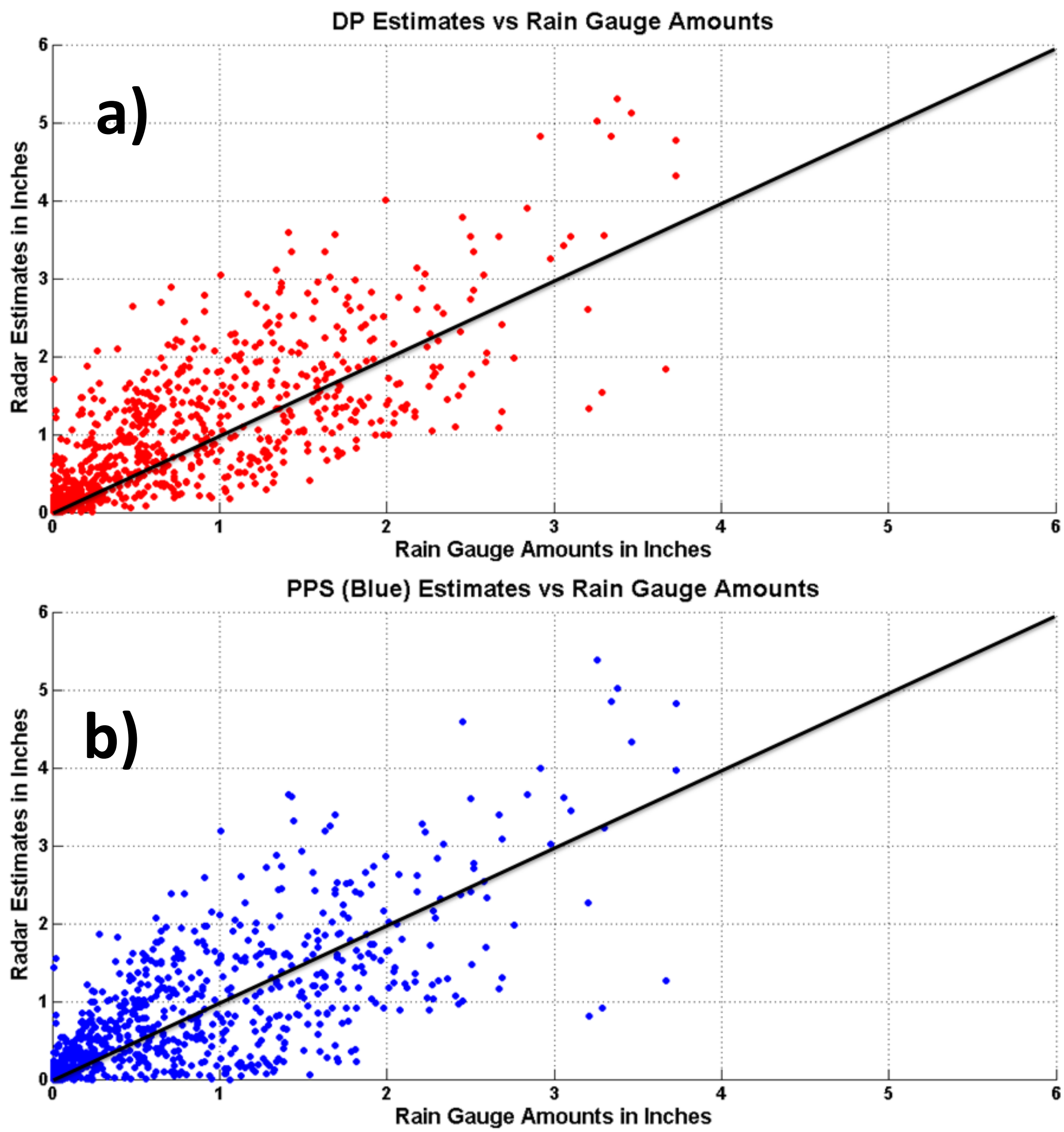

***Figure 5**: Scatter plots of **a)** DP rain estimates and **b)** PPS rain estimates vs. observed gauge measurements for all 807 gauge/radar pairs from KICT. In this case, the variability between DP and PPS estimates are approximately the same.*

increase the overall scatter or variability of the R/G errors. Second, in contrast to the cases evaluated for KOUN and KVNX, most of the rain events evaluated for KICT occurred in the September through December time period. A lower melting layer, less deep convection and the presence of more stratiform rain will affect the way the DP QPE algorithm estimates rainfall totals.

