5.3 INITIAL OPERATING CAPABILITIES OF QUANTITATIVE PRECIPITATION ESTIMATION IN THE MULTI-RADAR MULTI-SENSOR SYSTEM

JIAN ZHANG, KENNETH HOWARD, STEVE VASILOFF
NOAA/OAR National Severe Storms Laboratory
Norman, OK

CARRIE LANGSTON, BRIAN KANEY, YOUCUN QI, LIN TANG, HEATHER GRAMS
Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma,
Norman, OK

DAVID KITZMILLER
NOAA/NWS Office of Hydrologic Development
Silver Spring, MD

JASON LEVIT
NOAA/NWS Office of Science and Technology
Silver Spring, MD

1. Introduction

The National Mosaic and Multi-Sensor Quantitative Precipitation Estimation (QPE) (NMQ, Zhang et al. 2011) system developed at the National Severe Storms Lab (NSSL) of National Oceanic and Atmospheric Administration (NOAA) is a real-time system that integrates radar, rain gauge and numerical weather prediction model data and generates automated, seamless national 3D radar mosaic and quantitative precipitation estimates at high temporal and spatial resolution. The NMQ system has been running in real-time since June 2006 and a suite of experimental products are provided to users from government agencies, universities, research institutions, and the private sector and have been utilized in various meteorological, aviation, and hydrological applications. Specifically, high-resolution gridded NMQ precipitation products are prototyped as inputs into the National Weather Service's (NWS) Flash Flood Monitoring and Prediction program. Several River Forecast Centers (RFCs), including the West Gulf, Southeast, Ohio, and North Central are using the NMQ radar rainfall products in their operations. In coordination with RFCs, several Weather Forecast Offices (WFOs) are beginning to experiment with NMQ data in their Site Specific Headwater Predictor model.

During 2013, major changes were implemented in the NMQ system to accommodate the polarimetric upgrade to the United States Weather Surveillance Radar-1988 Doppler (WSR-88D) network. The updated NMQ system, combined with the Warning Decision Support System – Integrated Information (WDSS-II, Lakshmanan et al. 2007) system, constituted a new Multi-Radar Multi-Sensor (MRMS) system, which is now in transition into NWS operations. The operational transition of MRMS system will provide users with a large number of severe weather and QPE products at very high spatial (1 km) and temporal (2 min) resolution. It integrates ~180 operational weather radars from conterminous United States (CONUS) and Canada and generates a 3-D national radar mosaic every 2 min with 1km horizontal resolution and 33 vertical levels stretching from 500m to 19km above mean sea level. Advanced polarimetric radar techniques are applied in the system to provide improved qualities of the products. The severe weather products include national composite reflectivity, storm top heights, hail area and severity, storm rotation tracks, etc. The precipitation products include an ensemble of radar-based QPE, gauge-based QPE, a radar QPE with a local gauge bias correction and a gauge and orographic precipitation climatology merged QPE.

This paper focuses on the QPE component of the MRMS system and provides an overview of the initial operating capabilities of the MRMS QPE products. The rest of the paper is organized as follows: section 2 describes the MRMS QPE algorithms. Section 3 provides a summary and an outlook for the future research and development efforts.

2. MRMS QPE System

The MRMS domain covers CONUS area with latitude bounds of 20 and 55°N and longitude bounds of 130 and 60°W (Figure 1). The MRMS grid uses a cylindrical equidistant projection with a horizontal resolution of 0.01° in both latitude and longitude directions. This grid resolution is equivalent to ~1.11km in the north-south direction. In the west-east direction, the grid resolution varies from ~ 1km at the southern bound to ~ 0.6km at the northern bound.

