Evaluation of dual-polarization QPE: Initial results for spring and summer 2012

Final Report

MOU Task1.1

September 2012

Prepared for:

The WSR-88D Radar Operations Center, Applications Branch

NOAA national severe storms laboratory

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Executive summary

A major objective of the dual polarization (DP) technology upgrade is to improve quantitative precipitation estimates (QPE). The Radar Operations Center commissioned the National Severe Storms Laboratory (NSSL) to develop web-based verification tools and perform an evaluation of DP QPE vs. Legacy Precipitation Processing System (PPS) algorithms. NSSL's QPE Verification System (QVS) was upgraded to include dual polarization data. Due to time constraints, the evaluation portion of this study uses storm totals and is more relevant to general hydrologic forecasting, such as the work done by River Forecast Centers. However, there are strong indications that DP QPE is an improvement for shorter time scales.

Using rain gauges as ground truth, DP QPE demonstrated improvement over Legacy PPS. DP QPE showed a 19% improvement over Legacy. For gauge amounts greater than 2", DP QPE provided a 23% improvement over Legacy.

With the dual polarization upgrade, additional variables are available to estimate precipitation. Some short-term recommendations are investigating performance using continental vs. tropical equations, increasing reliance on the use of specific differential phase (Kdp), and introducing a rainfall equation based on specific attenuation. Longer-term solutions include monitoring and correcting for differential reflectivity (Zdr) bias errors, evaluating methods for mitigating the melting layer discontinuity, and conducting precipitation verification analysis on an hourly and sub-hourly basis.

1. Project objectives

Dual-polarization was initially field tested and found to improve upon precipitation estimates during the Joint Polarization Experiment (Ryzhkov et al. 2005). The goal of this report is to document DP QPE performance compared to Legacy PPS.

Specific objectives include:

- Documentation of DP QPE and Legacy algorithm performance overall and for individual storms
- Provide examples of successes and failures
- Recommendations for improvements

2. Reporting

This final report is pursuant to requirements in the Memorandum of Understanding between the WSR-88D Radar Operations Center, Applications Branch and NOAA's National Severe Storms Laboratory Task 1.1 "Evaluation of DP QPE." A substantial portion of the MOU involved enhancement of the QPE Verification System (QVS; nmq.ou.edu/qvs-2012.html) to include data from DP radars. This study was greatly facilitated by this new capability that allows rapid processing of large amounts of data.

3. Agency responsibilities

The WSR-88D Radar Operations Center, Applications Branch is responsible for maintenance of algorithms in the ORPG and implementation of new algorithms.

4. Evaluation methodologies

4.1 DP QPE and Legacy construction within QVS

With ROC funding support, the NSSL QPE Verification System (QVS; nmq.ou.edu/qvs-2012.html) was expanded to include single-radar products in polar format. Data in Level 3 format are used. The Legacy product is reconstructed from the Digital Hybrid Reflectivity (DHR) using the Z-R relation used operationally and "max precip rate" from the Level-3 file header. Thus, 1-h products on QVS may differ slightly from operational products. The "DHR" method was chosen over using One Hour Precipitation (OHP) from Level-3 since DHR has 1-km range resolution while OHP has 2-km range resolution. DP QPE is recreated from the Level-3 Digital Precipitation Rate (DPR) at .25 km range resolution. As with the Legacy product, DP QPE may differ slightly from operational products.

Uncertainties in radar-gauge comparisons partially result from different radar bin resolution with larger scales having less uncertainty (Seo and Krajewski, 2010). Thus, if both are equal, DP would actually have better skill. Quantification of these effects is beyond the scope of this study.

The DP QPE algorithm is based on the Hybrid Hydrometeor Classification algorithm (HHC) which in turn depends on the Melting Layer (ML) algorithm (Giangrande et al. 2008; Park et al. 2009; Ryzhkov et al. 2011; Ryzhkov et al. 2012). Appendix 1 shows which rain rate (R) relation is used for the different HHC categories. For instance, Kdp is used only when rain mixed with hail (HA) is classified. A combination of Z and Zdr is used for other precipitation classes below the ML. Above the ML, Z is used with different coefficients depending on HHC output. Z and Zdr are linearized at the front end of the QPE algorithm. Appendix 1 also provides the R equations for the Legacy algorithm.

Equation 1 is the default equation for DP QPE and is referred to as the "Tropical" relation. This replaced the initial "Continental" relation (equation 2) since it results in higher precipitation rates that performed better in southeast storms during initial development. Appendix 1 also provides R curves for different Z, Zdr values and shows the sensitivity of R on small changes in Zdr. For instance, a 0.1 dB difference in Zdr results in a difference in R of ~.2 in h^{-1} at 45 dBZ. Equation 3 is used when hail is identified by the HHC.

$$R(Z, Z_{DR}) = 6.7010^{-3} Z^{0.927} Z_{dr}^{-3.43} \quad (1)$$

$$R(Z, Z_{DR}) = 1.4210^{-2} Z^{0.770} Z_{dr}^{-1.67} \quad (2)$$

$$R(Kdp) = 44.0|Kdp|^{.822} \mathrm{sign}(Kdp) \quad (3)$$

4.2 Ground truth

Rain gauges are generally assumed to be ground truth. The primary gauges used are from the hourly Hydrometeorological Automated Data System (HADS; http://www.nws.noaa.gov/oh/hads/) and the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS; http://www.cocorahs.org/). 24-h CoCoRaHS observations are typically taken at 0700 LT. Perhaps an order of magnitude more CoCoRaHS gauges are available along the East Coast. Other "local" high-quality networks include the Oklahoma Mesonet, West Texas Mesonet, Maricopa County, AZ Flood ALERT network and the Lower Colorado River Authority, TX network. Efforts to use additional networks are in progress and can be viewed on the QVS system. Regions with few gauges have more analysis uncertainty.

There are many factors that affect the quality of gauge observations. For instance, gauges can be subject to under-catch due to clogging, high winds and heavy rain. In-depth gauge quality control and uncertainty analysis is beyond the scope of this study. Due to the large number of gauges used in this report, small numbers of bad gauges have little effect on overall statistics.

4.3 Statistics

The statistics explored are the mean bias, the mean absolute error (MAE), the root-mean-square error (RMSE) and the correlation coefficient (CC) between the gauge catchment and the QPE method. Biases are additive. Statistics are computed using the commercial product “S+.”

Data are combined into "cases," where a case consists of the storm total for an entire event, regardless of duration. Events typically are less than 24 h long, but some exceed 24 h in duration. Data are grouped into cases, rather than maintaining separate radar-gauge pairs, so as to address issues of spatial correlation between gauges. Radar-gauge pairs are spatially correlated and thus not statistically independent. Lack of independence means that the number of degrees of freedom is less than the number of gauges and, in some cases, may be much less. If the degrees of freedom are erroneously high, then the resulting p-values will be too low and generate “Type I” errors. Events or cases are, however, assumed to be serially independent for each radar. The MAE preferred over mean bias error because in order to identify the QPE method that is closest to the gauge catchment, regardless of sign. However, mean bias is used in discussion of individual events.

P-values are generated using a Monte Carlo approximation of the one-sided Fisher’s exact permutation test under a matched-pairs analysis using 3999 permutations (more simply, a matched pairs permutation test). The various QPE methods are grouped under the assumed hierarchy that the errors produced are ordered as Legacy > DP QPE and that correlations are ordered as Legacy < DP QPE. Thus the null hypothesis is that these conditions do not hold (e.g. for MAE, Legacy ≥ DP QPE). A p-value < 0.05 is considered “significant” for the purposes of this analysis and any p-value smaller than 0.001 is considered “highly significant.”

A non-parametric permutation test is employed, rather than the more familiar t-test, because the distribution of the errors is unknown. The t-test relies on the assumption that the values are drawn from a Normal distribution, an assumption that is violated. More typical measures of precipitation error, such as percent, are not used here because percentage error is unstable for small precipitation amounts and insensitive for large amounts.

The analysis is broken down into four separate categories for 24 h totals: the first includes all gauges amounts, the second includes only gauges > 0.5”, the third includes only gauges > 1.0”, and the fourth includes only gauges > 2.0”. This breakdown helps reveal whether the different QPE methods show strengths at higher amounts, which are more prone to generate flash flood events. Only data within 150 km slant-range (recalling that the beam height increases with range) from a radar are considered to avoid issues related to the ML. Sporadic decreases in the ML height to within 150 km from a radar were observed and further study needs to be done to understand the effects of the ML algorithm on QPE. Gaingrande and Ryzhkov (2008) showed that the best DP QPE algorithm performance was within 150 km range. This range also effectively covers most of the area east of the Rocky Mountains (for warm season storms). Optimally, several years of data from all radars are required for a robust analysis and high confidence in results. As of this writing (September 2012), ~90 of the radars have been upgraded and are in the QVS.

5. Analysis results

A list of radar-case "events" evaluated in this study is provided in Table 1. The storm types are defined in Table 2 and further described in section 5.3. DP QPE data for significant storms have been available only since March 2012 and this study includes five cool season events (all from one storm that affected five radars). Notably, three tropical storms (Beryl, Debby and Isaac) affecting 12 radars are included. There were a limited number of events in the West with cases from southern Arizona and southern California.

Results are presented in the following categories:

1. Overall results
2. Events by gauge amounts > .5", > 1", and >2"
3. Results by storm type
4. Individual case examples

5.1 Overall results

Statistical results for all gauge amounts are shown in Table 3. For gauge amounts > 0", DP QPE has a MAE = 0.230, an RMSE = 0.584, and a CC = 0.762. Legacy has a MAE = 0.283, an RMSE = 0.625 and a CC = 0.751. This represents a decrease in MAE of 19% for DP QPE over Legacy. Statistical significance at the 95% confidence level is indicated by a p-value < 0.05. At this threshold, DP QPE is better than Legacy for MAE and RMSE but not for CC.

Plots of DP QPE and Legacy mean biases for each radar/date are shown in figure 1. The DP QPE biases are more closely grouped about the zero line than are Legacy biases. This reflects the statistical results. Note that the spread of the biases appears to increase with time, perhaps due to a wider variety of storm types toward the end of the summer season.

Tables 4 and 5 show which algorithm had the lowest MAE and RMSE and the highest CC and was determined by which simply had the best value. DP QPE outperforms Legacy for MAR, RMSE by ~2 to 1 but not for CC.

Another way to assess differences between DP QPE and Legacy performance is by noting the differences between the absolute values of the mean biases (Table 6). Negative values indicate better performance for DP QPE. DP QPE has smaller errors in almost two thirds of the events, again confirming the statistical results. Examples of good and poor performance for DP QPE are presented in the following sections.

5.2 Results by gauge amounts > .5", > 1", and >2".

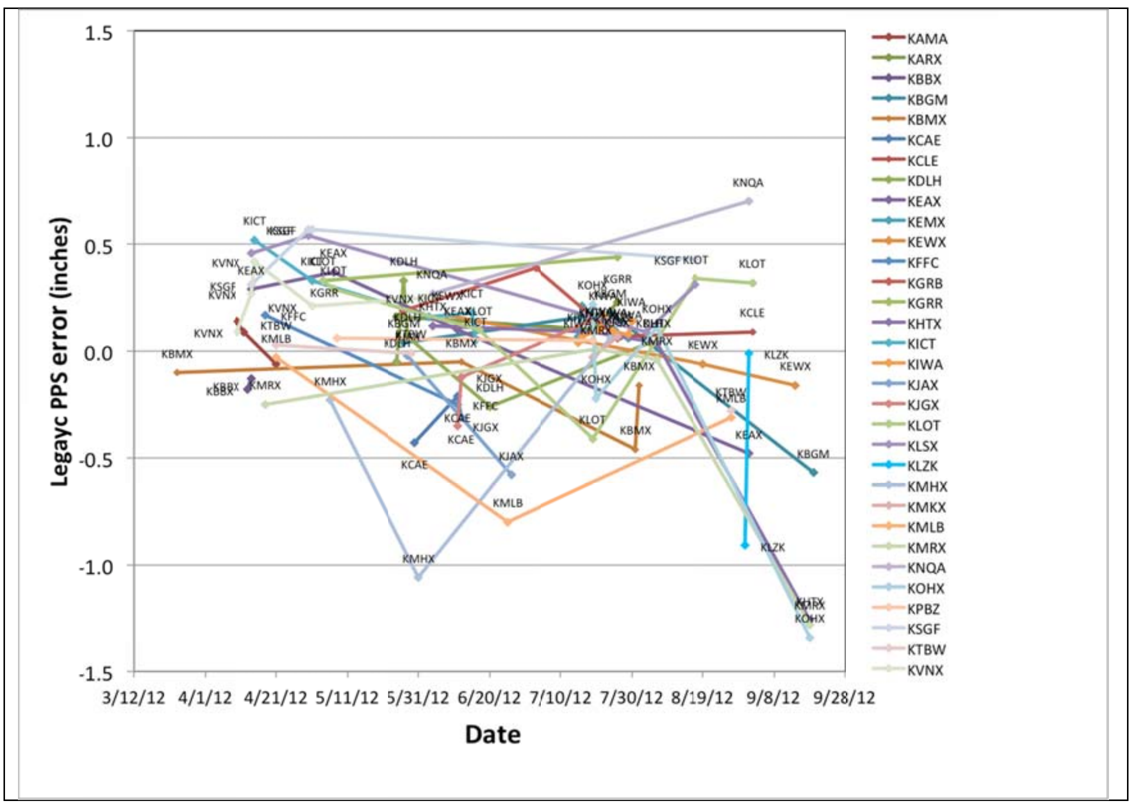
Slightly better results occur for gauge amount thresholds > 0.5" (Table 7) with DP QPE showing increasing reductions in MAE and RMSE over Legacy. The improvement in MAE for DP QPE is 21.5% (0.328 compared to .418). The CC for DP QPE is slightly higher but is not statistically significant (therefore practically identical).

For the > 1” category (Table 8), DP QPE MAE reduction increases to 22% (0.416 compared to 0.536). Also, the DP QPE CC (0.597) is higher than the Legacy CC (.582) at the 95% confidence level.

For gauge amounts > 2” (Table 9), DP QPE is statistically significantly better than Legacy for MAE and RMSE. The reduction in MAE for DP QPE over Legacy increased to 23% (0.62 compared to 0.803). While DP QPE has a higher CC than Legacy, all CCs are low, indicative of the smaller number of gauges at this threshold. Note that there are only 47 events with 15 or more gauges > 2”.

