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STATUS OF DUAL POL QPE IN THE WSR-88D NETWORK

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1. INTRODUCTION

A new Quantitative Precipitation Estimation (QPE) algorithm is being fielded with the dual polarization upgrade to the Weather Surveillance Radar-1988 Doppler (WSR-88D) network. Early evaluations of the QPE algorithm performance were done with data from August 2011's Hurricane Irene (Goodall *et al.*, 2012) and from 31 (April to December 2011) events in Oklahoma and southern Kansas (Cocks *et al.*, 2012).

Later, the algorithm was examined by the Hydrometeorology Research Group of NSSL for 139 radar cases across the contiguous United States for a wide variety of rainfall events, all occurring during the spring and summer of 2012. The results indicated that dual polarization QPE was an improvement over legacy estimates for most of the cases.

The nature of these improvements appeared to depend on whether the beam was above the melting layer or below it. The height of the melting layer is usually provided by the Melting Layer Detection Algorithm, which also affects the Hydrometeor Classification Algorithm. QPE performance is entirely dependent on accurate information from both of these algorithms.

Dense, high-quality rain gauge networks are needed to provide robust statistical analyses of radar-based precipitation algorithms such as the QPE. Field offices are being encouraged to use a new web-based QPE diagnostic tool for dual polarization performance in their areas. This paper provides an update on the QPE dual polarization rainfall estimation, challenges in the analysis of QPE, training efforts, NSSL's QPE Verification System (QVS), and a discussion of future work.

2. DERIVATION OF DUAL POLARIZATION QUANTITATIVE PRECIPITATION ESTIMATES

The dual polarization (hereafter called "dual pol") QPE algorithm resides in the WSR-88D's Radar Product Generator (RPG) and receives data from the Radar Data Acquisition (RDA) computer at "super-resolution" (0.5° by 0.25 km). The RPG then decreases the resolution and smoothes the data before passing the data to the Hydrometeor Classification Algorithm (HCA) and the Melting Layer Detection Algorithm (MLDA). The HCA and MLDA interact with each other, and the resulting data are then passed to the QPE algorithm. The Dual Pol QPE algorithm requires high quality base data to provide optimum results. The diagram below (Figure 1) shows the flow of the data and how the QPE and other algorithms ingest base data.

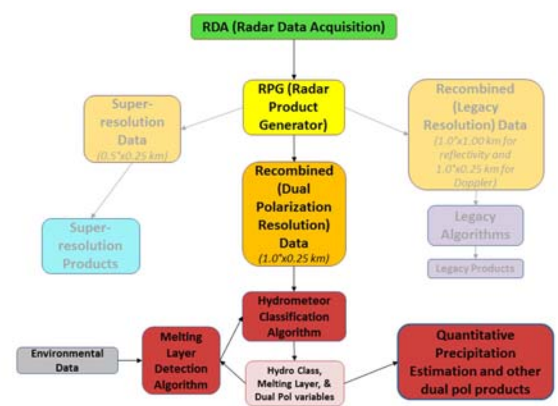

Figure 1. Flow diagram for derivation of dual pol and other products from base data.

2.1 *Hydrometeor Classification Algorithm*

The HCA is based on fuzzy logic (e.g., Vivekanandan *et al.*, 1999), where the interest fields, or variables, are reflectivity (Z), differential reflectivity (Z_{DR}), the logarithm of specific differential phase (LK_{dp}), cross-correlation coefficient between horizontally- and vertically-polarized radar returns (ρ_{hv}), texture of reflectivity (SD(Z)), and texture of differential phase ($SD(\Phi_{DP})$), each with a degree of membership ranging from 0 to 1. Nearly all of these variables undergo processing (thresholding and smoothing) before being used in the fuzzy logic. Various weights are applied when deriving an aggregate score for final determination of a classification.