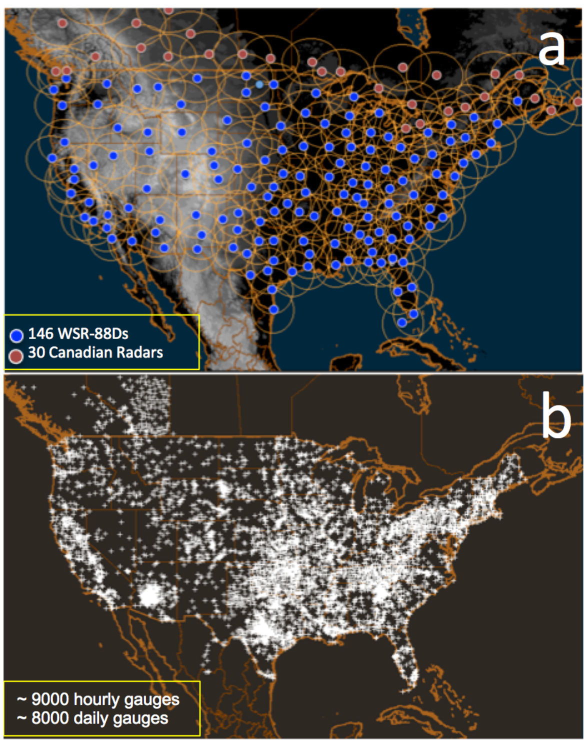

Figure 1. MRMS domain and locations of the radar and rain gauge sites. The blue dots indicate the US WSR-88D radar sites and maroon dots the Canadian radar sites (a). Brown circles are the 250km range rings (a) and white "+"s indicate locations of the hourly and daily gauges (b).

The MRMS system ingests 3-D volume scan data from 146 radars in the WSR-88D network and 30 radars in the Environment Canada weather radar network (Fig.1a). The volume scan update cycles range from 3 to 10 minutes. The MRMS system ingests about ~9000 rain gauges reporting hourly precipitation accumulations and ~8000 gauges that report daily accumulations. The hourly gauges are used for generating the gauge-based QPE and for the local bias correction of the radar-derived QPE. The daily gauges are used for evaluations of various MRMS QPE products.

Hourly analyses of Rapid Refresh (RAP; http://rapidrefresh.noaa.gov) model are used extensively in the MRMS system. The RAP 3-D temperature, wind and relative humidity fields are used in single radar processes such as the reflectivity quality control and in multi-radar multi-sensor processes such as the surface precipitation classifications.

A special data set of monthly precipitation climatologies are used in the MRMS system for the QPEs in the western US. The climatology is from the Parameter-elevation Relationships on Independent Slopes Model (PRISM, Daly et al. 2008; www.prism.oregonstate.edu), which is derived using 30-years of gauge observations, atmospheric environmental data, and terrain elevation information.

Figure 2 shows an overview flowchart of the MRMS QPE system. Brief descriptions of each algorithm are provided below.

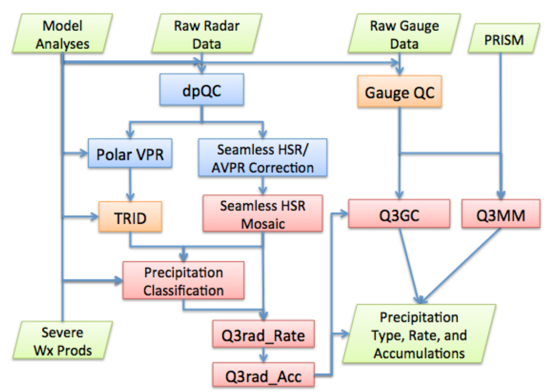

Figure 2 MRMS QPE process data flow. The green parallelograms at the top show the input data from different sources, and those at the bottom show the MRMS product outputs. Note that the MRMS severe weather products are inputs for the precipitation classification. Blue boxes indicate processes applied to single radar volume scan data, pink boxes represent processes applied on the MRMS CONUS Cartesian grid, and orange boxes indicates point data or profile data processes.

2.1 Dual-polarization radar data quality control (dpQC)

The radar data quality control (QC) in the

NMQ system was mainly based on the structure of reflectivity, radial wind and spectrum width. It had limitations in removing biological echoes during the peak migration seasons for birds, due to the fact that reflectivity signatures of biological echoes ("blooms") are very similar to the shallow stratiform precipitation. The polarimetric radar variable of correlation coefficient (ρ_{HV}), however, shows distinctively different characteristics between the two types of echoes (Fig. 3). Taking advantages of the WSR-88Ds' polarimetric capabilities, a dual-polarization radar data QC ("dpQC") (Tang et al., 2014) is developed in the MRMS system to segregate precipitation and non-precipitation echoes. dpQC eliminates nearly 100% of the bloom echoes (Fig. 4) and significantly reduces contamination of wind farms and chaffs in the radar QPE.