5.3 Results by storm type

The dominant storm type was identified for each event (Table 2). Identification of a single type for each event has some uncertainty since multiple modes of precipitation mechanisms often occurred during an event. The pulse storm (PS) type was perhaps the most straightforward since those storms occurred in the absence of synoptic forcing. Similarly, California orographic forcing was a singular mode. The remaining types were more complex. Even the tropical storm (TS) type may have had warm rain mixed with continental air mass characteristics when TS Isaac moved into the Great Lakes Region. Supercell storms (SC) in OK and KS evolved into squall lines (SL). However, the SL type does not include trailing stratiform precipitation. The Mesoscale Convective type (MC) type includes both Mesoscale Convective Complexes and fronts with



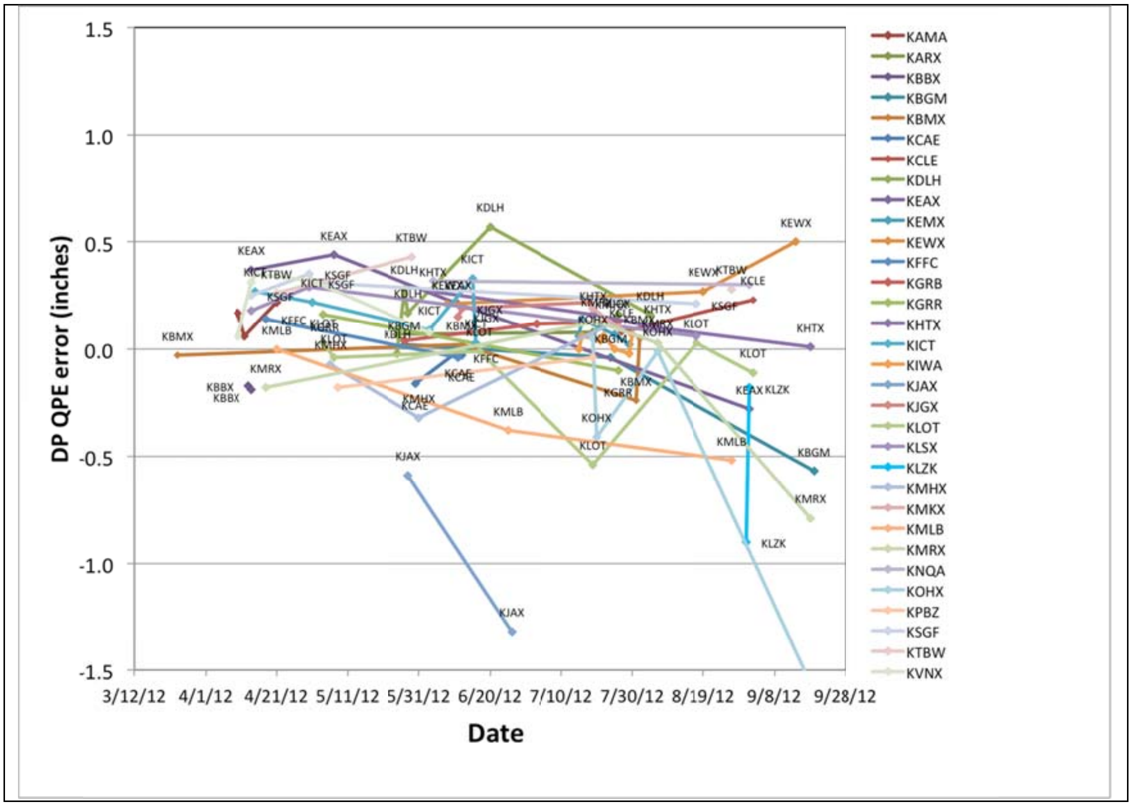


Figure 1. Mean biases for each event by radar and date for Legacy PPS (top) and DP QPE (bottom).

trailing stratiform precipitation (e.g., Maddox 1983). The differences between frontal (FR) and weak frontal (WF), simply due to differences in maximum reflectivity values, may be somewhat arbitrary. Because there are mixed precipitation classes in each type category, these results are somewhat general and should be further analyzed on a sub-hourly basis and compared to DP HHC designations.

Results for MAE for the different storm types are shown in Table 10. DP QPE MAE is lower than Legacy MAE for all storm types except PS where they are nearly identical. It is hypothesized that these storms have less uncertainty due to milder meteorological conditions that affect gauge measurements (e.g., low vertical wind shear and less variation in precipitation type). The largest decrease in MAE for DP QPE is 32% for MC storms, the most frequent storm type (44). Statistical significance has not been established for these results although 44 events for MC are likely significant.

5.4 Case examples

All events were documented in cursory evaluations called "Quick Looks" available on the ftp site ftp://ftp.nssl.noaa.gov/users/vasiloff/PPTs/QuickLooks/. These overviews contain statistical summaries that slightly differ from those in the tables in this report due to different gauge data being used. For instance, CoCoRaHS data from both 1100 UTC and 1200 UTC are included in this report but not in the Quick Looks due to current limitations of the QVS. The Quick Looks provide supplemental data including images of various algorithm products, scatterplots of radar-gauge data and a number of statistics.

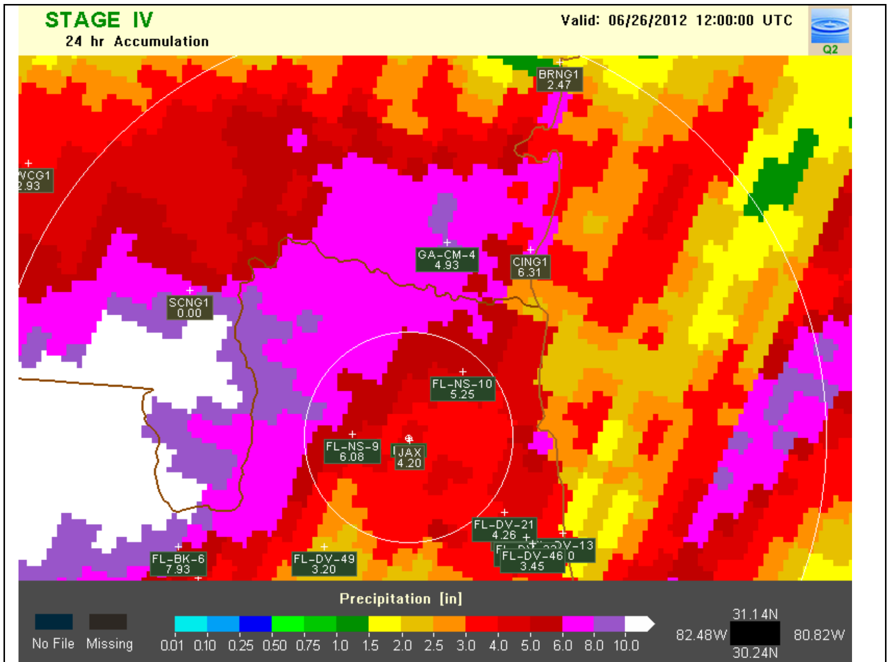
5.4.1 KJAX during tropical storms Debby and Beryl

As seen in Table 6, the largest DP QPE underperformance was for KJAX during TS Debby on 6/26/12. The Legacy bias = -.58 and DP QPE bias = -1.32. The DP QPE underperformed compared to Legacy and Stage 4 with results shown in figure 2. Stage 4 precipitation data (see e.g., http://water.weather.gov/precip/) is generated at RFCs and is assumed to be closest to ground truth. Legacy showed lower precipitation amounts than Stage 4 and DP QPE had the lowest amounts. The two-product difference (TPD) clearly indicates that DP QPE was less than Legacy. Since the DP QPE rain rate relations were developed for tropical-like rain microphysics, these results are perplexing. However, there was a Zdr bias error of 0.41 that may have suppressed the DP QPE values. Note that there is severe partial beam blockage for KJAX.

KJAX had the second largest bias difference on 5/28/12 during TS Beryl (Legacy = -0.02 compared to DP QPE = -0.59) and had a Zdr bias error of 0.4. Thus, as for TS Debby, it appears that accounting for the Zdr bias error would have improved DP QPE performance in this event.

5.4.2 KDLH during heavy rain on 6/20/12

The KDLH event of 6/20/12 was operationally significant with 24 h precipitation amounts over 8”. DP QPE (bias = 0.5) over-estimated while Legacy (bias = -0.26) under-estimated. Figure 3 shows that DP QPE over-estimated in only part of the domain. Data time series at gauge SDYM5 in the area of overestimation (Fig. 4) depicts DPR rates greater than Legacy rates when the HHC algorithm indicates HR. This indicates that the “Tropical” DP QPE rain rate relation may not have been appropriate in this region of the storm and is further addressed in section 7 that provides algorithm sensitivity testing results.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24 hr Accumulation
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Q2
BRNG1 2.47
WCG1 2.93
GA-CM-4 4.93
CING1 6.31
SCNG1 0.00
FL-NS-10 5.25
FL-NS-9 6.08
JAX 4.20
FL-DV-21 4.26
FL-DV-46 0 3.45
FL-BK-6 7.93
FL-DV-49 3.20
Precipitation [in]
No File
Missing
0.01 0.10 0.25 0.50 0.75 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 8.0 10.0
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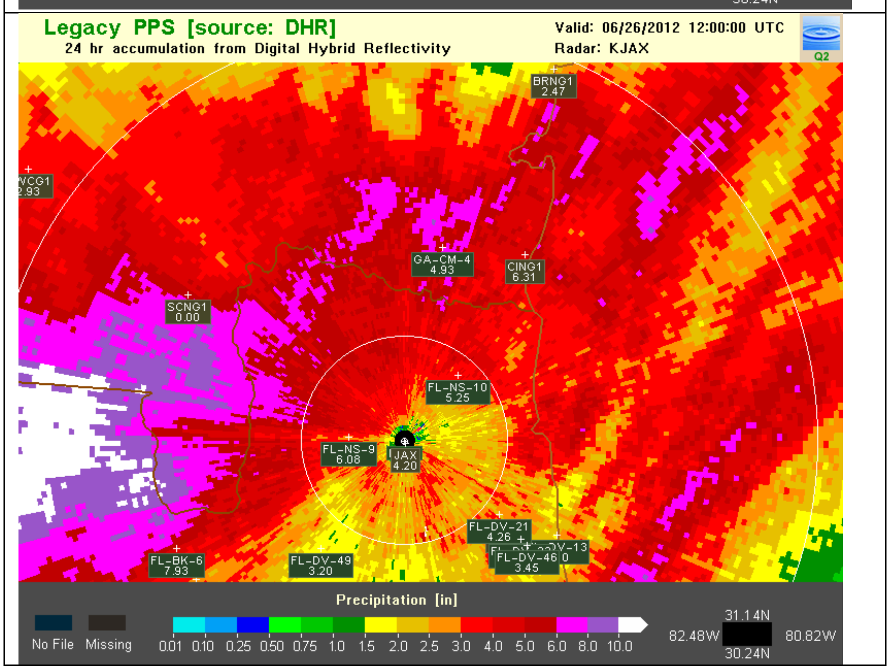
82.48W
80.82W
30.24N


Legacy PPS [source: DHR]
24 hr accumulation from Digital Hybrid Reflectivity
Valid: 06/26/2012 12:00:00 UTC
Radar: KJAX
Q2
BRNG1 2.47
WCG1 2.93
GA-CM-4 4.93
CING1 6.31
SCNG1 0.00
FL-NS-10 5.25
FL-NS-9 6.08
JAX 4.20
FL-DV-21 4.26
FL-DV-46 0 3.45
FL-BK-6 7.93
FL-DV-49 3.20
Precipitation [in]
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0.01 0.10 0.25 0.50 0.75 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 8.0 10.0
31.14N
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80.82W
30.24N

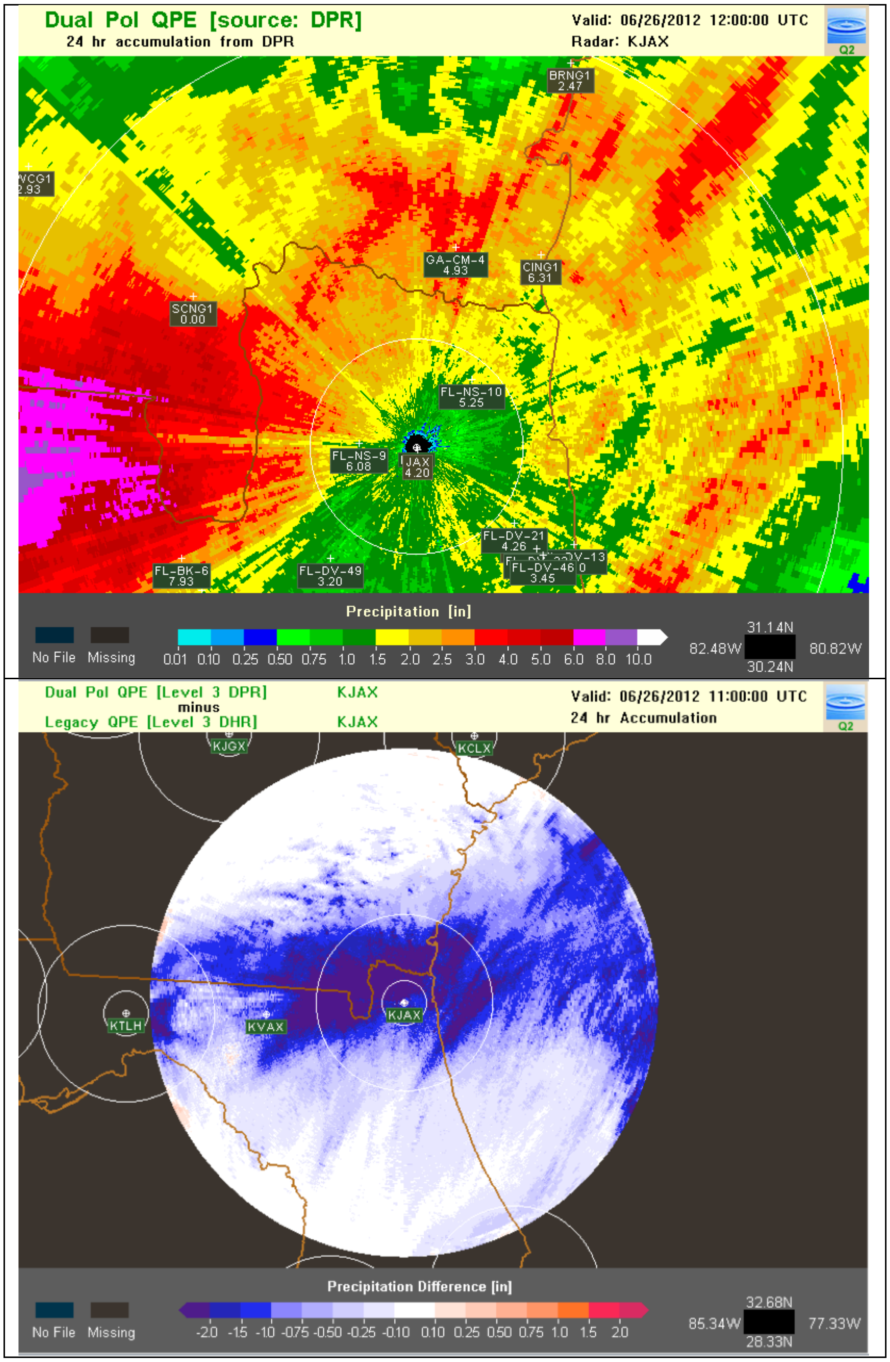
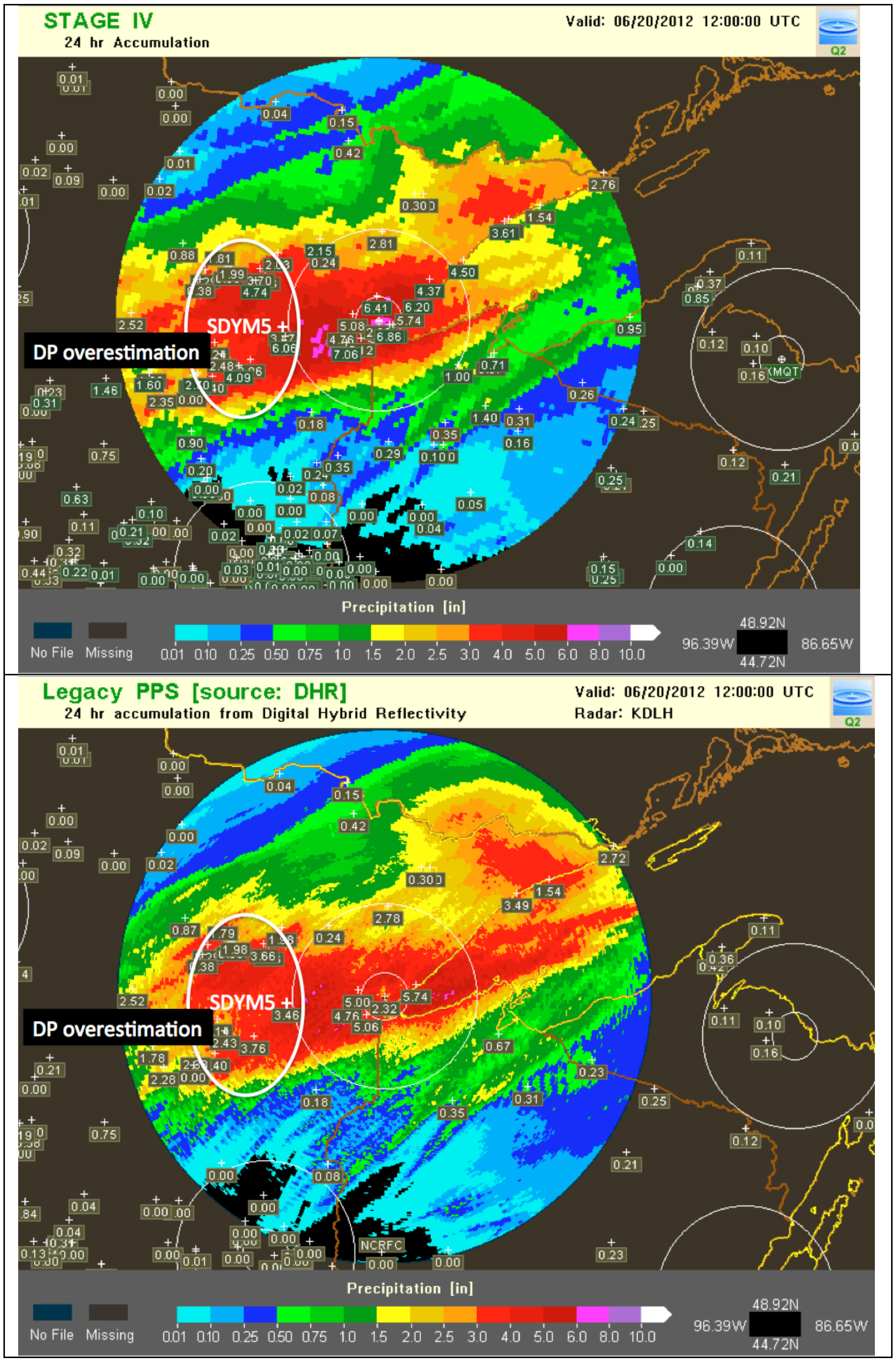


Figure 2. 24-h products for KJAX ending 1200 UTC on 6/26/12. From the top are: Stage 4, Legacy, DP QPE, and the two-product difference (DP-Legacy) over the entire radar umbrella. 24 h gauge amounts are overlaid. Range rings are 20 and 80 km.