As described in Park *et al.* (2009) the following are the classifications in the currently operational version of the WSR-88D HCA: ground clutter (GC, including that due to anomalous propagation), biological scatterers (BI), dry aggregated snow (DS), wet snow (WS), ice crystals of various orientations (IC), graupel (GR), big drops (BD), light and moderate rain (RA), heavy rain (HR), and a mixture of rain and hail (HA). Where there is no discernible echo, a classification of no data (ND) is used. Otherwise, the sample volume is classified as unknown (UK), where the algorithm cannot clearly conclude which

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classification to assign there.

Most of the fuzzy logic for the HCA uses trapezoidal membership functions, but both Z_{DR} and LK_{dp} use two-dimensional membership functions, taking into account the interaction with reflectivity. There are also several rules applied that restrict certain classifications depending upon the location of the sample bin relative to the melting layer.

2.2 *Melting Layer Detection Algorithm*

Melting is assumed to take place below the highest elevation that encounters a melting level. This is estimated from an upper-air sounding, output from the Rapid Update Cycle (RUC) numerical model (or its successor), or, if radar echoes cover a sufficient depth and area, from the MLDA. The MLDA utilizes Z_{DR}, Z, and ρ_{hv} (often referred to as CC) between the 4° and 10° elevation angles to determine the slant range where the radar beam enters the bottom of the melting layer, where the center of the beam enters the melting layer, where the center of the beam goes above the melting layer, and where the bottom of the beam goes above the melting layer for any elevation angle. See Giangrande *et al.* (2008) and Park *et al.* (2009) for more details about the MLDA.

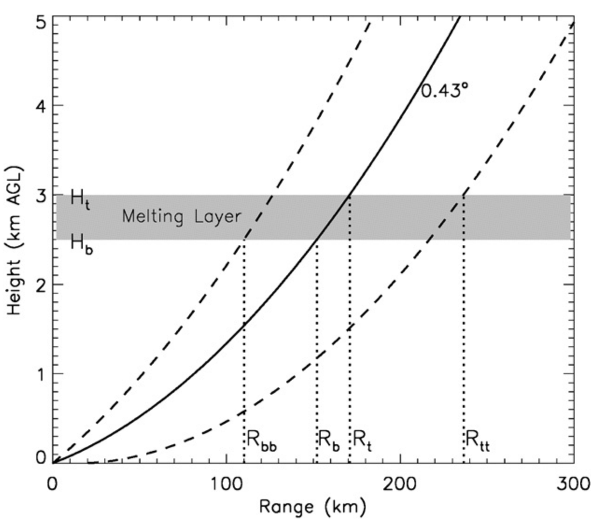

Figure 2. Geometry of the radar beam with respect to the melting layer. (Park et al., 2009)

2.3 *Quantitative Precipitation Estimation Algorithm*

Based on the output of the MLDA and HCA, the QPE algorithm applies one of three basic rainfall rate relationships (one based on reflectivity alone, one on a combination of Z and Z_{DR}, and one on K_{dp}) to estimate the amount of liquid precipitation reaching the ground. This echo classification-based method is described by Giangrande and Ryzhkov (2008). The three relationships in the WSR-88D deployed version of QPE are as follows (all giving estimates in mm h^{-1}), with Z and Z_{DR} given in linear units, not logarithmic ones, and K_{dp} given in degrees per kilometer:

$$R(Z) = .0171 * (Z)^{0.714},$$

$$R(K_{DP}) = 44 * |K_{dp}|^{0.822} * \text{sign}(K_{dp}) \text{, and}$$

$$R(Z,Z_{DR}) = 0.0067 * (Z)^{0.927} * (Z_{DR})^{-3.43} .$$

Note that the currently operational version of the WSR-88D QPE only estimates the amount of liquid, not frozen precipitation. The QPE assigns the relationship to use according to the following table:

Echo Classes	Method
GC	Not computed
UK	Not computed
NE	0
BI	0
RA	$R(Z,Z_{DR})$
HR	$R(Z,Z_{DR})$
BD	$R(Z,Z_{DR})$
HA (echo below top of melting layer)	$R(K_{DP})$
HA (echo above top of melting layer)	0.8*R(Z)
GR	0.8*R(Z)
WS	0.6*R(Z)
DS (echo below top of melting layer)	R(Z)
DS (echo above top of melting layer)	2.8*R(Z)
IC	2.8*R(Z)

Table 1. Rainfall estimation method for each echo classification.