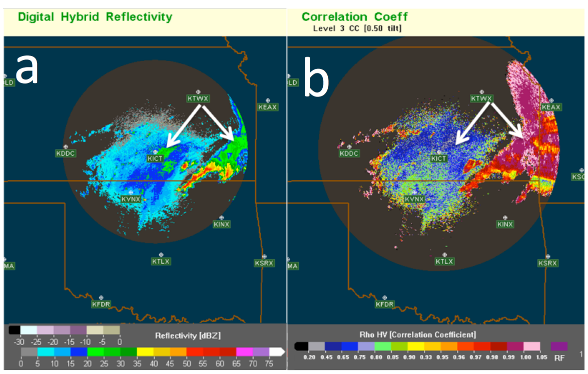

Figure 3 Base reflectivity (a) and correlation coefficient (b) fields from KICT radar valid at 06:00UTC on 20 May 2013. The two white arrows indicate areas of anomalous propagation and biological echoes towards the west and an area of precipitation to the east.

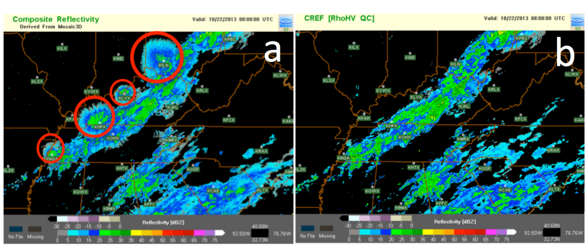

Figure 4 Composite reflectivity fields (a) from the NMQ single-polarization radar QC and (b) from the MRMS dpQC.

2.2 Polar Vertical Profile of Reflectivity (VPR) and Tropical Rain Identification (TRID)

The polar VPRs are derived from the quality-controlled base reflectivity field (Zhang et al. 2008), and the process is the same as in the NMQ system. The tropical rain identification process follows Xu et al. 2008 and is also the same as in the NMQ.

2.3 Seamless Hybrid Scan Reflectivity

Radar QPEs in the NMQ are derived from a standard "hybrid scan reflectivity" (HSR) field, which is a 2-D polar grid consisting of reflectivities in the lowest (in altitude) bins at each range/azimuth location that are not severely blocked (e.g., < 50%). Further, the bin bottom is required to clear the ground by a certain height (e.g., 50m). The standard HSR is determined using the digital elevation model (DEM) data and assuming a normal beam propagation. The HSR does not account for "non-standard" blockages due to objects above the ground such as man-made towers and growing trees. The non-standard blockages often result in gaps in rainfall fields (Figs. 5a and 5c). In the MRMS system, such gaps are identified from precipitation accumulation maps. Azimuth/range bounds of the gaps are manually tabulated. A cross-azimuth interpolation is applied to fill in the small gaps (Fig.5b). Large gaps are filled with data from the unblocked upper tilt (Fig. 5d). This process is called the "non-standard blockage mitigation" (NSBM, Tang et al. 2013) in the MRMS system, and the resultant HSR field is called "seamless" HSR.

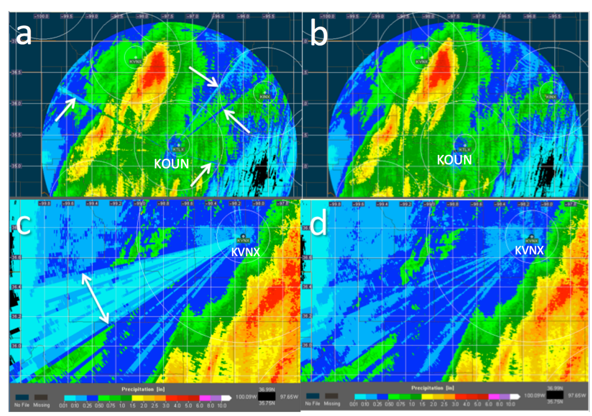

Figure 5 Example QPE accumulation fields without the non-standard blockage mitigation (a, c) and with the mitigation (b, d). White arrows indicate areas of discontinuities due to cellphone and water towers (a) and growing trees (c).