STAGE IV
24 hr Accumulation
Valid: 06/20/2012 12:00:00 UTC
SDYM5
DP overestimation
KMQT
Precipitation [in]
No File
Missing
0.01 0.10 0.25 0.50 0.75 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 8.0 10.0
48.92N
96.39W
86.65W
44.72N
Legacy PPS [source: DHR]
24 hr accumulation from Digital Hybrid Reflectivity
Valid: 06/20/2012 12:00:00 UTC
Radar: KDLH
SDYM5
DP overestimation
NCRFC
Precipitation [in]
No File
Missing
0.01 0.10 0.25 0.50 0.75 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 8.0 10.0
48.92N
96.39W
86.65W
44.72N

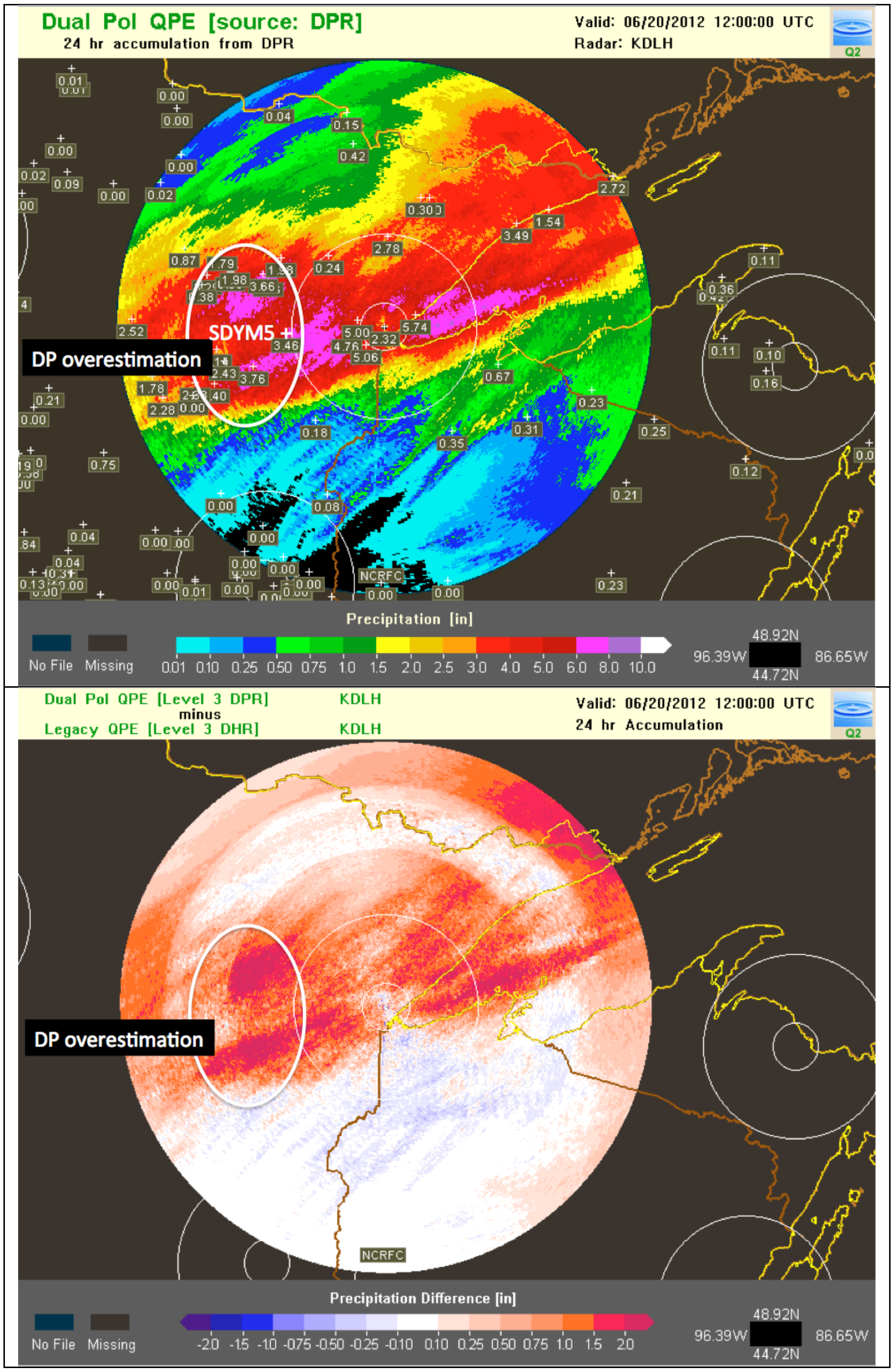


Figure 3. As in figure 2 except for KDLH on 6/20/12. The primary region of DP QPE over-estimation is indicated by the white oval. Gauge SDYM5 is shown in the time series in figure 4.

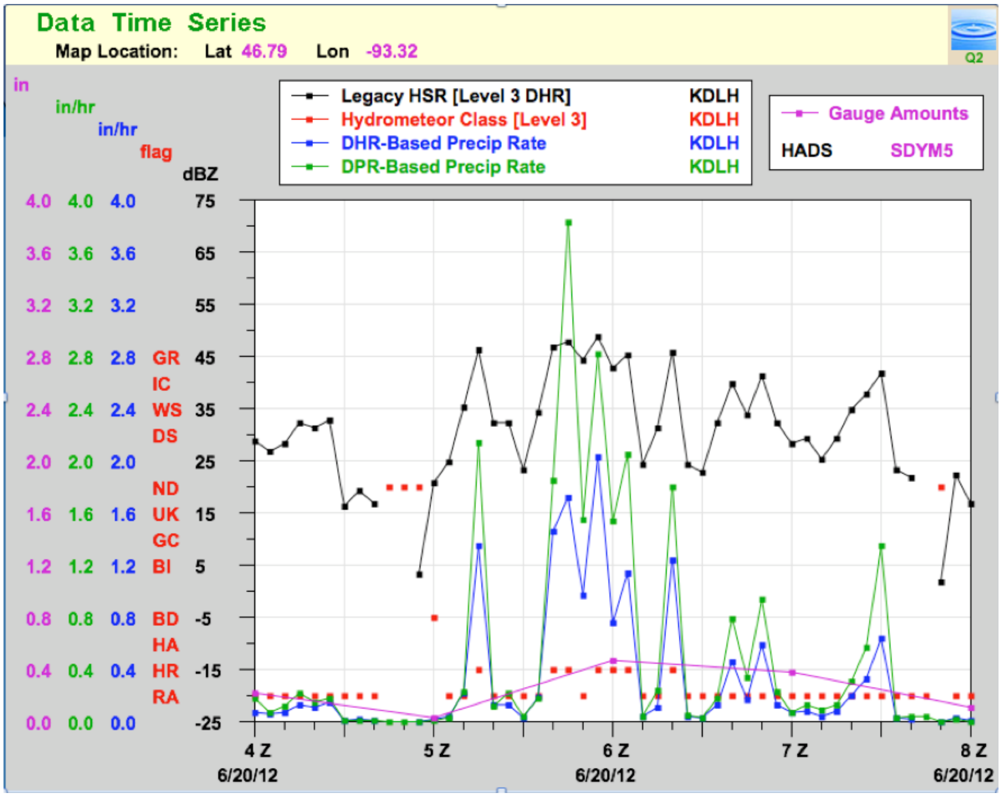
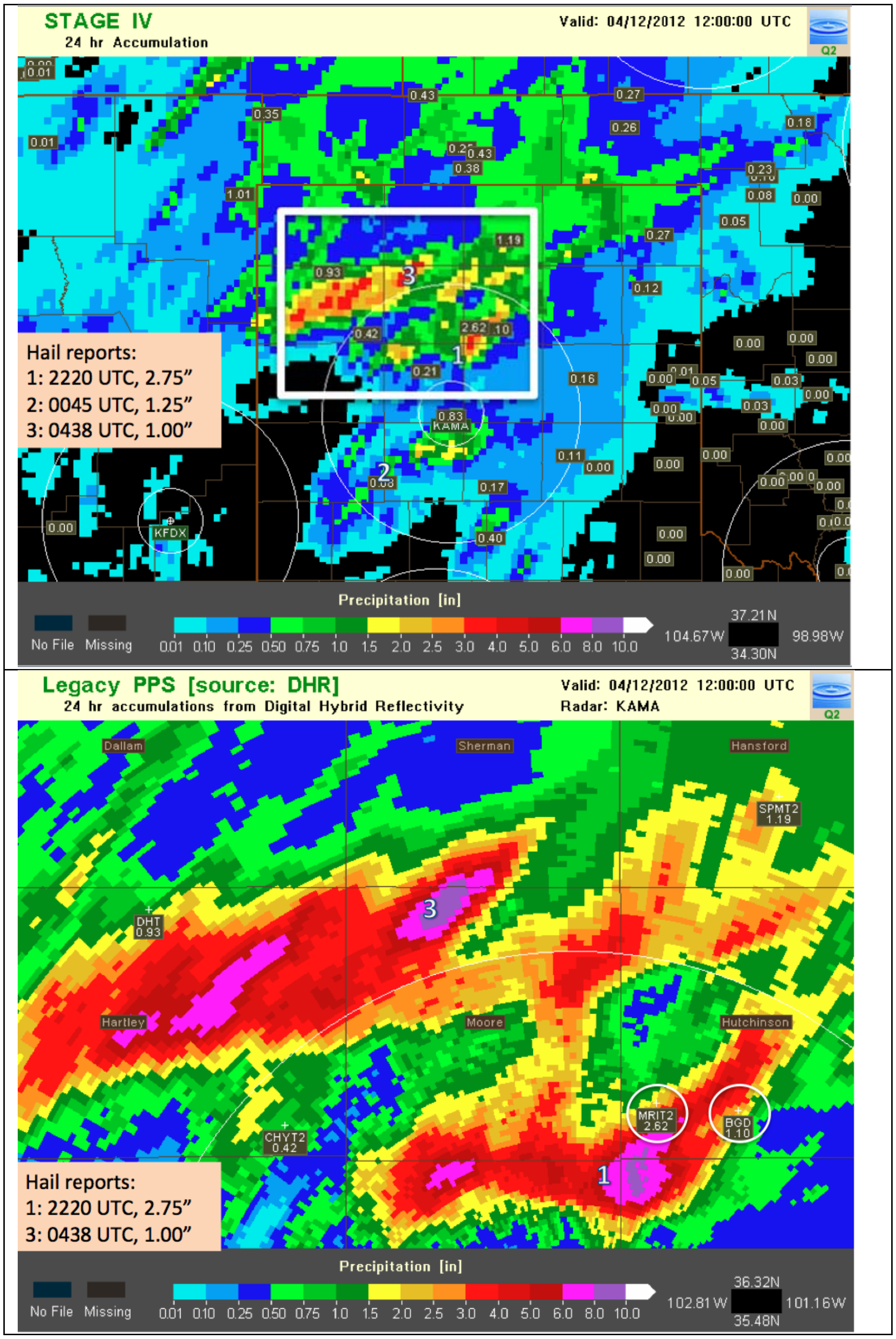


Figure 4. Time series at gauge SDYM5 of DHR (black), rates from DHR (blue) and DPR (green), and HHC (red). Gauge amounts for HADS gauge SDYM5 are in purple. The time period is 4 h ending 0800 UTC on 6/20/12.

5.4.3 Amarillo, TX (KAMA) during hail storms on 4/12/12

As discussed earlier, Kdp is used when rain/hail is indicated by the HHC. Precipitation accumulations and hail reports for KAMA on 4/12/12 are shown in figure 5. Stage 4 amounts are much less than DP QPE and Legacy and DP QPE is less than Legacy. The lack of hail reports and gauges in the rain cores are limitations of this analysis. Note that the storm core associated with report #2 appears to be in a blockage region. Scatterplots show that DP QPE is a better match to gauges than is Legacy for large gauge amounts and over-estimates compared to Legacy for smaller gauge amounts (Fig. 6). Time series for gauges BGD and MRIT (Fig. 7) show that DP rates were much less than DHR rates and are classified as mostly RA. Note that HA is not indicated at these locations; both gauges were outside of the hail core associated with report 1.


STAGE IV
24 hr Accumulation
Valid: 04/12/2012 12:00:00 UTC
Q2
Hail reports:
1: 2220 UTC, 2.75”
2: 0045 UTC, 1.25”
3: 0438 UTC, 1.00”
KAMA
KFDX
Precipitation [in]
No File
Missing
0.01 0.10 0.25 0.50 0.75 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 8.0 10.0
37.21N
104.67W
98.98W
34.30N
Legacy PPS [source: DHR]
24 hr accumulations from Digital Hybrid Reflectivity
Valid: 04/12/2012 12:00:00 UTC
Radar: KAMA
Dallam
Sherman
Hansford
SPMT2 1.19
DHT 0.93
Hartley
Moore
Hutchinson
MRIT2 2.62
BGD 1.10
CHYT2 0.42
Hail reports:
1: 2220 UTC, 2.75”
3: 0438 UTC, 1.00”
Precipitation [in]
No File
Missing
0.01 0.10 0.25 0.50 0.75 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 8.0 10.0
36.32N
102.81W
101.16W
35.48N

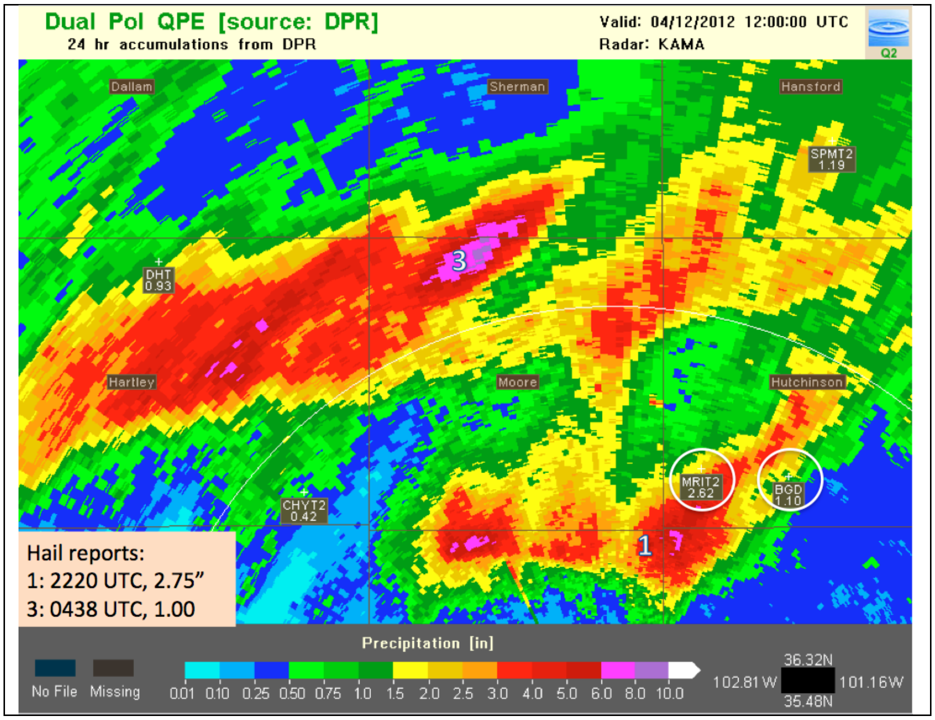


Figure 5. As in Fig. 2 except for KAMA on 4/12/12 with no two-product difference. Hail reports from the Storm Prediction Center are shown for 4/11/12. Legacy and DP QPE are enlarged for the box in the top panel. MRIT and BGD are circled and indicated in figures 6 and 7.