For the two echo classes that do not compute any rainfall estimate, a sample bin from the next higher elevation is used until an adequate amount of coverage (i.e., 99.7% of all sample bins) is achieved.

An early test of QPE performance took place August 26th to 28th in 2011 as Hurricane Irene moved slowly over eastern North Carolina and neighboring states. Irene caused very heavy rainfall totals, with one location reporting nearly 398 mm (15.66 inches). The WSR-88D near Morehead City (KMHX) recorded a region of storm total rainfall exceeding 380 mm (15 inches) due north of the radar site. The legacy PPS had this region extending from roughly 45 to 75 km north of the radar, while the dual pol QPE indicated this region from roughly 30 to 90 km north of the radar, approximately twice the area of the legacy PPS where rainfall exceeded 380 mm.

Figure 3 shows the legacy PPS, while Figure 4 shows the dual pol estimates. Figure 5 zooms in on the dual pol estimate's heaviest precipitation region with rain gauge reports for that three-day event. (All of these are in inches using the scale above Figure 5.)

Statistical analyses by the ROC and NSSL determined that the dual pol QPE's mean error and root mean square error (RMSE) were significantly less than those of the legacy PPS using a tropical R(Z) relationship.

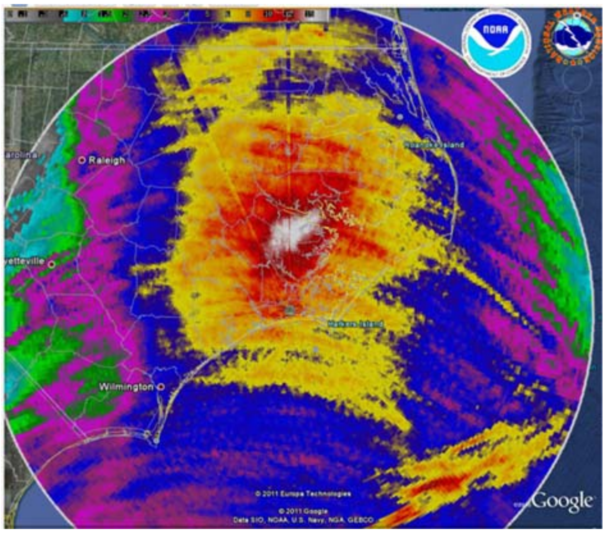

Figure 3. Hurricane Irene storm total rainfall estimates from the legacy PPS. (Goodall *et al.*, 2012)

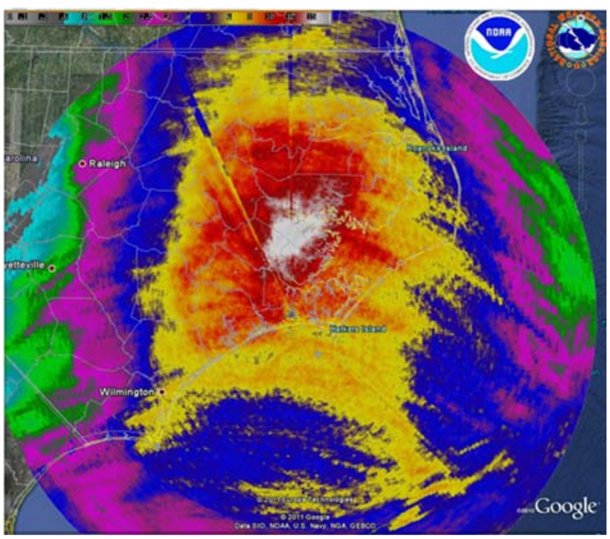

Figure 4. Hurricane Irene storm total estimates from dual pol QPE. (Goodall *et al.*, 2012)