2.4 Apparent VPR (AVPR) Correction

One of the range-dependent radar QPE errors is the overestimation in the "bright band"

(BB) – an inflated reflectivity zone where radar beams intersect the melting layer. Another is the underestimation in regions where radar beams sample in the ice region while the surface precipitation is rain. To correct for these errors, the MRMS system adapted an apparent vertical profile of reflectivity (AVPR) correction scheme developed by Zhang and Qi (2010), later refined by Zhang et al. (2012a) and Qi et al. (2013a, b), in which hybrid scan reflectivities are adjusted to its corresponding value at the BB bottom according to a linear AVPR. Each linear AVPR is a least squares fit to the range profile of azimuthal mean reflectivities in the stratiform precipitation area. Example AVPRs from KLWX observations during Hurricane Sandy are shown in Fig. 6. Assuming the vertical structure of the stratiform precipitation is horizontally uniform and the precipitation rate below the BB bottom is constant, the AVPRs show range-dependent radar QPE biases. Reflectivities in (above) the BB are higher (lower) than the reflectivity at the BB bottom (Fig. 6) and corresponding to overestimation (underestimation) errors in the radar QPE. By adjusting the reflectivities to its corresponding value at the BB bottom, the range-dependent errors can be mitigated.

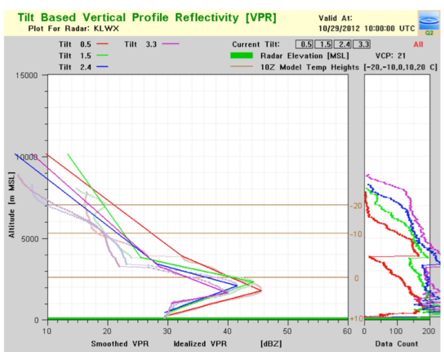

Figure 6 AVPRs from KLWX radar at 10:00UTC on 29 Oct. 2012. Colored curves in the main panel show profiles of azimuthally averaged reflectivities from stratiform precipitation areas on different tilts. The straight lines are the linear fitting AVPRs. Curves in the right panel shows number of data samples associated with the azimuthal mean reflectivities.

Figure 7 shows example 24-hr radar QPEs from the KLWX radar before and after the AVPR correction. The overestimation is apparent in an area west of the radar (solid blue circles in Fig.7b), which resulted in a high bias ratio (1.75) when compared to the gauge observations. After the correction, the bias ratio was reduced to 1.07 and the root mean square error was reduced by ~58% (Figs. 7c vs. 7f).

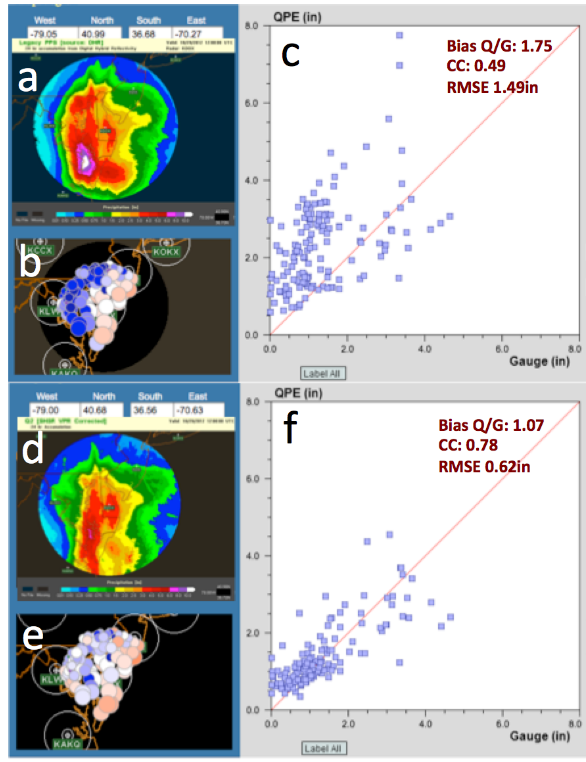

Figure 7 Daily QPE maps before (a) and after (c) the AVPR correction. Bias ratios of the QPEs vs. gauge observations are shown as the bubble charts in panels (b) and (e), respectively. The size of the bubbles represents the gauge amounts and the color represents the QPE bias (pink means underestimation and blue means overestimation). The scatter plots of the two QPEs vs. gauge data are shown in panels (c), and (f), respectively.