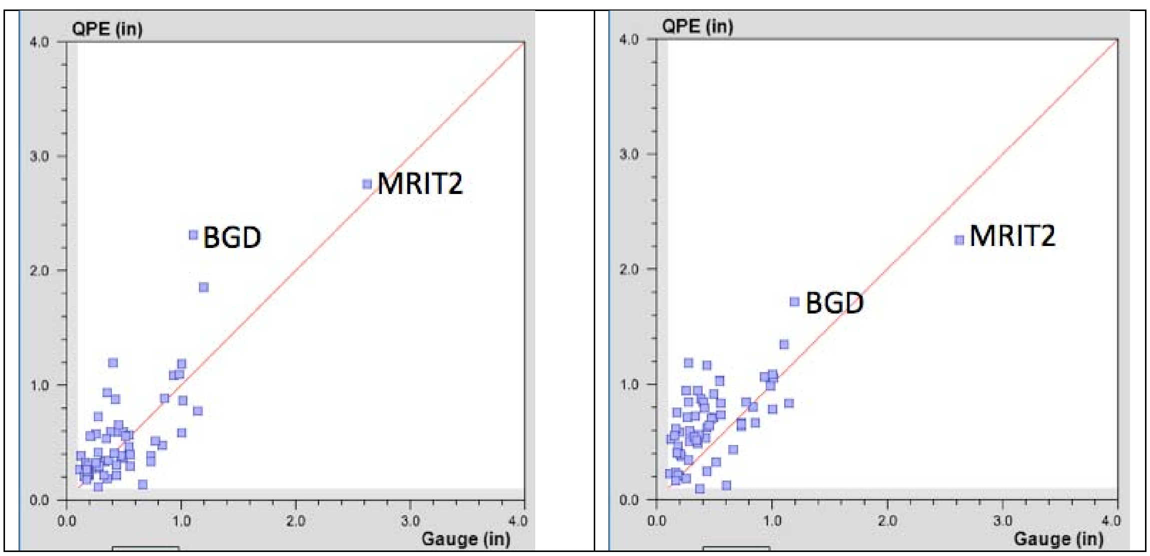


Figure 6. Scatterplots of 24 h accumulations compared to gauges for KAMA on 4/12/12: Legacy (left) and DP QPE (right).

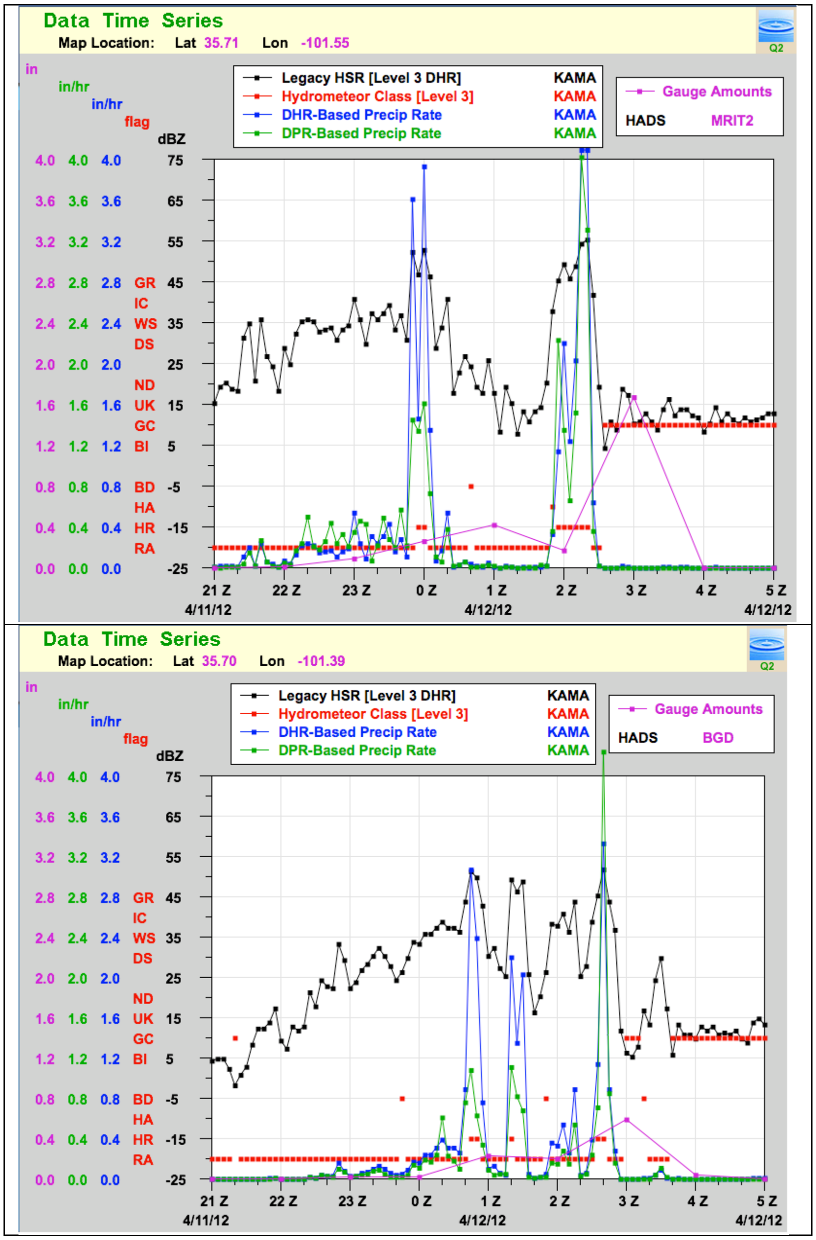


Figure 7. As in Fig. 4 except for KAMA gauges MRIT2 (top) and BGD (bottom) for an 8 h time period ending 0500 UTC on 4/12/12. Locations are shown in figure 5.

In order to understand DP QPE performance in large hail, details of a hail core are examined. One-hour precipitation amounts for the storm cell associated with hail report 1 are shown in figure 8 and further illustrate the DP QPE reduction in precipitation amounts compared to Legacy, again with DP QPE being closer to the "truth." DP QPE rain rates are much lower than the capped Legacy rates except when HA is indicated at 2240 and 0150 UTC (Fig. 9). There were flash floods reported with these storms and the higher DP QPE rates were likely justified. As indicated between 2300 UTC 4/11 and 0000 UTC 4/12: a) use of Zdr for HR reduces estimates over those for Legacy and b) Kdp works as expected for hail.

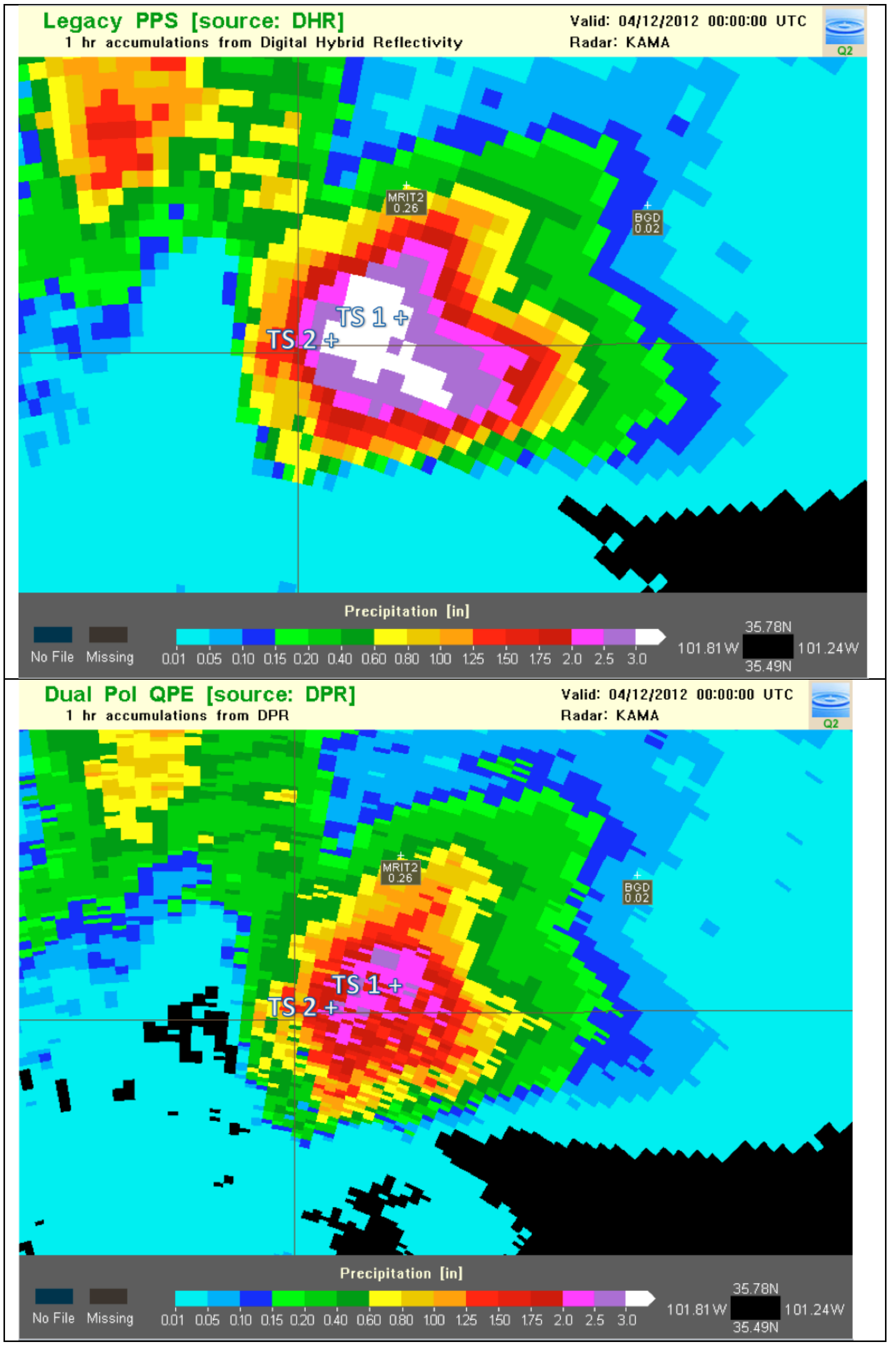


Figure 8. One-hour precipitation totals for KAMA ending 0000 UTC on 4/12/12: Legacy (top) and DP QPE (bottom). TS 1 and 2 indicate locations for time series shown in figure 9.

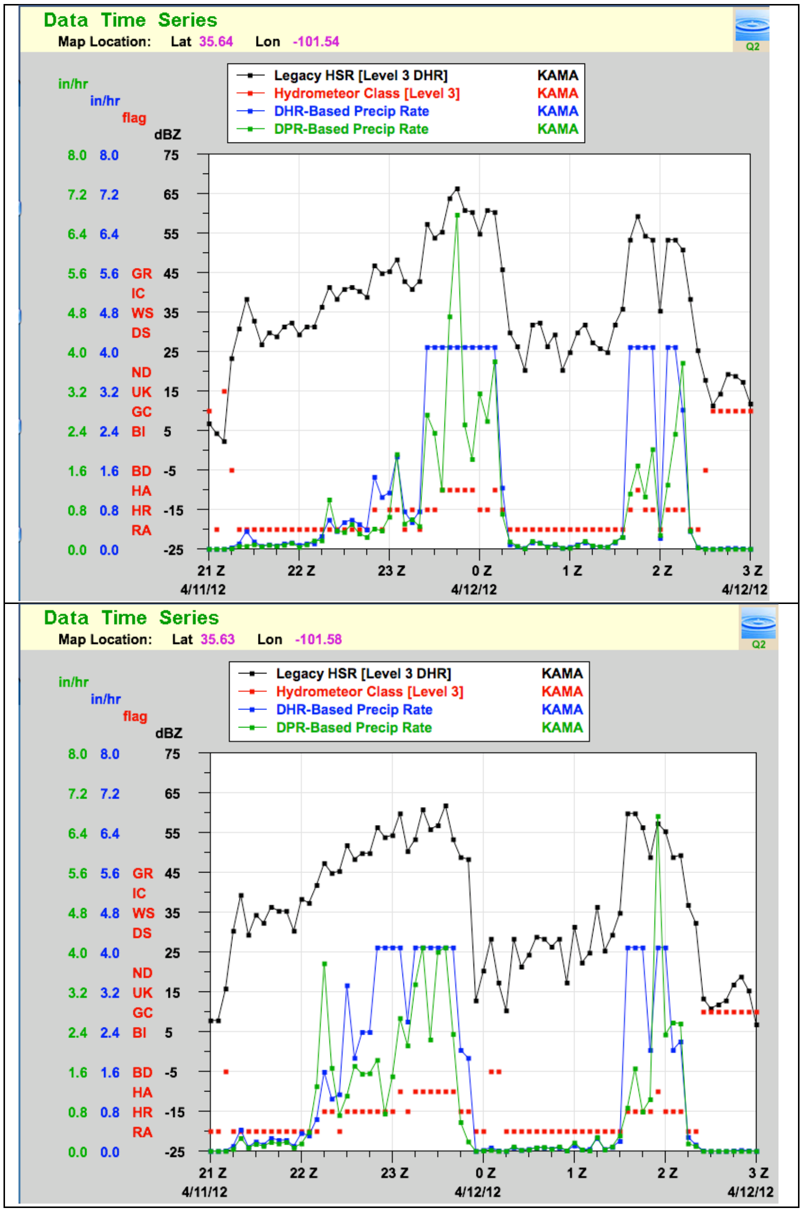
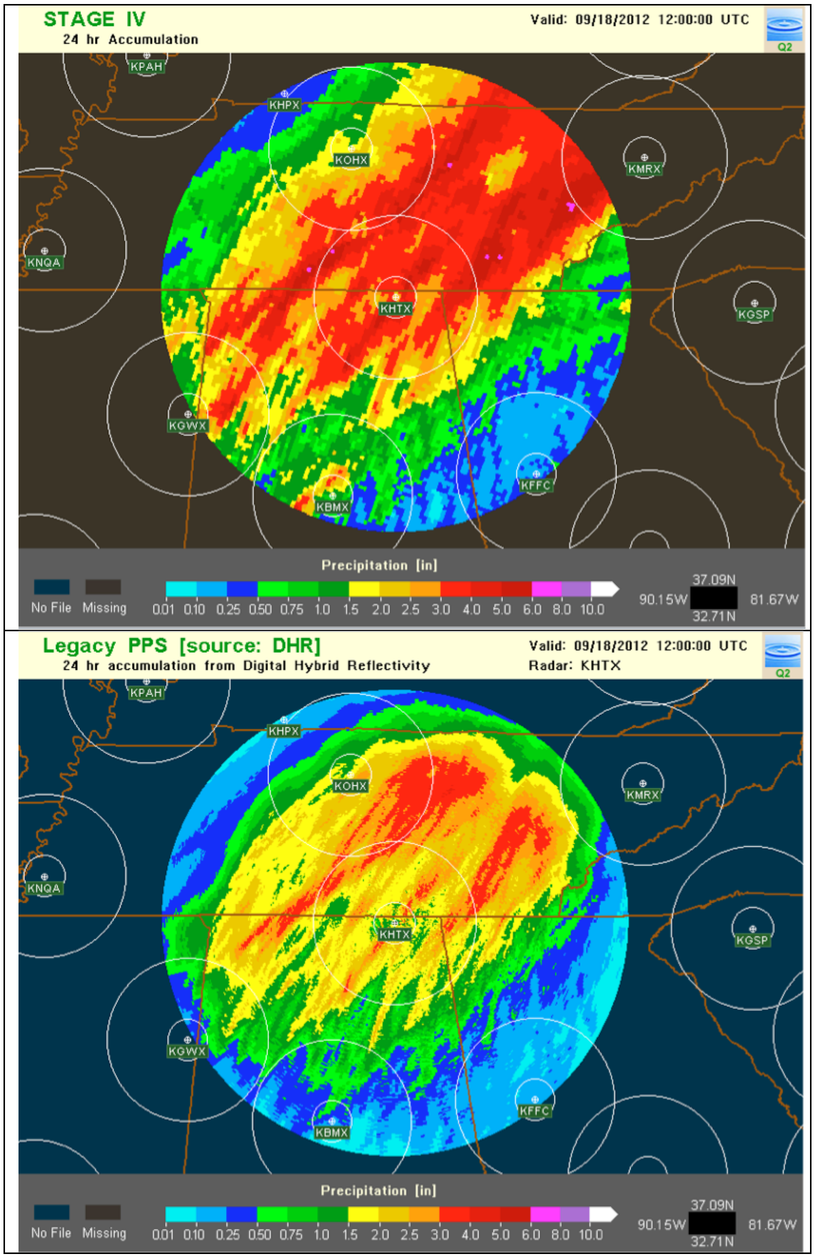


Figure 9. As in Fig. 4 except for points 1 (top) and 2 (bottom) shown in Fig. 8. The time period is 6 h ending 0300 UTC on 4/12/12.