The melting layer determination has a major impact on the performance of the QPE. As shown in Figure 6, for long term events there is often a sharp discontinuity at the top of the melting layer corresponding to the inner range where the dual pol QPE yields overestimates above the melting layer. As mentioned in section 2.2 above, the melting layer can be determined from a sounding, from a numerical forecast model, or from the MLDA. Work is in progress at NSSL to improve this melting layer determination.

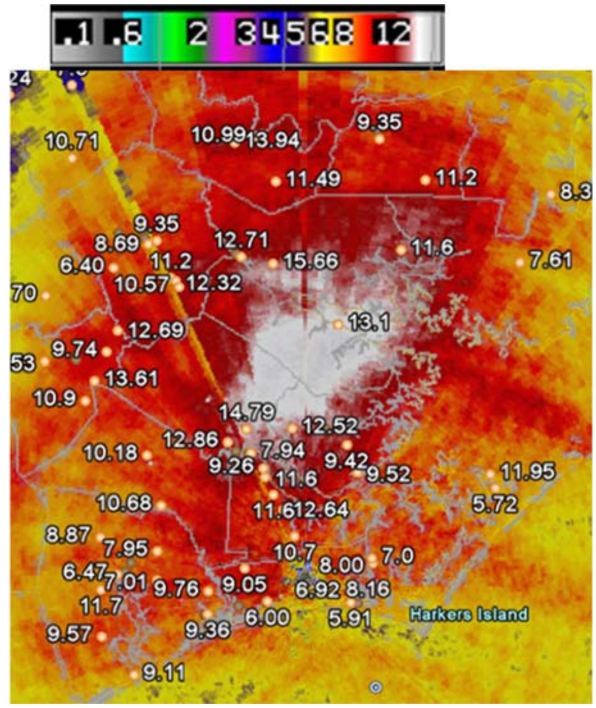

Figure 5. Hurricane Irene dual pol QPE with rain gauge reports in the heaviest rainfall region of North Carolina. (Courtesy Morehead City, NC, Weather Forecast Office)

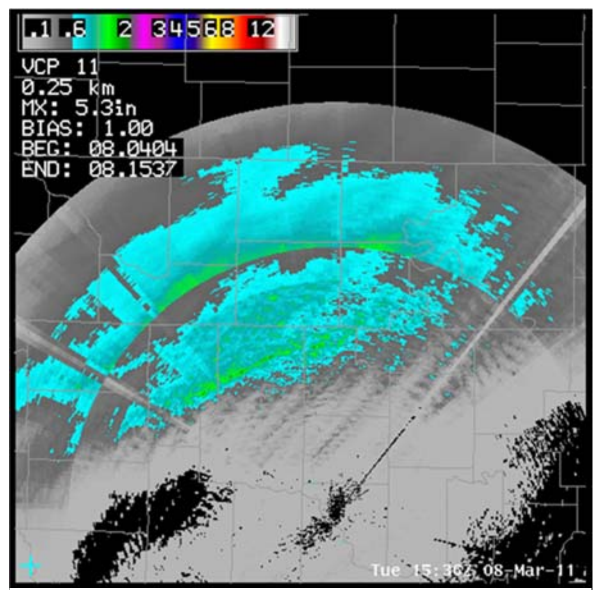

Figure 6. Sharp discontinuity at the top of the melting layer.

3. NSSL STUDY RESULTS

An extensive study was undertaken by NSSL (Vasiloff, 2012), using statistics from a dual polarization version of the QPE Verification System (QVS) based on a variety of rain gauges and rainfall estimates derived from

WSR-88D rainfall accumulation products. The QVS (http://nmq.ou.edu/qvs-2012.html) provides a standard tool that can emulate the accumulations that network radars compute (derived from actual RPG products) but for specified time intervals. It ingests rain gauge data from many sources including the Hydrometeorological Automated Data System (HADS), Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS), and some other high quality rainfall observation networks.