2.5 Seamless HSR Mosaic

Many areas in the MRMS domain are covered by multiple radars (Fig. 1a). Ideally, taking the lowest (in altitude) HSR datum among the multiple radars covering the same point should provide the most accurate precipitation rate estimate at the ground. However, such an approach inevitably introduces discontinuities in the QPE field midway between neighboring radars. The discontinuities may be due to different calibration biases among the radars or different beam propagation paths from the radars to the overlapping point. The NMQ system took a weighted mean approach (Zhang et al. 2011) that avoids such discontinuities and provides a spatially continuous QPE field. HSR data from multiple radars covering the same point are combined as long as the data are below a certain height (default = 5km above ground level). A couple of issues were found with such blending of HSR data. One issue was the false surface precipitation introduced from overhanging precipitation, and another is the dampening of the HSR data in the rain region by the HSR data in the ice region. To mitigate these issues, the weighted mean scheme is modified in the MRMS seamless HSR (SHSR) mosaic.

The MRMS SHSR mosaic value at any given point is computed according to the following logic. If the lowest (in altitude) SHSR datum among all radars covering the same point shows no precipitation, then the mosaicked SHSR is set to no precipitation. Otherwise, the multiple radars' SHSR data are grouped into "liquid", "mixed" and "ice" categories according to their heights with respect to the BB top and bottom. The BB top and bottom height fields are the 2-D CONUS analyses as described in Zhang et al. (2011). If valid data are found in a lower altitude group, then a weighted mean of the data is taken as the mosaicked SHSR and the higher altitude groups are ignored. This approach prevents usage of higher altitude data in the SHSR mosaic when the lower altitude data are available, and it allows a smooth transition across the midway between neighboring radars.

The weighting functions are similar to what was used in the NMQ system and are defined below:

$$SHSR_m = \frac{\sum_i w_r^i \bullet w_h^i \bullet SHSR_s^i}{\sum_i w_r^i \bullet w_h^i} \qquad (1)$$

$$w_r = \exp\left(-r^2 / L^2\right) \qquad (2)$$

$$w_h = \exp\left(-h^2 / H^2\right) \qquad (3)$$

Here $SHSR_m$ represents the mosaicked SHSR, i is the radar index, and $SHSR_s$ is the single radar SHSR data. There are two components in the weighting function, one in horizontal (w_r) and another vertical (w_h) directions. The variable r represents the distance between the analysis point and the radar, and h represents the height (above mean sea level) of the single radar SHSR bin. The parameters L (default = 100km) and H (default = 2km) are adaptable shape factors of the two weighting functions, respectively.

2.6 Surface Precipitation Classification

The MRMS surface precipitation type has seven categories (Fig. 8), which include 1) warm stratiform rain, 2) cool stratiform rain, 3) convective rain, 4) tropical/stratiform rain mix, 5) tropical/convective rain mix, 6) hail and 7) snow. The classification is based on the precipitation type scheme in the NMQ system (Zhang et al. 2011) but with several major changes. First, the reflectivity thresholds that define the precipitation existence are relaxed from 10 to 5 dBZ in warm season and from 5 to 0 dBZ in cold season. This change improves the depiction of light precipitation in the radar QPE without introducing false precipitation because the new dpQC is much more effective in removing bloom echoes than the old single-polarization radar QC.

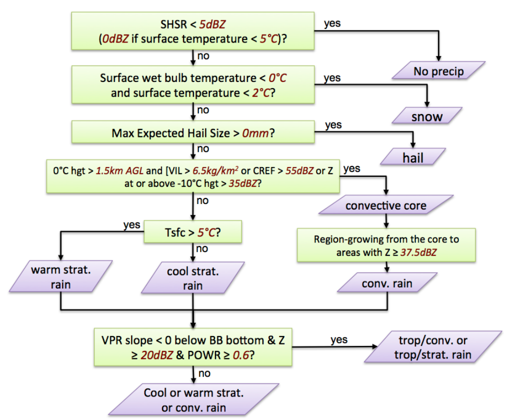

Figure 8 The surface precipitation classification process in the MRMS system.

Convective rain delineation in the MRMS involves two steps: first the convective cores are identified and then the cores are expanded to obtain convective rain regions. The convective cores are identified through similar logic for the convective rain identification in the NMQ, but with much more stringent criteria. Further, a freezing level height constraint and a VIL (vertically integrated liquid) threshold are applied. The stringent criteria and additional constraints help reducing false convective identifications in bright band areas (Qi et al. 2013a).

Major changes are made to the tropical rain delineation in the MRMS system. A new probability of warm rain (POWR) is developed in the MRMS for improved tropical rain delineation. POWR field is derived using decision trees based on a number of environment predictors from the RAP analysis (Grams et al., 2014). It is trained using biases of radar QPEs vs. hourly gauge observations. The key predictors in the decision trees included 850-500hPa lapse rate of temperature, height of freezing level and 1000-700hPa mean relative humidity. Enhanced tropical rain rates are related to high freezing level, moist adiabatic profile (weak lapse rate) and high relative humidity in the lower and middle atmosphere.