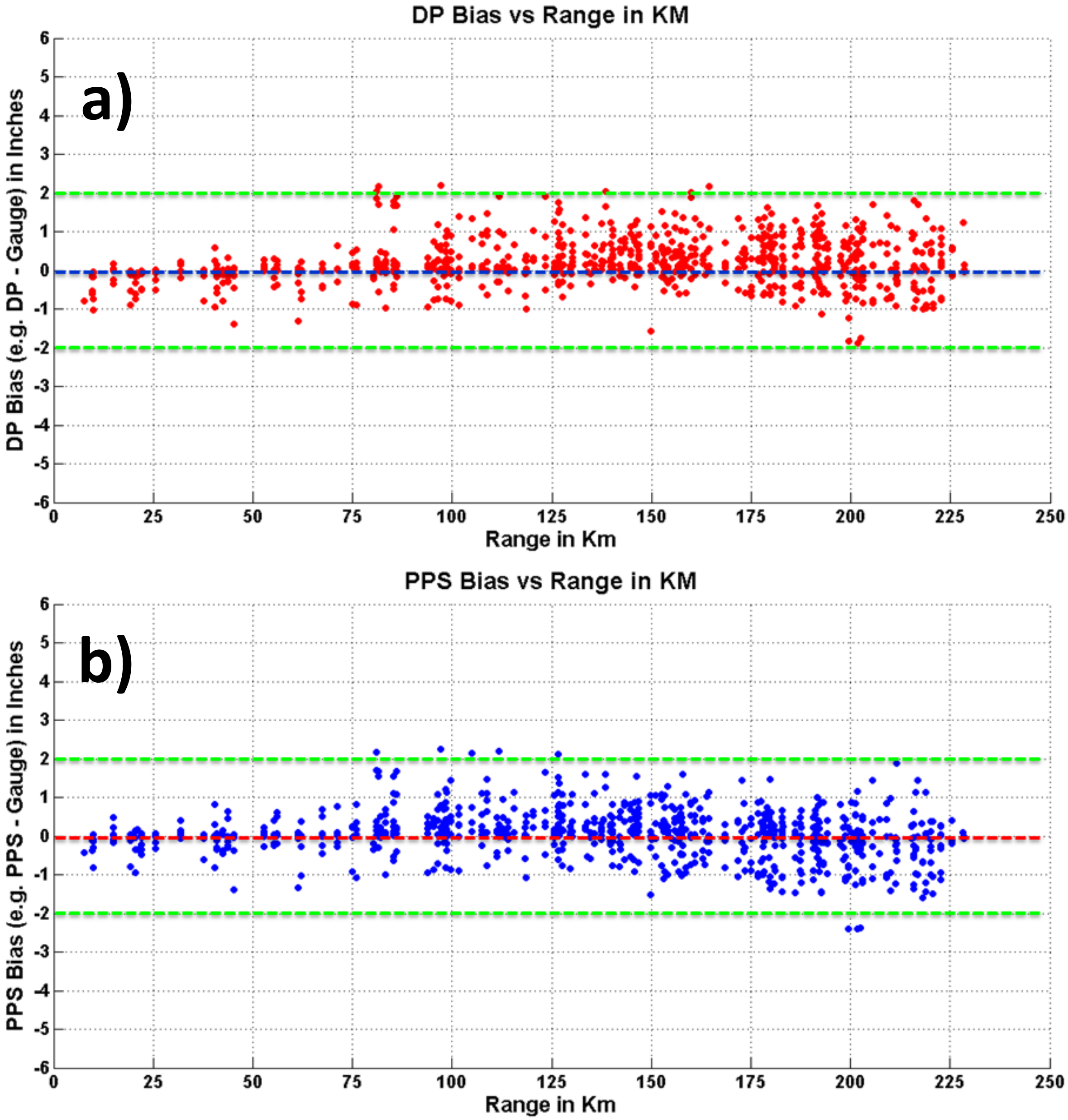

***Figure 6**:* *Scatter plots **a)** DP Bias and **b)** PPS Bias Errors as a function of range for all 807 radar/gauge pairs from KICT. Note the presence of substantial variability beginning for ranges greater than 75 km from the radar.*

From Table 3, the DP QPE bias values are significantly larger than PPS and at magnitudes higher than previously seen with KOUN or KVNX for the first two gauge categories. However, for the categories only containing R/G pairs with higher rainfall totals the trend is reversed: DP QPE bias values decrease and are better than PPS.