NSSL examined 139 cases with 47 radars during the Spring and Summer of 2012. All of the rain gauges were limited to within 150 km of the radar in an attempt to stay below any melting layer effects, considering that the radar beam height increases with range. In order to determine the statistical significance of any improvement by the dual pol QPE over legacy PPS, NSSL used a Monte Carlo approximation of the one-sided Fisher's exact permutation test (Efron and Tibshirani, 1993) under a matched-pairs analysis using 3999 permutations (more simply, a matched pairs permutation test). This non-parametric permutation test was employed, rather than the more familiar t-test, because the distribution of the errors was unknown and was very unlikely to be a normal distribution. Using this method, the results of this study were found to be statistically significant at $p = 0.05$.

Overall, the dual pol QPE showed improvement over legacy PPS. A bar graph (Figure 7) illustrates the improvement in Mean Absolute Error (MAE). For all gauges there was a 19% improvement in MAE. For gauges reporting greater than 50.8 mm (2 inches) there was a 23% improvement. The events were also classified by storm type. The Mesoscale Convective System (MCS) type showed the greatest improvement for dual pol QPE, with a 32% improvement in MAE.

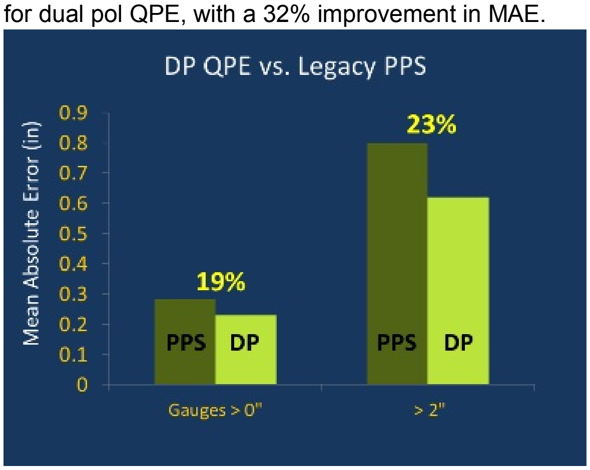

Figure 7. Dual Pol QPE (DP) Compared With Legacy PPS Estimates.

4. RECOMMENDATIONS

Based on the ROC and NSSL evaluations, several areas for QPE algorithm improvement were identified. These areas of improvement include (but are not limited to) precipitation estimation in the cool season, discontinuities due to the melting layer, performance in tropical (or warm rain) environments as opposed to continental ones, Z_{DR} calibration, selection of Initial System Differential Phase (ISDP), and other adjustments, such as changes in rainfall relationship coefficients. It should be noted that the QPE algorithm was developed in Oklahoma, a mostly continental environment.

4.1 *Melting Layer Challenges*

The QPE aims to estimate precipitation falling at the ground. Since the radar beam intercepts and goes above the melting layer at far ranges, below beam effects in these areas significantly affect precipitation estimations at the ground. NSSL is testing a new algorithm which uses model data to determine the vertical profile of temperature in these areas to evaluate the precipitation that might be reaching the ground. In doing so, it is hypothesized that there will be improvements in rainfall estimation at ranges where the radar beam intercepts and goes above the melting layer.

4.2 *Hardware Challenges*

The single-polarization WSR-88D only required calibration of horizontally-polarized reflectivity. Dual polarization requires calibration of vertical reflectivity, too. Because of observed variations in Z_{DR} that are not apparently due to meteorology, and because of the performance of HCA classifications and dual pol QPE rainfall estimates that are based on Z_{DR}, some algorithm changes have been recommended by NSSL that decrease reliance on Z_{DR} in HCA and QPE algorithms and, instead, increase reliance on K_{DP}, particularly in heavy rain.