5.4.4 Tennessee-Virginia flood event of 9/18/12

Several flood warnings were issued in Tennessee and surrounding areas on 9/18/12. This event provides an example of superior performance by DP QPE although, as with the 6/20 Duluth example, performance varied within the domain; here primarily due to ML effects. DP QPE had the largest improvement in bias out of all events with a Legacy bias = -1.26 and DP QPE bias = 0.01 (Table 6). Stage 4, DP QPE and Legacy accumulations for KHTX are shown in figure 10. Note the multiple ML ring artifacts in the TPD. DP QPE amounts are much larger than Legacy within ~120 km. Recalling that the statistics used in this study used data within 150 km of a radar, data for this event were adversely affected beyond ~ 120 km. This is shown by the scatterplots shown in figure 11 where there are fewer DP QPE underestimates < 120 km (lower right panel). Resulting DP performance < 120 km is slight over-estimation. Range effects for Legacy are less obvious.



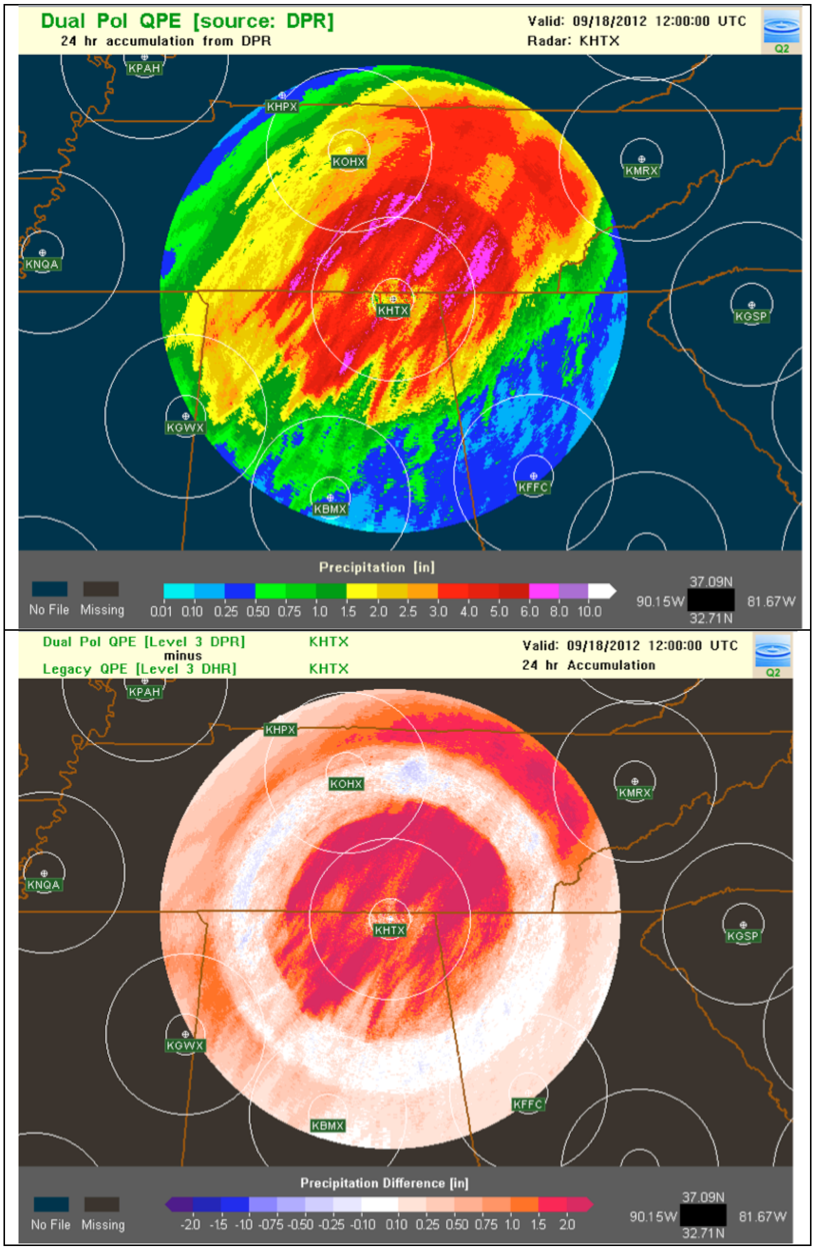


Figure 10. As in Fig. 2 except for KHTX on 9/18/12.

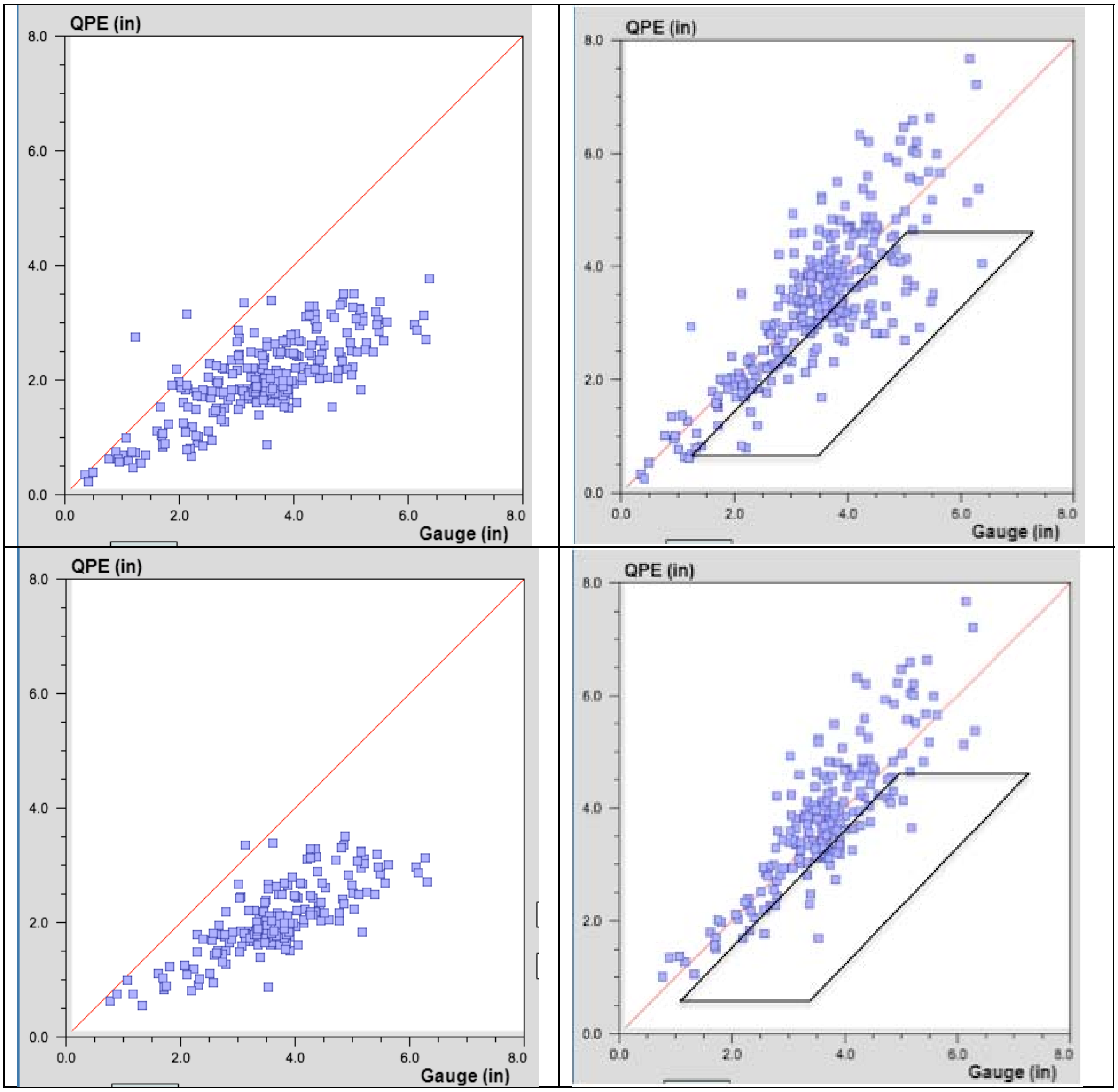


Figure 11. As in Fig. 6 except for KHTX on 9/18/12 ending 1200 UTC: Legacy vs. gauges < 150 km (upper left), DP QPE vs. gauges < 150 km (upper right), Legacy vs. gauges < 120 km (lower left) and DP QPE vs. gauges < 120 km (lower right). The polygon indicates DP QPE underestimation between 120 and 150 km.

6. Summary and discussion

A large number of cases (139) from the spring and summer of 2012 have been examined and comparatively assessed between the current operational DP QPE algorithm and the Legacy algorithm. Sufficient data have been accumulated for statistical significance testing with the following major findings:

1. DP QPE is statistically significantly better than Legacy. DP QPE has lower MAE (0.23 vs. 0.28), RMSE (0.58 vs. 0.62) and a larger CC (0.76 vs. 0.75) than Legacy for all gauge amounts > 0”. DP QPE MAEs are 19% lower than those for Legacy

for all gauge amounts; the improvement increases to 23% for gauges > 2”. Results for MAE and RMSE are statistically significant for all amount categories. Results for CC are statistically significant only for the gauge amount category > 1”.

2. Algorithm performance was assessed for different storm types ranging from pulse to mesoscale to tropical storms. DP QPE MAEs were markedly lower for all storm types except for pulse storms. DP QPE performance was best for the MC category of which there were 44 events, which was the only class with a statistically significant number. For the MC category, DP QPE has a MAE improvement of 32% over Legacy.

3. While 24 h totals in these events often consisted of relatively-short periods of heavy rain, overall they are more generally relevant to RFC operations. Further analysis at the sub-hourly time scale should be done in order to assess performance for the flash flood scale.

4. DP QPE allows for rain rates up to ~8 in h^{-1} which may be better suited for flash flood warnings than Legacy rates capped at ~4 in h^{-1}.

5. It is hypothesized that DP QPE over-estimation in some areas is due to using the “Tropical” relation in continental rain.

6. DP QPE over- and under-estimation may be due to Zdr bias errors that negatively affect DP QPE performance.

7. The DP melting layer algorithm produces artificial boundaries in the precipitation estimates.

8. All QPE algorithms are hindered by partial beam blockage.

7. DP QPE rain rate relation and specific attenuation R(A) sensitivity tests

The four R equation sets for each test are shown below and results can be found on the “case study” QVS http://csnmq.ou.edu. The first set is the current operational “Tropical” set. The second expands the use of Kdp to heavy rain (HR). The third is the “Continental” set that was initially prototyped in Oklahoma but replaced by the “Tropical” set to maximize performance for warm rain microphysics. The fourth set eliminates the use of Zdr and instead uses the standard Z-R relation used in the Legacy PPS algorithm for rain (RA) and uses Kdp for HR and hail (HA).

para1: Tropical R(Z,Zdr) for RA and HR; R(Kdp) for HA (current algorithm)

para2: Tropical R(Z,Zdr) for RA; R(Kdp) for HR and HA

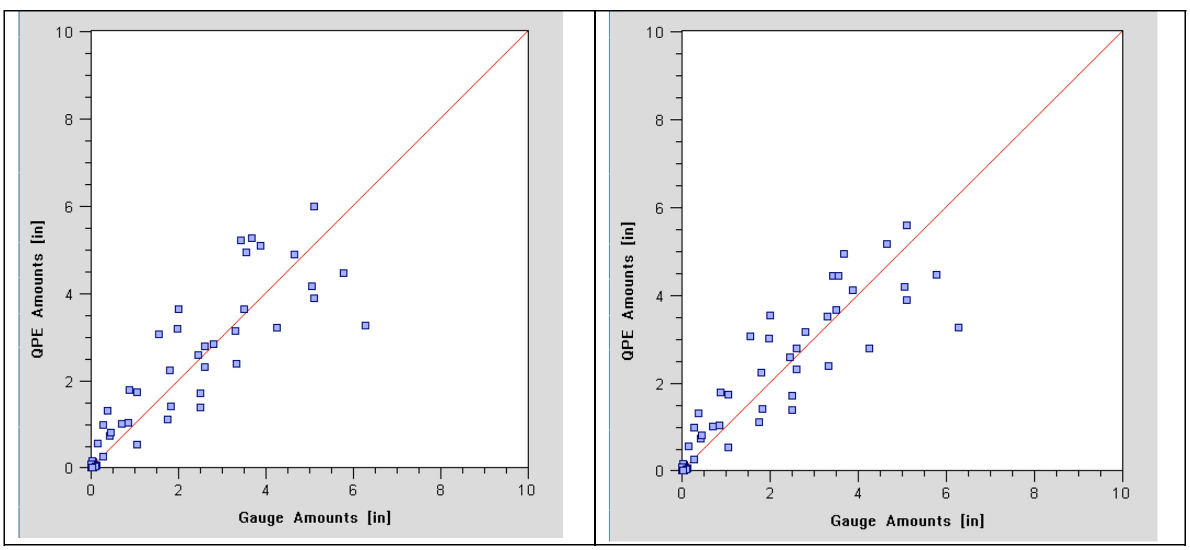
para3: Continental R(Z,Zdr) for RA; R(Kdp) for HR and HA

para4: R(Z) for RA; R(Kdp) for HR and HA

Testing for further improvement in DP QPE was performed using an algorithm based on specific attenuation R(A). Relative insensitivity of the R(A) relation to DSD variability is well known and pointed out by Atlas and Ulbrich (1977) and Matrosov (2005). R(A) is also expected to be less immune to partial beam blockage.

7.1 Duluth, MN (KDLH) case of 6/20/12

Recall that this event was discussed earlier and had DP QPE overestimation in only part of the domain. Algorithm parameter sets para2 and 3 show modest improvements with RMSEs of 0.75 and 0.78, respectively (Fig. 12) compared to an RMSE = 0.81for the operational algorithm. Set 4 shows the most improvement with an RMSE = 0.71. The reduction in error was mostly seen in reduction in overestimation for larger gauge amounts. Also, the attenuation algorithm R(A) improved performance (Figs. 13 and 14) as compared to set para4.