Figure 6 shows KICT DP QPE and PPS bias values as a function of distance from KICT. Once again, the variability seen is substantially higher than previously seen with KOUN and KVNX. For DP QPE there was a slightly negative bias trend that changed to a positive trend, indicating overestimates, at distances greater than 100 km from the radar. This suggests that the higher bias noted in Table 3 for the first two gauge categories may be related to R/G pairs at farther distances from the radar. At distances > 100km, the radar beam is high above the ground and the likelihood that the DP QPE rain estimates were made in the melting layer of the atmosphere is high. KICT PPS bias values also show increased further from the radar, again likely because the radar beam is well above the ground. The KICT PPS bias values show a trend towards rainfall underestimates at distances past 150 km, a result consistent with KOUN and KVNX.

DP QPE MELTING LAYER CHALLENGES: It is clear from the analysis of KICT the performance of DP QPE is not as favorable as seen with the data from KOUN and KVNX. Part of the difference may be related to the higher proportion of cooler season rain events in the KICT data set. More cool-season rain events need to be collected and analyzed for KOUN and KVNX to fully evaluate this possibility. However, the initial KICT results also suggest that the higher bias and RMSE values are related to the method used by the deployed DP QPE algorithm to estimate rainfall in the melting layer.

The melting layer (ML) is defined as the region of the atmosphere where precipitation falling from clouds changes from a frozen to a liquid state. Under certain conditions the melting layer can be seen in standard radar data as a bright band in reflectivity. Giangrande and Ryzhkov (2008) evaluated the effectiveness of a polarimetric echo classification system, one similar to the DP QPE and Hybrid-Hydro-meteorological Classification (HHC) algorithms deployed to the WSR-88D network. Their results showed that the DP RMSE errors for the system's rainfall estimates increased at distances between 100 and 200 km from the radar as a result of contamination from the melting layer. Similarly the KICT DP QPE rainfall estimates show increased variability and higher bias errors at distances greater than 100 km.

The deployed DP QPE algorithm is dependent upon HHC algorithm input; for a given echo classification provided by the HHC, the DP QPE uses a particular equation to calculate rain rates. Based on the HHC echo classification data, the DP QPE algorithm calculates rain estimates in three atmospheric regions: 1) above the melting layer where all precipitation is frozen; 2) in the melting layer where precipitation transitions from frozen to liquid; 3) below the melting layer where precipitation is all liquid. Below the melting layer, the DP QPE algorithm primarily uses DP variables. For example, when the HHC classifies an echo as rain or heavy rain the DP QPE rainfall equation is a function of the DP variable of differential reflectivity (ZDR) and reflectivity (Z):

1) DP QPE Rain Rate = f(Z, ZDR) for classification of rain or heavy rain

If the HHC classifies the echo as hail mixed with rain the DP QPE rainfall equation is a function of the DP variable specific differential phase (KDP):

2) DP QPE Rain Rate = f(KDP) for classification of hail/rain

In and above the melting layer (ML), the DP QPE algorithm primarily uses the legacy default PPS rain rate equation (PPSE) multiplied by a constant. For example, if the HHC classifies an echo as wet snow the DP QPE equation is the same as the legacy default PPS equation multiplied by 0.8:

3) DP QPE Rain Rate = PPSE*0.8 for classification of wet snow

When light precipitation is detected by the radar beam in and above the ML it is likely to be classified by the HHC as dry snow. The DP QPE equation used to calculate the rain rates are:

4) DP QPE Rain Rate = PPSE*1.0 for classification of dry snow *in* the ML

5) DP QPE Rain Rate = PPSE*2.8 for classification of dry snow *above* the ML

This means that for light precipitation, the DP QPE estimate can be either the same as the legacy PPS or almost three times higher.

Data Category	**Mean DP QPE Bias (in)**	**Mean PPS Bias (in)**	**DP QPE RMSE (in)**	**PPS RMSE (in)**	**Significant Difference Between DP & PPS?**
R/G Pairs for Gauge Amts ≤ 1.0” 388 obs	**0.38”**	**0.13”**	**0.63”**	**0.47”**	**Bias = YES** **RMSE = YES**
R/G Pairs for Gauge Amts > 1.0” 119 obs	**-0.04”**	**-0.59”**	**0.78”**	**0.95”**	**Bias = YES** **RMSE = YES**

Table 4: *Comparison of DP QPE & PPS bias and RMSE errors for KICT data at distances greater than 150 km from the radar.*

Table 4 shows the KICT DP QPE and PPS bias and RMSE values for distances greater than 150 km from the radar. The height of the radar beam above the ground at this distance (~ 9000 feet) ensures that approximately 80% or more of the radar estimates were made in and above the ML. For those R/G pairs where the gauge had rainfall totals less than or equal to an inch, the DP QPE

Bias is significantly higher than PPS. Similarly, the DP QPE RMSE values are also significantly higher than PPS. For those R/G pairs where the gauge had rainfall totals greater than an inch, the DP QPE bias was nearly zero and the PPS had a significantly low bias.