Differential phase is measured relative to the ISDP setting. The displayed PHIDP value may drift over time due to maintenance procedures or other reasons. The presence of light precipitation is needed to obtain the best ISDP setting. This value should be routinely monitored and adjusted when necessary. Incorrect PHIDP values will result in impacts to dual pol QPE performance.

4.3 *Partial Beam Blockage Challenges*

One of the biggest challenges for any weather radar is mitigation of blockage (or occultation) of the radar beam due to terrain, trees, or man-made obstacles like buildings and towers. The approach taken in WSR-88D precipitation estimation software is to develop a hybrid scan by which any sample bin at the lowest elevation that has a blockage exceeding a specified threshold would be replaced by one from a higher elevation where that threshold is not exceeded. Both the PPS and dual pol QPE utilize methods where the degree of that blockage is determined from surface elevation data derived from both ground elevations and elevations measured by the February 2000 Shuttle Radar Topography Mission (including trees and man-made objects). Dual pol QPE has a more sophisticated formula to adjust for partial beam blockage than the legacy PPS.

Nevertheless, there are often cultural (man-made) objects constructed and changes in vegetation (especially new tree growth) that did not exist in February 2000. Therefore, NSSL has investigated a method that is not dependent on a static data file but, instead, dynamically adjusts the degree of blockage according to changes in differential phase. This method is called specific attenuation (**R(A_h)** in Figure 8).

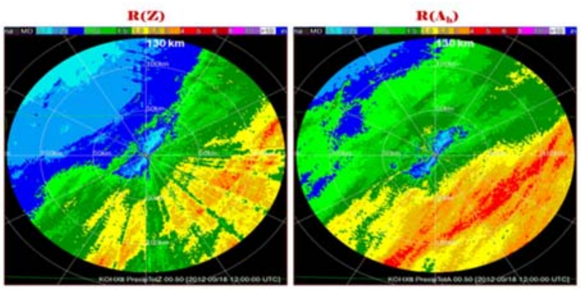

Figure 8. This is an example of the work by NSSL using a rainfall rate based on specific attenuation (right image) versus the legacy PPS rainfall rate using Z from Nashville's KOHX radar, where trees cause a blockage to the southeast.

5. TRAINING CHALLENGES

The training emphasis for the National Weather Service's Warning Decision Training Branch (WDTB) with respect to dual polarization has been on understanding base data, the traditional moments (reflectivity, velocity, and spectrum width) plus the polarimetric variables (differential reflectivity, cross-correlation coefficient, and specific differential phase). In order to illustrate how the values of these data relate to various hydrometeors (as determined by the HCA), WDTB has created special training aids like Figure 9.

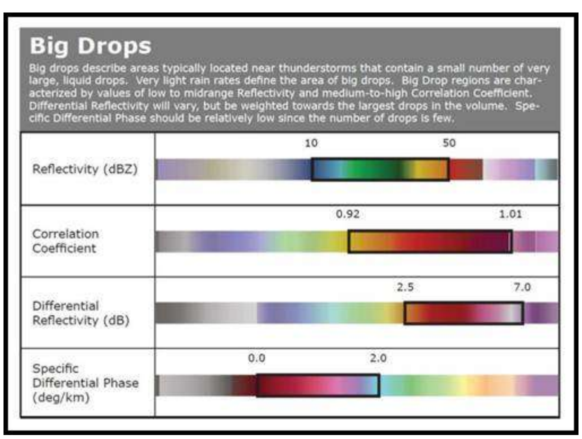

Figure 9. Variables used in HCA fuzzy logic to identify "big drops."