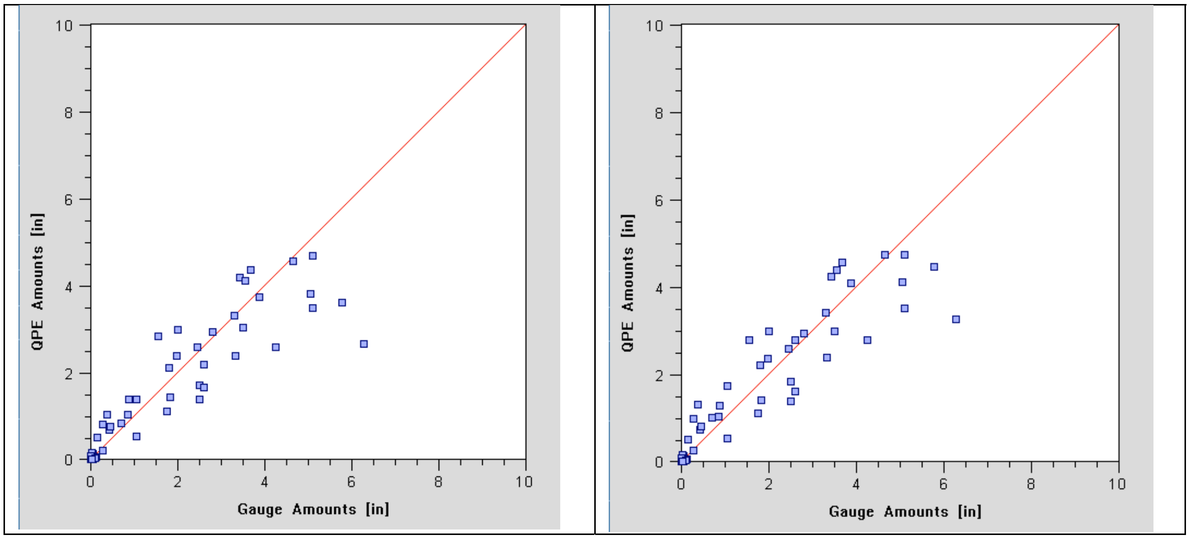


Figure 12. Scatterplots of DP QPE versus gauges for KDLH on 6/20/12 using rain rate relations: para1 (upper left; RMSE = 0.81); para2 (upper right; RMSE = 0.75); para3 (lower left; RMSE = 0.78); and para4 (lower right; RMSE = 0.71).

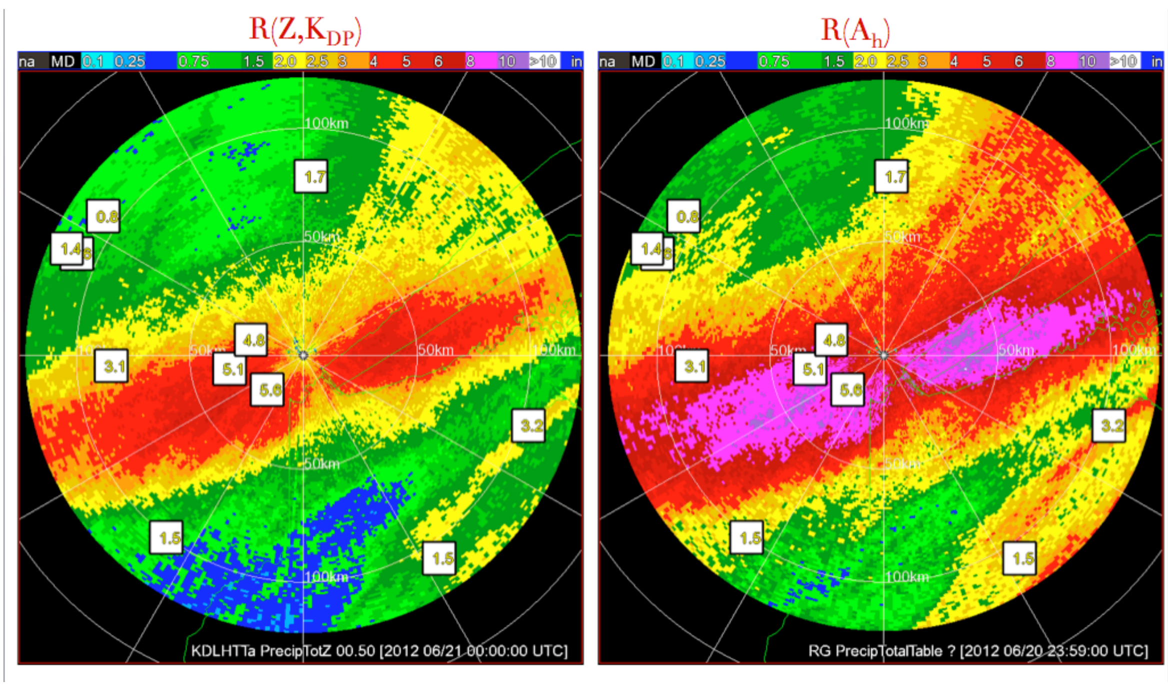


Fig. 13. Images of 24-hour rain total for the Duluth flash flood event obtained from the R(Z,K_{DP}) (left) and R(A) algorithms (right).

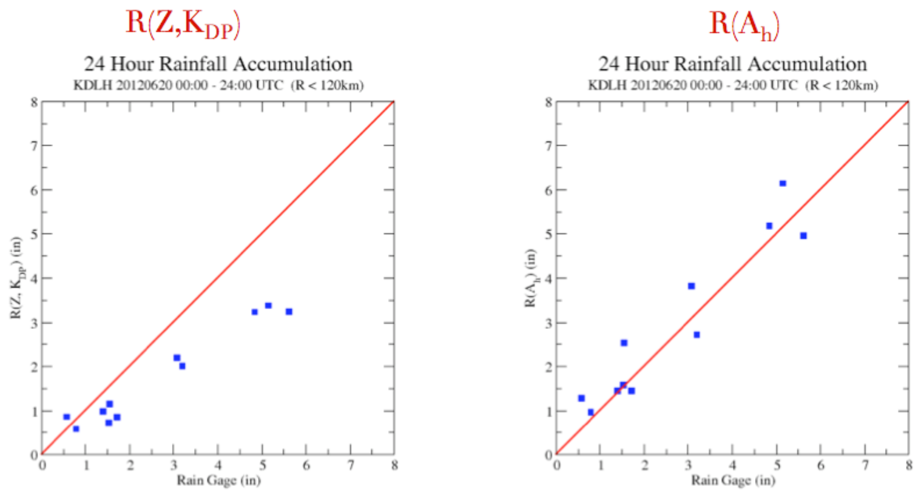
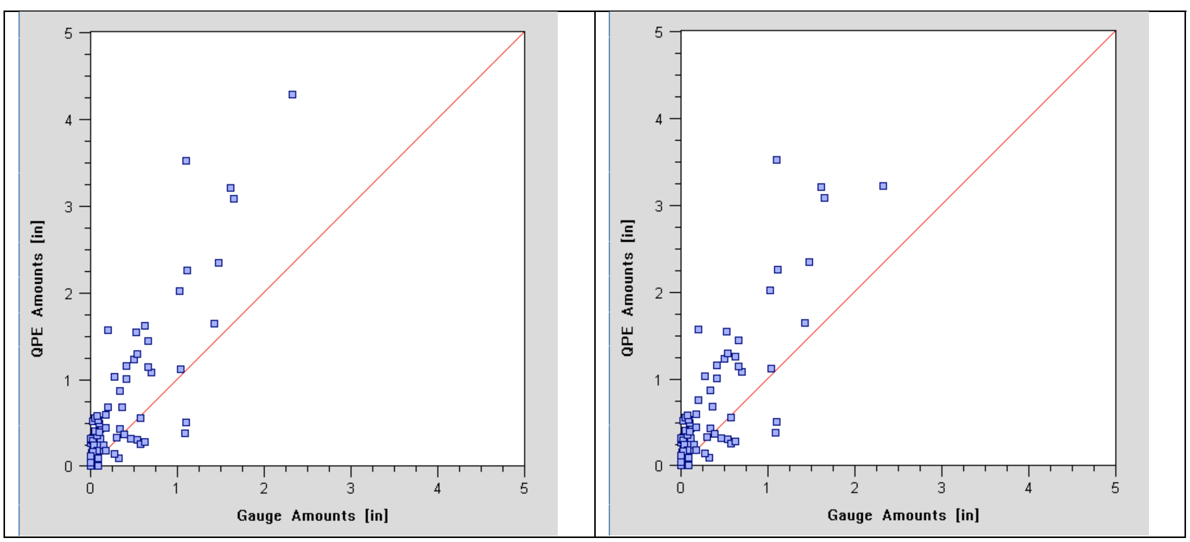


Fig. 14. Scatterplots of 24-hour gauge rain total versus its estimate for KDLH on 6/20/12 for the R(Z,K_{DP}) algorithm (left) and R(A) algorithm (right).

7.2 State College, PA (KCCX) case of 5/27/12

As shown in figure 15, DP QPE significantly over-estimated gauge amounts by nearly 200% (RMSE = 0.33). Overestimation is somewhat reduced using parameter sets 2 and 4 and nearly eliminated with the “Continental” set with an RMSE = 0.18.



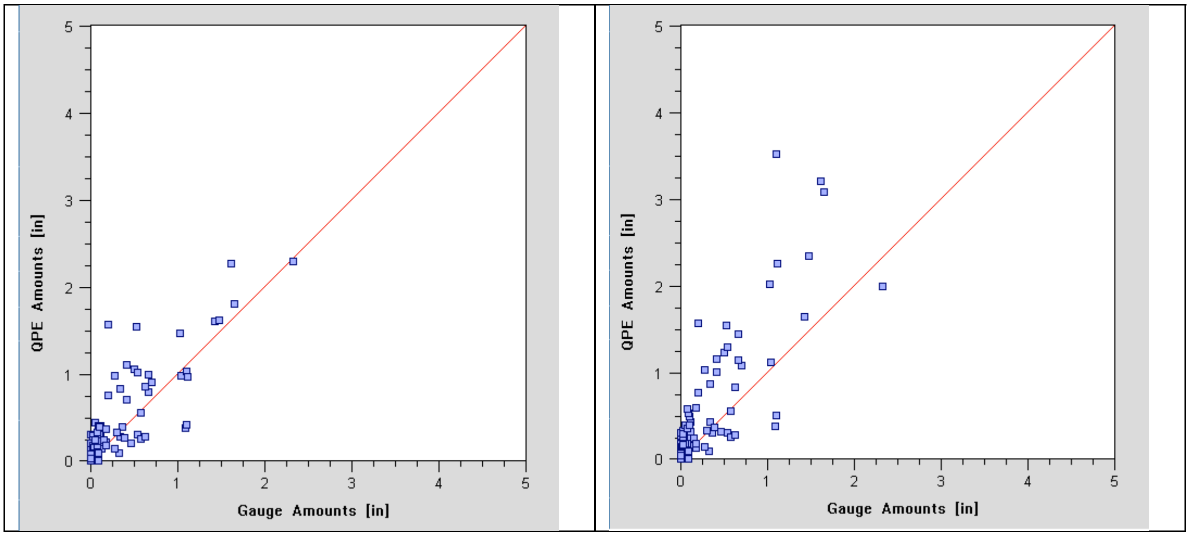
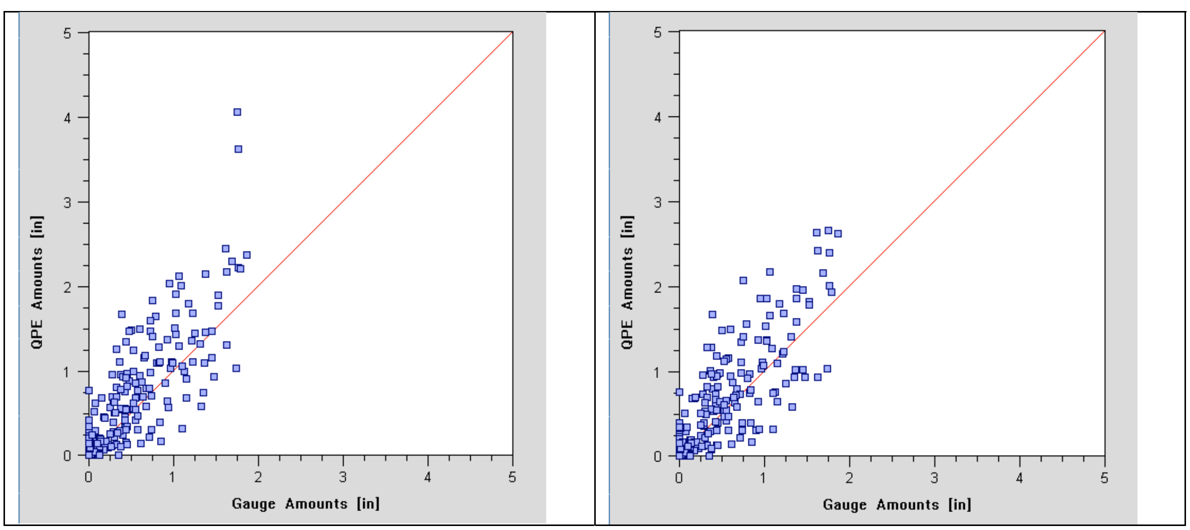


Figure 15. As in figure 12 except for KCCX on 5/27/12: para1 (upper left; RMSE = 0.33); para2 (upper right; RMSE = 0.31); para3 (lower left; RMSE = 0.18); and para4 (lower right; RMSE = 0.30).

7.3 Kansas City, MO (KEAX) case of 6/12/12

This was also a modest rain event that further illustrates improvement using different parameters. The "Continental" set has the lowest RMSE (0.27 vs. 0.34 for "Tropical") and shows large reductions in overestimates at a few gauge locations (Fig. 16).



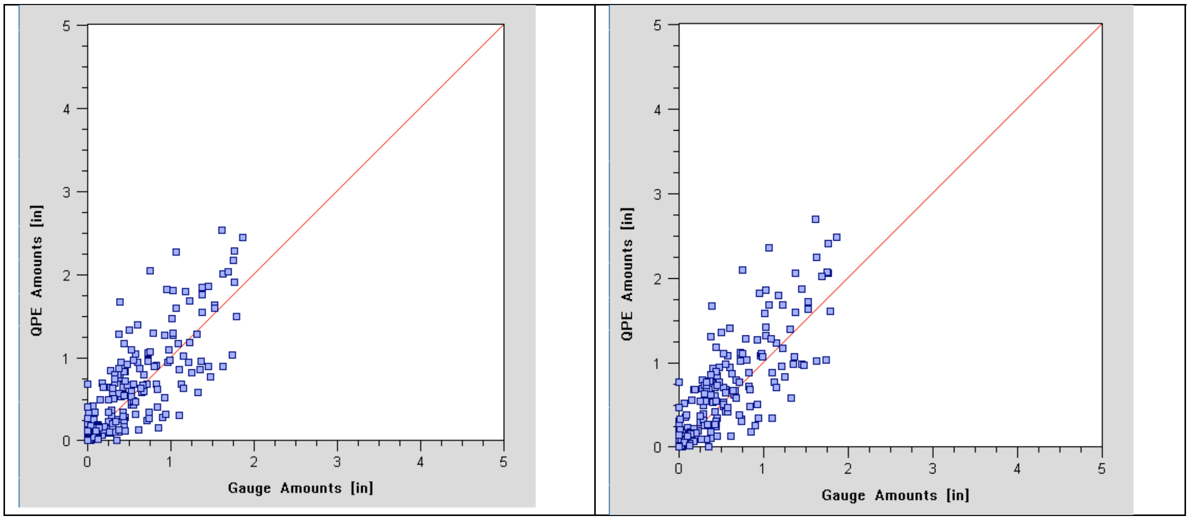


Figure 16. As in figure 12 except for KEAX on 6/12/12 for: para1 (upper left; RMSE = 0.34); para2 (upper right; RMSE = 0.30); para3 (lower left; RMSE = 0.27); and para4 (lower right; RMSE = 0.28).

7.4 Vance Air Force Base, OK (KVNX) case of 5/20/11

R(A) precipitation estimates were compared to R(Z,Kdp) estimates for the Vance Air Force Base, OK (KVNX) case of 5/20/11. Beam blockage southwest of KVNX is a persistent problem that severely degrades QPE in that sector (Fig. 17). The R(A) algorithm greatly improved performance in the blockage region. Comparisons between R(A) and DP QPE are not available for this analysis.