Figure 9 shows the POWR field from two different areas, one (Fig. 9a_1) is associated with a mesoscale convective system in south Texas and another (Fig.9b_1) with the tropical storm Andrea in northeastern US. The VPR based TRID (Xu et al. 2008) was positive in both areas (i.e., from KEWX and KBOX radars). The tropical rain delineation in south Texas erroneously expanded into the BB area (Fig.9a_2) because of the relatively high reflectivities (Fig.9a_3) even after the AVPR correction. The erroneous tropical rain delineation resulted in an overestimation of radar QPE (Fig.9a_4). The POWR values in the region were mostly lower than 0.6 indicating a moderate to low probability for enhanced rain rates. The new tropical rain delineation mitigates this issue by prohibiting tropical rain delineations where POWR < 0.6.

In the northeast US, the tropical rain delineation was limited to very small areas (Fig.9b_2) where the SHSR > 30 dBZ (Fig.9b_3), even though the POWR field showed very high value of 0.9-1.0 across the region. The stratiform Z-R relationship was applied in majority of the areas and resulted in an underestimation (Fig.9b_4). The new tropical rain delineation with lower SHSR threshold (20dBZ) and a POWR constraint (≥ 0.6) would expand the tropical rain areas and reduce the underestimation errors for such cases in the future.

2.7 Radar-based Precipitation Rate ("Q3rad_Rate") and Accumulations (Q3rad_Acc")

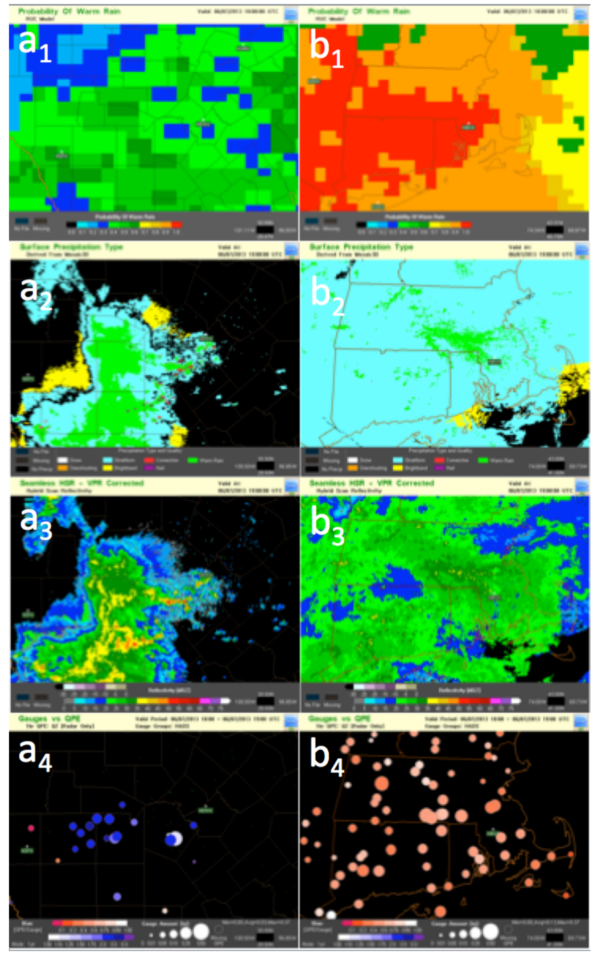

Figure 9 The POWR fields valid at 19:00UTC on 9 June 2013 in south Texas (a_1) and northeastern US (b_1), Corresponding NMQ surface precipitation type (a_2 and b_2), SHSR (a_3 and b_3), and bias ratio maps of the hourly NMQ radar QPE vs. gauges (a_4 and b_4) are also shown.

The MRMS surface precipitation rate at each grid point is computed based on the following relationships:

Warm and cold stratiform rain:

$$R_{stra} = max\ \{0.0365 \bullet Z^{0.625},\ 0.1155 \bullet Z^{0.5}\} \quad (4)$$

Convective rain and hail:

$$R_{conv} = 0.017 \bullet Z^{0.714} \quad (5)$$

Snow:

$$R_{snow} = 0.1155 \bullet Z^{0.5} \quad (6)$$

Here, Z represents the radar reflectivity in $mm^6\ m^{-3}$), and R represents rain rate [Eqs. (4)–(5)] or snow water equivalent [Eq. (6)] in $mm \bullet hr^{-1}$.