Data Category	**Mean DP QPE Bias (in)**	**Mean PPS Bias (in)**	**DP QPE RMSE (in)**	**PPS RMSE (in)**	**Significant Difference Between DP & PPS?**
R/G Pairs for Gauge Amts ≤ 1.0" 254 obs	**0.14"**	**0.02"**	**0.29"**	**0.30"**	**Bias = YES RMSE = NO**
R/G Pairs for Gauge Amts > 1.0" 54 obs	**-0.30"**	**-0.61"**	**0.70"**	**1.01"**	**Bias = YES RMSE = YES**

Table 5: *Comparison of DP QPE & PPS bias and RMSE errors for KOUN data at distances greater than 150 km from the radar.*

Data Category	**Mean DP QPE Bias (in)**	**Mean PPS Bias (in)**	**DP QPE RMSE (in)**	**PPS RMSE (in)**	**Significant Difference Between DP & PPS?**
R/G Pairs for Gauge Amts ≤ 1.0" 214 obs	**0.25"**	**0.11"**	**0.42"**	**0.37"**	**Bias = YES RMSE = YES**
R/G Pairs for Gauge Amts > 1.0" 72 obs	**0.06"**	**-0.25"**	**0.58"**	**0.72"**	**Bias = YES RMSE = YES**

Table 6: *Comparison of DP QPE & PPS bias and RMSE errors for KVNX data at distances greater than 150 km from the radar.*

The data suggests that the DP QPE algorithm may be overestimating the lighter rain events due to the way it is calculating rain rates in the melting layer. As a further test, we looked at the KOUN and KVNX DP QPE and PPS bias and RMSE values for distances greater than 150 km from the radar, again to ensure that the majority of the DP QPE radar estimates were made in the ML. As Tables 5 and 6 indicate, a trend seen in KICT data is similarly seen in KOUN and KVNX data. That is, DP QPE bias is significantly higher than PPS for the lighter rain amounts; this trend reverses to DP QPE out-performing PPS for higher rain amounts. Additionally, early feedback from Weather Forecast Offices at Cleveland and Pittsburgh has noted a similar trend of the DP QPE algorithm overestimating light precipitation events in the ML.

CURRENT AND FUTURE WORK: Clearly further analysis is needed to more explicitly evaluate DP QPE calculations of rain rates in the melting layer, particularly during events where light precipitation is present. Examination of HHC echo classifications for each volume scan for those radar estimates primarily made in and above the ML will likely be required. More cool season rain events need to be collected and analyzed for KOUN, KVNX and KICT to formally determine seasonal trends on the DP QPE algorithm's performance. Data from other DP radars in different climatic regimes need to be examined to see if and how the DP QPE algorithm performs differently in these areas. These efforts will be required to effectively fine tune the DP QPE algorithm to perform better during the cooler season. The process for doing this will likely last through the ongoing winter season and into the coming spring.

The ROC Applications Branch, Office of Science and Technology Software Engineering Center and National Severe Storms Laboratory (NSSL) are working together to:

1) Evaluate DP QPE and PPS performance for DP radars in different climatic regimes in the U.S as additional radars are upgraded
2) Document performance of the deployed DP QPE algorithm
3) Tune algorithm code to improve performance

In addition, NSSL is currently developing a more advanced Hydro-meteorological Classification Algorithm (HCA) with the goal of improving the echo classification performance in the fall and winter seasons across the U.S. This effort will ultimately lead to improved rain estimates during the cool season as the HCA provides input to the DP QPE algorithm. The efforts to mature the DP QPE and other DP algorithms will be a multi-year process, with the DP QPE algorithm having top priority.

SUMMARY: An initial analysis of DP QPE performance has been completed using a limited data set collected over Oklahoma and Kansas. Analysis indicated the DP QPE algorithm typically performed better than PPS for the data sets collected for KOUN and KVNX, data sets dominated by warm season rain events. For KICT, the DP QPE algorithm did not perform as well as PPS until R/G pairs with gauge totals greater than an inch were only considered. Analysis indicates that a good portion of the errors are likely related to DP QPE ML challenges when light precipitation is present. As more data is collected from other radars across other climatic regimes, further analysis will be conducted to more explicitly diagnose where and how the DP QPE algorithm is overestimating rainfall in the ML. Finally, the legacy PPS system will remain available to forecasters until the DP QPE algorithm becomes fully mature.

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