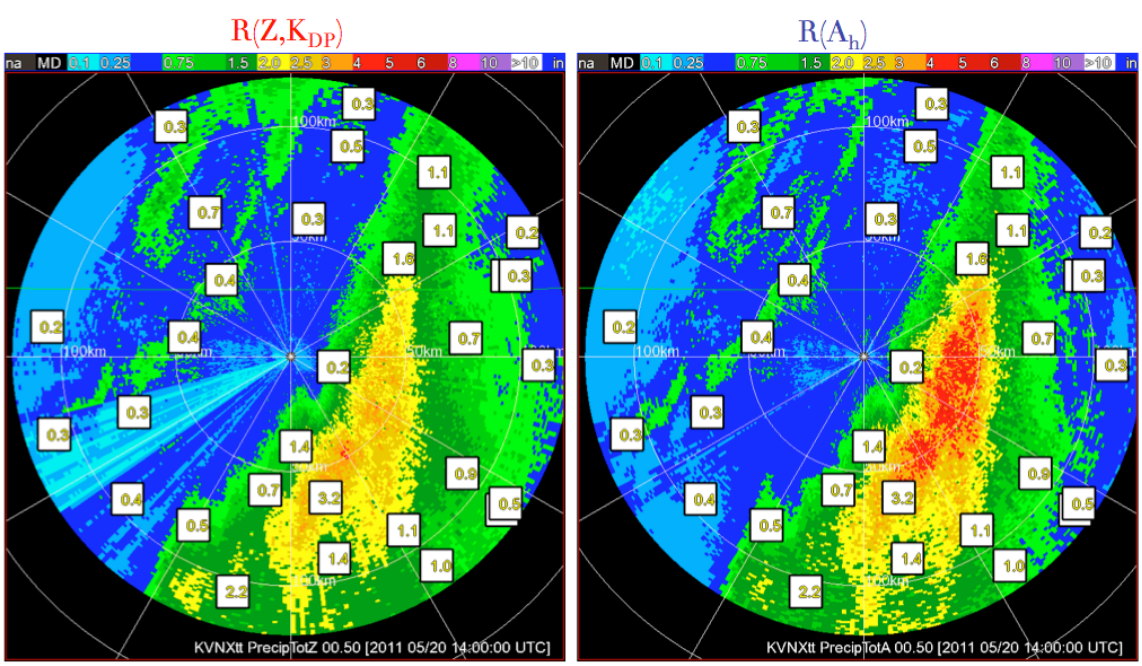


Fig. 17. Images of 6 h rain totals on 5/20/12 for the KVNX WSR-88D radar retrievd by R(Z,Kdp) (left) and R(A) (right).

8. Recommendations

As the result of limited sensitivity tests, follow-up efforts are recommended in order to fully achieve the potential for DP:

1. Continue DP QPE rainfall relationship sensitivity studies.
2. Continue to evaluate rainfall relations using the attenuation algorithm R(A).
3. Investigate methods for automatic switching between DP rain rate relations.
4. Continue to monitor and correct for Zdr bias errors.
5. Evaluate algorithm performance on an hourly and sub-hourly basis.
6. Evaluate algorithm performance across all regions and seasons.

Acknowledgments

This report would not have been possible without the NSSL QVS. The QVS was adapted for DP with funding from the ROC Applications Branch by Dr. Brian Kaney and Carry Langston. Dr. Kimberly Elmore performed statistical significance testing. Dr. Alexander Ryzhkov and John Krause provided insight into DP performance and methods for improvements to DP QPE with support from Dr. Lin Tang and Dr. Yandong Wang. Mr. David Zittel assisted with several graphics. Mr. Robert Lee provided Zdr bias error data.

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Table 1. List of radar events, storm type and number of gauges > 0” and > 2” and their averages. Types with the letter “L” at the end indicate at least one SPC hail report under the radar umbrella.

Date	Radar	Type	No. gauge	Av. gauge	No. gauge>2”	Av. Gauge>2”
3/24/12	KBMX	FR	137	0.35		
4/10/12	KAMA	HAL	55	0.11		
4/10/12	KVNX	HAL	187	0.05		
4/12/12	KAMA	HAL	66	0.16		
4/13/12	KBBX	OR	157	0.94	16	2.6
4/14/12	KBBX	OR	79	0.47		
4/14/12	KEAX	MC	69	0.69	5	2.3
4/14/12	KEYX	OR	42	0.70		
4/14/12	KLSX	MC	162	1.12	25	2.56
4/14/12	KSGF	MC	116	0.69	9	2.32
4/14/12	KVBX	OR	59	0.89	3	2.66
4/14/12	KVNX	MC	157	0.77	21	2.74
4/15/12	KDDC	SCL	83	0.70		
4/15/12	KICT	SCL	182	0.67	11	2.67
4/15/12	KTWX	MC	191	0.45	7	2.9
4/15/12	KVNX	SCL	155	0.54	4	2.25
4/18/12	KFFC	WF	265	0.64		
4/18/12	KMRX	WF	267	1.05	50	2.61
4/21/12	KAMX	PS	42	1.46	10	3.31
4/21/12	KBYX	PS	10	1.31		
4/21/12	KMLB	PS	72	0.84	3	2.15
4/21/12	KTBW	PS	160	0.44		
4/23/12	KAKQ	WF/CS	34	1.11		
4/23/12	KBOX	WF/CS	93	2.11	56	2.6
4/23/12	KDIX	WF/CS	146	2.05	90	2.33
4/23/12	KDOX	WF/CS	79	1.84	31	2.26
4/23/12	KOKX	WF/CS	88	2.26	62	2.53
4/30/12	KLSX	MC	180	0.70	22	2.53
4/30/12	KSGF	MC	172	0.86	30	2.88
5/1/12	KICT	SCL	203	0.50	8	2.56
5/1/12	KSGF	MC	168	0.79	6	2.69
5/1/12	KVNX	SCL	145	0.54	8	2.73
5/4/12	KGRR	MCH	45	0.59		
5/4/12	KLOT	MCH	267	0.48	8	2.24
5/6/12	KMHX	PSH	39	0.96	3	3.19
5/7/12	KEAX	PSH	179	0.79	14	2.83
5/7/12	KLOT	MCH	254	1.26	39	2.74
5/8/12	KCLE	WFH	109	0.96	8	2.49
5/8/12	KPBZ	WFH	168	0.75	10	2.53
5/25/12	KARX*	FRH	134	0.53		
5/25/12	KDLH	MC	22	0.99	4	2.4
5/27/12	KBGM	FRH	121	0.03		
5/27/12	KCCX	FRH	143	0.18		
5/27/12	KDLH	MC	37	0.83	3	2.28
5/27/12	KGRB	FRH	34	0.49		

5/28/12	KDLH	FRH	41	0.71		
5/28/12	KJAX*	TS Beryl	169	1.40	41	2.72
5/29/12	KTBW	TS Beryl	212	0.59	14	3.14
5/30/12	KCAE	TS Beryl	174	1.17	33	3.19
5/31/12	KMHX	TS Beryl	77	2.25	48	2.8
6/2/12	KAKQ	FRH	90	1.21	17	2.8
6/2/12	KCCX	FR	142	0.97	5	2.23
6/2/12	KDIX	FR	274	1.02	20	2.27
6/2/12	KDOX	FR	179	1.06	25	2.62
6/2/12	KLWX	FR	160	1.38	32	2.59
6/3/12	KDDC	MCH	113	0.20		
6/3/12	KICT	MCH	206	0.25		
6/3/12	KVNX	MCH	165	0.39		
6/4/12	KHTX	MCH	401	0.50	12	2.39
6/4/12	KNQA	MCH	95	0.98	13	2.78
6/8/12	KEWX	PS	267	0.36	5	2.46
6/11/12	KCAE	SL	221	0.69	20	2.81
6/11/12	KEAX	MC	160	0.45		
6/11/12	KFFC	SL	282	0.89	10	2.35
6/11/12	KJGX	SL	159	1.15	15	2.52
6/11/12	KTWX	MC	124	0.46		
6/12/12	KBMX*	MC	189	0.36	3	2.11
6/12/12	KCAE	MC	161	0.91	12	2.44
6/12/12	KJGX	MC	117	0.68		
6/12/12	KSJT	MC	199	0.06		
6/15/12	KDDC	MCH	113	0.61		
6/15/12	KICT	MCH	221	1.29	34	2.32
6/15/12	KTWX	MC	237	0.84	21	2.81
6/16/12	KDDC	MCH	114	0.50		
6/16/12	KICT	MCH	206	0.18		
6/17/12	KLOT	MCH	269	0.93	23	3.18
6/20/12	KDLH	FRH	42	2.84	24	4.56
6/24/12	KTBW*	TS Deb.	186	5.19	142	6.45
6/25/12	KMLB	TS Deb.	92	2.16	46	3.65
6/26/12	KJAX	TS Deb.	104	2.44	47	4.22
6/30/12	KDVN	MCH	138	0.54	8	2.77
7/3/12	KGRB	MCH	30	0.71		
7/3/12	KMQT	MCH	20	0.79		
7/15/12	KEMX	PSH	24	0.13		
7/15/12	KIWA	PS	469	0.45	18	2.86
7/16/12	KEMX	PS	110	0.64	7	2.31
7/16/12	KIWA	PS	97	0.31		
7/18/12	KJGX	PSH	160	0.24		
7/19/12	KARX	MCH	77	0.38		
7/19/12	KHTX	PS	346	0.34	3	2.51
7/19/12	KLOT	FR	264	1.13	51	2.29
7/19/12	KMKX	MC	158	1.23	29	2.27
7/19/12	KOHX	MCH	251	0.34		
7/19/12	KPBZ	PSH	142	0.39	4	2.87
7/20/12	KMRX	MC	180	0.59	5	2.38

7/20/12	KOHX	MC	279	1.69	89	3.02
7/21/12	KIWA	PS	442	0.05		
7/22/12	KIWA	PS	469	0.15		
7/24/12	KBGM	PS	179	0.42	7	2.5
7/24/12	KMHX	PS	69	0.67		
7/25/12	KEMX	PS	93	0.19		
7/25/12	KIWA	PS	433	0.07		
7/26/12	KAPX	FRH	37	0.95	4	3.66
7/26/12	KARX	FRH	76	0.30		
7/26/12	KGRB	FRH	42	0.72	4	2.74
7/26/12	KGRR	FRH	94	0.47		
7/26/12	KMKX	FR	182	0.36	3	2.71
7/27/12	KCLE	FRH	123	0.42		
7/27/12	KPBZ	FRH	171	0.75	9	2.49
7/29/12	KEMX	PS	105	0.32		
7/29/12	KIWA	PS	471	0.15		
7/30/12	KIWA	PS	479	0.32	10	2.48
7/31/12	KBMX	PSH	103	1.29	25	3.84
8/1/12	KBMX	PS	86	0.83	11	2.88
8/3/12	KLSX	MC	161	0.18		
8/4/12	KDLH	MC	42	0.73		
8/6/12	KHTX	FR	419	0.32		
8/6/12	KMRX	MC	271	0.49	9	2.72
8/6/12	KOHX	MC	305	0.61	5	2.84
8/17/12	KLOT	FR	311	0.46	3	2.21
8/17/12	KLSX	FRH	167	0.48	9	2.7
8/17/12	KSGF	FRH	196	0.45	7	2.57
8/19/12	KEWX	PS	489	1.16	100	2.94
8/27/12	KAMX	TS Isaac	53	3.67	38	4.85
8/27/12	KMLB	TS Isaac	100	1.85	40	3.45
8/27/12	KTBW	TS Isaac	173	1.67	51	2.85
8/31/12	KLZK	TS Isaac	161	1.90	75	3.68
9/1/12	KEAX	TS Isaac	143	1.84	48	3.89
9/1/12	KLSX	TS Isaac	166	1.97	62	2.97
9/1/12	KLZK	TS Isaac	145	0.75	13	3.68
9/1/12*	KNQA	TS Isaac	102	0.98	20	3.28
9/2/12	KCLE	TS Isaac	110	0.63	9	2.5
9/2/12	KLOT	TS Isaac	282	0.53	15	2.68
9/14/12	KEWX	PS	486	1.95	209	3.11
9/18/12	KHTX	FR	372	3.33	314	3.71
9/18/12	KMRX	FR	270	2.58	145	3.59
9/18/12	KOHX	FR	305	2.69	200	3.6
9/19/12	KBGM	FR	183	1.38	33	2.81
9/19/12	KENX	FR	146	1.72	52	2.6

*Multi-day events: KARX 5/25,26,27; KBMX 6/11,12; KJAX 5/28,29,30; KNQA 9/1,2; KTBW 6/24,25

Table 2. Description of storm types and number of radar-events per type.

Type	Number	Description
Cool season (CS)*	5	Stratiform precipitation with low ML; all NE radars
Front (FR)	29	Storms along a front; no trailing stratiform precip
Weak front (WF)	9	Weak convection along a front
Hail (HA)	3	Hail in SPC data base under radar umbrella
Mesoscale conv. (MC)	44	MCC or squall line/front with trailing stratiform (MCS)
Orographic (OR)	4	Complex terrain in S CA
Pulse storms (PS)	27	Thermally forced convection
Supercells (SC)	8	TX, OK, and KS
Squall line (SL)	4	Squall line with no trailing stratiform rain
Tropical storm (TS)	17	Beryl, Debby and Isaac

*These events had ML heights below the slant range of 150 km.

Table 3. List of statistics for all gauges > 0.0” and ranges less than 150 km. Note that MAE is less sensitive to outliers than RMSE. Significance test results: 95% confidence is signified by a p-value of 0.05 or less and that is used as a test for "statistically significant" results.

Mean Absolute Error

LEGACY	DPQPE
0.28315	0.23099

Root Mean Square Error

LEGACY	DPQPE
0.62562	0.58431

Correlation Coefficient

LEGACY	DPQPE
0.7518	0.76216

Significance test results:

MAE:

Test	p-value	Significant?
DP < LEGACY	0.0036	Y

RMSE:

Test	p-value	Significant?
DP < LEGACY	0.0105	Y

CC:

Test	p-value	Significant?
DP > LEGACY	0.1415	N

Table 4. List of events, storm type and algorithm with lowest mean bias, RMSE and highest CC. D=DP QPE; L=Legacy. Blank spaces indicate a tie for the best algorithm.