Currently the two stratiform categories use the same R-Z relationships. A study on the spatial and temporal variability of R-Z relationships in the CONUS is ongoing. The categories are kept separate for potential R-Z scheme changes in the future. Both stratiform rain rates are currently capped at $48.6\ mm \bullet hr^{-1}$; the convective is capped at $103.8\ mm \bullet hr^{-1}$ and hail at $53.8\ mm \bullet hr^{-1}$.

The tropical/stratiform mixed rain rate, R_{tsmix}, is calculated as follows:

$$R_{tsmix} = \frac{\alpha \cdot w_{trop} R_{trop} + w_{stra} R_{stra}}{w_{trop} + w_{stra}} \quad (7)$$

$$w_{trop} = \begin{cases} 0; & POWR \le p_1 \\ \dfrac{POWR - p_1}{p_2 - p_1} & p_1 < POWR < p_2 \\ 1; & POWR \ge p_2 \end{cases} \quad (8)$$

$$w_{stra} = 1 - w_{trop} \quad (9)$$

Here, R_{stra} represents a stratiform rain rate computed from Eq. (4) and $R_{trop}=0.010 \bullet Z^{0.833}$ represents a tropical rain rate (capped at $147.4\ mm \bullet hr^{-1}$). w_{stra} (w_{trop}) represent the weights given to the stratiform (tropical) rain rates. p_1 and p_2 are adaptable *POWR* thresholds (default values are 0.5 and 0.7, respectively). The tropical rain rate multiplier, α, is defined as follows:

$$\alpha = \begin{cases} 1; & POWR \le p_3 \\ \dfrac{POWR - p_3}{p_4 - p_3} & p_3 < POWR < p_4 \\ 1.5; & POWR \ge p_4 \end{cases} \quad (10)$$

α values can very from 1.0 to 1.5 based on the POWR values and the month of the year. p_3 and p_4 are also adaptive parameters (default values are 0.75 and 1.0, respectively). The tropical/convective mixed rain rate, R_{tcmix}, is calculated in the same way as in Eq.(7), except that R_{stra} is replaced by R_{conv}.

It is noted that Eqs.(7) – (10) are used for tropical/stratiform and tropical/convective rain rates in areas east of 100W longitude, because the POWR was derived using data from the eastern US only. West of 102W, the rates are simply set to R_{trop}. In the transition zone of 102 – 100W, a linear ramping of the two rates (i.e., R_{trop} and R_{tsmix}, or R_{trop} and R_{tcmix}) is applied to assure the continuity of the rate field. This scheme may be modified in the future when a new POWR product become available for the western US.

The radar-based precipitation rate field ("Q3rad_rate") is calculated every 2 min. The 1-h accumulation ("Q3rad_1h") is computed every 2 min by aggregating the rate fields. Longer-term accumulations are then derived from the hourly accumulations at different update cycles. Table 1 summarizes the key products in the MRMS QPE system.

2.8 Gauge Data Quality Control

A multi-sensor gauge QC algorithm (Qi and Zhang 2014) is developed to censor the hourly gauge reports used in the MRMS system. The scheme is based on the consistency between a gauge report and the co-located Q3rad_1h value. The QC criteria are based on the Radar QPE Quality Index (RQI, Zhang et al. 2012b). The RQI product represents radar beam sampling characteristics (blockage, beam height and width) and their relationships with respect to the freezing level. The RQI value decreases with increasing beam height and with increasing blockages. It varies from 1 below the bright band bottom to 0 where the radar beam overshoots the cloud top.

The first step of the gauge QC checks the consistency of precipitation vs. no-precipitation events in a gauge observation and the co-located Q3rad_1h. The check is only applied when the RQI value is higher than 0.5. This assures that the radar observation is relatively close to the ground and provides a reliable information on the extent of precipitation area. If Q3rad_1h indicates precipitation (> 0.01 in) but the gauge report does not, or the other way around (i.e., Q3rad_1h = 0 but gauge report > 0), then the gauge report is considered bad and removed. These simple quality checks can effectively remove "stuck" gauges that report constant zero and gauges that report false precipitation in a clear air environment (e.g., in a situation when unheated gauges report precipitation from the melting snow after the precipitation has ended).