QPE is one of the most complex algorithms in the RPG. Unlike the PPS, QPE not only uses inputs of reflectivity (Z) and velocity (V), but it uses all the base data plus output from the HCA and MLDA. Thus, gaining an understanding of this algorithm and its strengths and limitations will take time due to all these intricacies. Therefore, the WDTB, ROC, and NSSL have teamed together to help spread the latest updates on QPE as we learn them. Efforts such as a "Focus on QPE" short course (a dedicated online module on the current state of QPE), "Storm of the Month," and other webinars are regularly provided to help keep the field apprised of the latest developments in QPE. (See Section 10 below.)

6. NSSL'S QVS

NSSL, with support from the ROC, added dual pol capabilities to the legacy QVS in early 2012 (Fig. 10 and http://nmq.ou.edu/qvs-2012.html). This system allows instant and open access for QPE evaluation for all WSR-88Ds and includes thousands of surface observations. The "Legacy PPS" and "Dual Pol" (QPE) rates and accumulations were derived from RPG-generated products: Digital Hybrid Reflectivity (DHR) and Digital Instantaneous Precipitation Rate (DPR), respectively. Products from NSSL's NMQ version 2 (Q2) also reside in the QVS (Zhang *et al.* 2011).

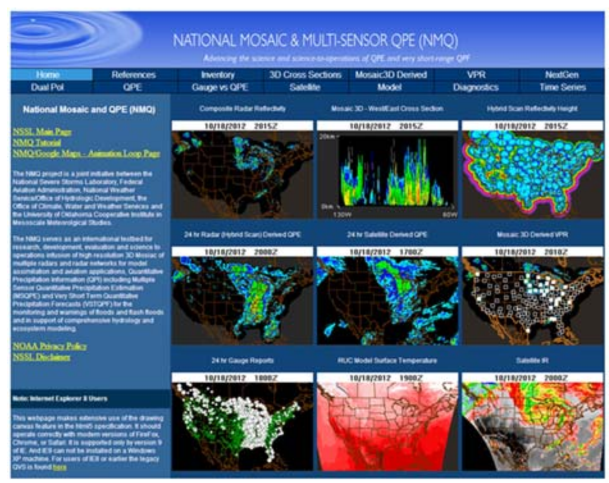

Figure 10. Home page for National Mosaic & Multi-sensor QPE (NMQ) including QVS options.

7. OUTREACH EFFORTS

The dual pol QPE algorithm is complex, and a variety of situations have challenged its performance. Several efforts have been undertaken to keep users of dual pol QPE products up to date and to allow them to provide feedback. These outreach efforts include (1.) promoting the use of NSSL's dual pol QVS software (home page in Figure 10) by National Weather Service meteorologists and hydrologists, (2.) an Internet chat room that is part of NWSChat, (3.) multimedia briefings developed by the ROC, and (4.) a QPE blog hosted by the ROC.

8. SUMMARY

The initial verification of dual pol QPE performance has shown improvement over legacy PPS, particularly during the warm season and high altitude melting layer situations. Efforts are ongoing to tune the QPE algorithm and its reliance upon dual pol algorithms. Among those efforts are a comparison between continental and tropical equations for $R(Z,Z_{DR})$, methods to evaluate and mitigate any Z_{DR} bias effects on QPE, improved estimation of the melting layer top and thickness, mitigation of beam blockage effects, and an increased focus on detecting flash flood-producing rainfall (which requires hourly and, sometimes, sub-hourly rainfall estimate studies). The ongoing training and outreach efforts encourage QPE users to participate in evaluation and in making improvements. Using QVS and other tools, verification studies will continue, particularly for cool season events

9. REFERENCES

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10. INTERNET RESOURCES

Focus on QPE (WDTB short course):
http://www.wdtb.noaa.gov/courses/dualpol/QPE/index.html

Multimedia Briefings:
http://www.roc.noaa.gov/WSR88D/Applications/Presentations.aspx

QPE Verification System (QVS):
http://nmq.ou.edu/qvs-2012.html

Storm of the Month:
http://www.wdtb.noaa.gov/courses/dualpol/SOTM/index.html