Radar	Date	Type	Bias	RMSE	CC
KAKQ	4/23/12	WF	L	L	L
KAKQ	6/2/12	FR	D	L	D
KAMA	4/10/12	HA	L	L	D
KAMA	4/12/12	HA	D	D	
KAMX	4/21/12	PS	L	L	D
KAMX	8/27/12	TS	D	D	D
KAPX	7/26/12	FR	L	L	D
KARX	5/25/12	FR	D	D	D
KARX	7/19/12	MC	D	D	L
KARX	7/26/12	FR	D	D	D
KBBX	4/13/12	OR	D	D	L
KBBX	4/14/12	OR	L	D	L
KBGM	5/27/12	FR	D	D	D
KBGM	7/24/12	PS	D	D	D
KBGM	9/19/12	FR	D		D
KBMX	3/24/12	FR	D		L
KBMX	6/12/12	MC	D	D	L
KBMX	7/31/12	PS	D	L	D
KBMX	8/1/12	PS	D	D	D
KBOX	4/23/12	WF	L	D	L
KBYX	4/21/12	PS	D	D	L
KCAE	5/30/12	TS	D	D	L
KCAE	6/11/12	SL	D	D	L
KCAE	6/12/12	MC	L	L	
KCCX	5/27/12	FR	L	L	L
KCCX	6/2/12	FR	L	L	D
KCLE	5/8/12	WF	L	D	L
KCLE	7/27/12	FR	L	L	L
KCLE	9/2/12	TS	D	D	D
KDDC	4/15/12	SC	D	D	D
KDDC	6/3/12	MC	D	D	D
KDDC	6/15/12	MC	D	D	D
KDDC	6/16/12	MC	D	D	L
KDIX	4/23/12	WF	D	D	L
KDIX	6/2/12	FR	D	L	D
KDLH	5/25/12	MC	D		L
KDLH	5/27/12	MC	L	L	
KDLH	5/28/12	FR	L	L	D
KDLH	6/20/12	FR	L	L	L

KDLH	8/4/12	MC	L	L	D
KDOX	4/23/12	WF	L	L	
KDOX	6/2/12	FR	D	D	L
KDVN	6/30/12	MC	L	L	
KEAX	4/14/12	MC	L	L	
KEAX	5/7/12	PS	L	L	D
KEAX	6/11/12	MC	D	D	L
KEAX	9/1/12	TS	D	L	D
KEMX	7/15/12	PS	D	D	L
KEMX	7/16/12	PS	D	D	L
KEMX	7/25/12	PS	D	D	
KEMX	7/29/12	PS	L	L	D
KENX	9/19/12	FR	L	L	L
KEWX	6/8/12	PS	L	L	D
KEWX	8/19/12	PS	D	D	D
KEWX	9/14/12	PS	D		
KEYX	4/14/12	OR	D	D	L
KFFC	4/18/12	WF	D	D	
KFFC	6/11/12	SL	D	D	D
KGRB	5/27/12	FR	L	L	L
KGRB	7/3/12	MC	D	D	L
KGRB	7/26/12	FR	D	D	
KGRR	5/4/12	MC	L	L	L
KGRR	7/26/12	FR	L	L	L
KHTX	6/4/12	MC	L	L	D
KHTX	7/19/12	PS	D	D	D
KHTX	8/6/12	FR	D	D	
KHTX	9/18/12	FR	D	D	D
KICT	4/15/12	SC	L	D	L
KICT	5/1/12	SC	D	L	D
KICT	6/3/12	MC	D	D	L
KICT	6/15/12	MC	D	L	D
KICT	6/16/12	MC	D	D	L
KIWA	7/15/12	PS	D	D	L
KIWA	7/16/12	PS	D	D	L
KIWA	7/21/12	PS	D	D	L
KIWA	7/22/12	PS	D	D	L
KIWA	7/25/12	PS	L	L	L
KIWA	7/29/12	PS	L	L	D
KIWA	7/30/12	PS	D		L
KJAX	5/28/12	TS	L	L	D
KJAX	6/26/12	TS	L	L	L

KJGX	6/11/12	SL	D	D	L
KJGX	6/12/12	MC	D	D	D
KJGX	7/18/12	PS	D	D	L
KLOT	5/4/12	MC	L	D	L
KLOT	5/7/12	MC	D	D	L
KLOT	6/17/12	MC	D	D	L
KLOT	7/19/12	FR	D	D	D
KLOT	8/17/12	FR	D	D	L
KLOT	9/2/12	TS		L	L
KLSX	4/14/12	MC	D	D	L
KLSX	4/30/12	MC	D	S	D
KLSX	8/3/12	MC	D	D	D
KLSX	8/17/12	FR	D	D	L
KLSX	9/1/12	TS	L		L
KLWX	6/2/12	FR	D	D	D
KLZK	8/31/12	TS	D	D	L
KLZK	9/1/12	TS	L	L	D
KMHX	5/6/12	PS	L	L	D
KMHX	5/31/12	TS	L	L	L
KMHX	7/24/12	PS	D	D	L
KMKX	7/19/12	MC	D	L	D
KMKX	7/26/12	FR	L	L	L
KMLB	4/21/12	PS	L	L	D
KMLB	6/25/12	TS	D	D	L
KMLB	8/27/12	TS	L	L	L
KMQT	7/3/12	MC	D	L	D
KMRX	4/18/12	WF	L	L	L
KMRX	7/20/12	MC	D	D	L
KMRX	8/6/12	MC	D	D	L
KMRX	9/18/12	FR	L	L	D
KNQA	6/4/12	MC	D	D	
KNQA	9/1/12	TS	L	L	D
KOHX	7/19/12	MC	L	L	D
KOHX	7/20/12	MC	D	D	L
KOHX	8/6/12	MC	L		L
KOHX	9/18/12	FR	D	D	L
KOKX	4/23/12	WF	D	D	D
KPBZ	5/8/12	WF	D	D	L
KPBZ	7/19/12	PS	D	D	L
KPBZ	7/27/12	FR		D	D
KSGF	4/14/12	MC	L	L	L
KSGF	4/30/12	MC	L	L	L

KSGF	5/1/12	MC	L	D	L
KSGF	8/17/12	FR	L	D	L
KSJT	6/12/12	MC	D	D	D
KTBW	4/21/12	PS	D	D	D
KTBW	5/29/12	TS	L	L	
KTBW	6/24/12	TS	D		D
KTBW	8/27/12	TS	D	D	D
KTWX	4/15/12	MC	L	L	D
KTWX	6/11/12	MC	D	D	L
KTWX	6/15/12	MC	L	L	D
KVBX	4/14/12	OR	D	D	D
KVNX	4/10/12	HA		D	D
KVNX	4/14/12	MC	D	D	D
KVNX	4/15/12	SC	D	D	L
KVNX	5/1/12	SC	L	L	D
KVNX	6/3/12	MC	D	D	L

*Multi-day events: KARX 5/25,26,27; KBMX 6/11,12; KJAX 5/28,29,30; KNQA 9/1,2; KTBW 6/24,25

Table 5. Summary of Table 4 showing the number of times an algorithm had best performance for bias, RMSE and CC.

	Bias	RMSE	CC
DP QPE	84	78	58
Legacy	52	53	68

Table 6. List of events, ave. gauge value, DP QPE mean bias, Legacy mean bias, and differences between their absolute values

Radar	Date	Ave.Gauge	Leg. bias	DP bias	Diff. ABS
KJAX	6/26/12	2.44	-0.58	-1.32	0.74
KJAX	5/28/12	1.4	-0.02	-0.59	0.56
KTBW	5/29/12	0.59	-0.01	0.43	0.42
KEWX	9/14/12	1.95	-0.16	0.50	0.34
KDLH	6/20/12	2.84	-0.26	0.57	0.31
KCCX	6/2/12	0.97	-0.13	0.40	0.27
KDOX	6/2/12	1.06	-0.06	-0.33	0.27
KTBW	4/21/12	0.44	0.03	0.26	0.23
KOHX	9/18/12	2.69	-1.34	-1.56	0.22
KEWX	8/19/12	1.16	-0.06	0.27	0.21
KMLB	8/27/12	1.85	-0.31	-0.52	0.21
KOHX	7/20/12	1.69	-0.22	-0.41	0.19
KLZK	9/1/12	0.75	-0.01	-0.18	0.17
KAMX	4/21/12	1.46	-0.06	0.22	0.16
KMKX	7/19/12	1.23	-0.03	0.19	0.15
KICT	6/15/12	1.29	0.18	0.33	0.15
KHTX	6/4/12	0.5	0.12	0.27	0.15
KCLE	9/2/12	0.63	0.09	0.23	0.14
KAPX	7/26/12	0.95	0.23	0.38	0.14
KLOT	7/19/12	1.13	-0.41	-0.54	0.13
KTBW	6/24/12	5.19	-2.04	2.16	0.12
KPBZ	5/8/12	0.75	0.06	-0.18	0.12
KMRX	7/20/12	0.59	0.01	0.13	0.12
KDLH	8/4/12	0.73	0.04	0.16	0.12
KVNX	5/1/12	0.54	0.21	0.32	0.11
KEAX	6/11/12	0.45	0.10	0.21	0.11
KDLH	5/28/12	0.71	0.07	0.17	0.10
KJGX	7/18/12	0.24	0.14	0.22	0.08
KHTX	7/19/12	0.34	0.09	0.16	0.08
KEAX	4/14/12	0.69	0.29	0.37	0.07
KJGX	6/12/12	0.68	-0.12	0.19	0.07
KGRB	7/26/12	0.72	0.06	0.13	0.07
KEAX	5/7/12	0.79	0.37	0.44	0.07
KMHX	7/24/12	0.67	0.06	0.12	0.07
KTWX	6/15/12	0.84	0.12	0.18	0.06
KHTX	8/6/12	0.32	0.04	0.10	0.06
KMQT	7/3/12	0.79	-0.02	-0.08	0.06
KBBX	4/14/12	0.47	-0.13	-0.19	0.05
KNQA	6/4/12	0.98	0.27	0.32	0.05

KVNX	4/14/12	0.77	0.27	0.31	0.04
KEWX	6/8/12	0.36	0.17	0.21	0.04
KMKX	7/26/12	0.36	0.07	0.10	0.04
KAMA	4/10/12	0.11	0.14	0.17	0.03
KCLE	7/27/12	0.42	0.07	0.08	0.01
KBYX	4/21/12	1.31	0.55	0.56	0.01
KTBW	8/27/12	1.67	-0.28	0.28	0.01
KSJT	6/12/12	0.06	0.14	0.15	0.00
KLSX	8/3/12	0.18	0.09	0.09	0.00
KBGM	9/19/12	1.38	-0.57	-0.57	0.00
KEMX	7/15/12	0.13	0.07	0.06	-0.01
KPBZ	7/19/12	0.39	0.05	-0.04	-0.01
KBBX	4/13/12	0.94	-0.18	-0.17	-0.01
KMRX	8/6/12	0.49	-0.04	0.03	-0.01
KLZK	8/31/12	1.9	-0.91	-0.90	-0.01
KICT	6/16/12	0.18	0.05	0.03	-0.02
KIWA	7/16/12	0.31	0.07	0.06	-0.02
KARX	7/19/12	0.38	0.10	0.08	-0.02
KBGM	5/27/12	0.03	0.04	0.02	-0.02
KEMX	7/25/12	0.19	0.10	0.07	-0.02
KDLH	5/25/12	0.99	-0.05	-0.02	-0.03
KMLB	4/21/12	0.84	-0.03	0.00	-0.03
KAMA	4/12/12	0.16	0.09	0.06	-0.03
KVNX	4/10/12	0.05	0.09	0.06	-0.03
KFFC	4/18/12	0.64	0.17	0.14	-0.03
KEMX	7/29/12	0.32	0.06	0.02	-0.04
KBMX	6/12/12	0.36	-0.05	0.02	-0.04
KIWA	7/15/12	0.45	0.04	0.00	-0.04
KAKQ	6/2/12	1.21	-0.14	-0.09	-0.05
KDLH	5/27/12	0.83	0.33	0.28	-0.05
KIWA	7/29/12	0.15	0.08	-0.02	-0.06
KMRX	4/18/12	1.05	-0.25	-0.18	-0.06
KARX	7/26/12	0.3	0.23	0.16	-0.06
KSGF	4/14/12	0.69	0.31	0.25	-0.07
KIWA	7/21/12	0.05	0.10	0.04	-0.07
KBMX	3/24/12	0.35	-0.10	-0.03	-0.07
KIWA	7/30/12	0.32	0.14	0.07	-0.07
KVNX	4/15/12	0.54	0.42	0.35	-0.07
KLWX	6/2/12	1.38	-0.55	-0.48	-0.07
KICT	6/3/12	0.25	0.16	0.09	-0.07
KEMX	7/16/12	0.64	0.21	0.14	-0.08
KLOT	6/17/12	0.93	0.10	-0.01	-0.08
KIWA	7/25/12	0.07	0.09	0.00	-0.09

KARX	5/25/12	0.53	0.16	0.07	-0.10
KOHX	8/6/12	0.61	0.11	-0.01	-0.10
KIWA	7/22/12	0.15	0.17	0.06	-0.10
KICT	5/1/12	0.5	0.33	0.22	-0.11
KBMX	8/1/12	0.83	-0.16	0.05	-0.12
KENX	9/19/12	1.72	-0.81	-0.68	-0.12
KBGM	7/24/12	0.42	0.18	-0.04	-0.14
KTWX	4/15/12	0.45	0.25	0.11	-0.14
KGRB	5/27/12	0.49	0.19	0.04	-0.15
KMHX	5/6/12	0.96	-0.23	-0.07	-0.16
KVNX	6/3/12	0.39	0.25	0.08	-0.16
KOHX	7/19/12	0.34	0.22	0.05	-0.17
KGRR	5/4/12	0.59	0.33	0.16	-0.17
KDDC	6/3/12	0.2	0.22	0.05	-0.17
KDVN	6/30/12	0.54	0.19	0.01	-0.18
KJGX	6/11/12	1.15	-0.35	0.15	-0.20
KCAE	6/11/12	0.69	-0.21	-0.01	-0.20
KEAX	9/1/12	1.84	-0.48	-0.28	-0.20
KLOT	9/2/12	0.53	0.32	-0.11	-0.21
KFFC	6/11/12	0.89	-0.25	-0.04	-0.21
KSGF	4/30/12	0.86	0.57	0.35	-0.22
KSGF	8/17/12	0.45	0.43	0.21	-0.22
KBMX	7/31/12	1.29	-0.46	-0.24	-0.22
KLOT	5/7/12	1.26	0.29	-0.04	-0.24
KICT	4/15/12	0.67	0.52	0.27	-0.25
KLSX	4/30/12	0.7	0.54	0.29	-0.25
KLSX	8/17/12	0.48	0.31	0.06	-0.25
KSGF	5/1/12	0.79	0.57	0.31	-0.26
KGRB	7/3/12	0.71	0.39	0.12	-0.27
KCAE	5/30/12	1.17	-0.43	-0.16	-0.27
KCAE	6/12/12	0.91	-0.31	-0.03	-0.28
KLSX	4/14/12	1.12	0.46	0.18	-0.28
KDIX	6/2/12	1.02	-0.42	-0.13	-0.28
KLOT	5/4/12	0.48	0.33	0.03	-0.30
KLOT	8/17/12	0.46	0.34	0.03	-0.31
KGRR	7/26/12	0.47	0.44	-0.10	-0.34
KNQA	9/1/12	0.98	0.70	0.30	-0.40
KMLB	6/25/12	2.16	-0.80	-0.38	-0.42
KMRX	9/18/12	2.58	-1.28	-0.79	-0.50
KMHX	5/31/12	2.25	-1.06	-0.32	-0.74
KHTX	9/18/12	3.33	-1.26	0.01	-1.25

Table 7. List of statistics for all gauges > 0.5” and ranges less than 150 km. Note that MAE is less sensitive to outliers than RMSE. Significance test results: 95% confidence is signified by a p-value of 0.05 or less and that is used as a test for "statistically significant" results.

Mean Absolute Error

LEGACY	DPQPE
0.418	0.328

Root Mean Square Error

LEGACY	DPQPE
0.757	0.7

Correlation Coefficient

LEGACY	DPQPE
0.683	0.695

Significance test results:

MAE:

Test	p-value	Significant?
DP < LEGACY	0.0005	Y

RMSE:

Test	p-value	Significant?
DP < LEGACY	0.0036	Y

CC:

Test	p-value	Significant?
DP > LEGACY	0.061	N

Table 8. List of statistics for all gauges > 1.0" and ranges less than 150 km. Note that MAE is less sensitive to outliers than RMSE. Significance test results: 95% confidence is signified by a p-value of 0.05 or less and that is used as a test for "statistically significant" results.

Mean Absolute Error

LEGACY	DPQPE
0.536	0.416

Root Mean Square Error

LEGACY	DPQPE
0.884	0.818

Correlation Coefficient

LEGACY	DPQPE
0.582	0.597

Significance test results:

MAE:

Test	p-value	Significant?
DP < LEGACY	<0.0005	Y

RMSE:

Test	p-value	Significant?
DP < LEGACY	0.0043	Y

CC:

Test	p-value	Significant?
DP > LEGACY	0.0312	Y

Table 9. List of statistics for all gauges > 2.0" and ranges less than 150 km. Note that MAE is less sensitive to outliers than RMSE. Significance test results: 95% confidence is signified by a p-value of 0.05 or less and that is used as a test for "statistically significant" results.

Mean Absolute Error

LEGACY	DPQPE
0.803	0.62

Root Mean Square Error

LEGACY	DPQPE
1.18	1.06

Correlation Coefficient

LEGACY	DPQPE
0.425	0.454

Significance test results:

MAE:

Test	p-value	Significant?
DP < LEGACY	<0.0005	Y

RMSE:

Test	p-value	Significant?
DP < LEGACY	0.0012	Y

CC:

Test	p-value	Significant?
DP > LEGACY	0.1641	N

Table 10. Mean absolute error by storm type.

Storm type	Legacy	DP QPE
FR (29)	.348	.277
PS (27)	.146	.146
TS (17)	.609	.547
MCS (44)	.238	.162