The second step is a "sanity" check on the gauge reports that indicate non-zero precipitation while the co-located Q3rad_1h estimates are also positive. In the sanity check, Q3rad_1h is converted into reflectivity values using all Z-R relationships (see section 2.7) and the minimum and maximum reflectivities (Z_{min}, Z_{max}) are recorded. The reflectivities are then converted back into precipitation rates using the Z-R relationships and the lowest and highest precipitation rates (R_{min}, R_{max}) are obtained. If the gauge report is below 0.8*R_{min} or above 1.2*R_{max}, then it is removed. The multipliers (0.8 and 1.2) are used to relax the criteria and to allow a maximum retention of good gauges.

2.9 Local Gauge Bias Corrected Radar QPE (Q3GC) and the Mountain Mapper (Q3MM)

No major changes are made to the local gauge bias correction of the radar QPE ("Q3GC") and the gauge and precipitation climatology merged QPE called "Mountain Mapper" ("Q3MM") (Zhang et al. 2011), except that a gauge data QC (see section 2.8) is applied before the two processes. In addition, the interpolation weighting function applied in the local gauge bias correction (Zhang et al. 2011) is now output as a new product called "Gauge Influence Index" (GII).

Table 1 List of Key MRMS Precipitation Products

ID	Unit	Update Cycle	Description
SHSR	dBZ	2 min	Seamless hybrid scan reflectivity
SHSRH	km above ground	2 min	Height of SHSR
RQI	none	2 min	Radar QPE quality index
POWR	none	1 hr	Probability of warm rain
PCP_FLAG	none	2 min	Surface Precipitation type
PCP_RATE	mm/hr	2 min	Surface Precipitation rate
Q3RAD_SHSR_1H	mm	2 min	radar-based 1-hr precipitation accumulations
Q3RAD_SHSR_3 (6, 12, 24)H	mm	1 hr	radar-based 3 (6, 12, 24)-hr precipitation accumulations
Q3RAD_SHSR_48 (72)H	mm	Daily at 12Z	radar-based 48 (72)-hr precipitation accumulations
Q3GC_SHSR_1 (3, 6, 12, 24)H	mm	1 hr	1 (3, 6, 12, 24)-h local gauge corrected radar precipitation acc.
Q3GC_SHSR_48 (72)H	mm	Daily at 12Z	48 (72)-hr local gauge corrected radar precipitation accumulations
GII	none	1 hr	Gauge influence index
Q3GAUGE_1 (3, 6, 12, 24)H	mm	1 hr	1 (3, 6, 12, 24)-h gauge-based precipitation accumulations
Q3GAUGE_48 (72)H	mm	Daily at 12Z	48 (72)-hr gauge-based precipitation accumulations
Q3MM_1 (3, 6, 12, 24)H	mm	1 hr	1 (3, 6, 12, 24)-h Mountain Mapper precipitation accumulations
Q3MM_48 (72)H	mm	Daily at 12Z	48 (72)-hr Mountain Mapper precipitation accumulations

3. Summary and Future Work

The National Mosaic and Multi-sensor QPE (NMQ) system at the National Severe Storms Lab (NSSL) has been upgraded with polarimetric radar techniques and merged with the Warning Decision Support System – Integrated Information (WDSS-II) to form a new system called "Multi-Radar Multi-Sensor" (MRMS). The MRMS system will be transitioned into the NWS operations at the National Center for Environmental Predictions in 2014. The system ingests data from ~180 radars, ~17000 hourly and daily gauges and the hourly RAP model analyses. It provides a suite of severe weather and QPE products at 1km resolution and 2min update cycle. This paper provides an overview of the initial operating capabilities of the MRMS QPE and the key products are listed in Table 1.

The MRMS products are routinely evaluated in real-time over CONUS in the research system running at the NSSL. The evaluations and feedbacks from the operational forecasters provide guidance for the enhancement of the system. The research MRMS system also serves as a testbed for advanced techniques and facilitates an effective science-to-operations transfer of the new techniques.

The ongoing research and development efforts for the MRMS product enhancement include:

1) the quantitative precipitation estimation based on the specific attenuation field derived from polarimetric radar observations;

2) a vertical profile of reflectivity correction to improve the radar QPE accuracy for orographic precipitation and for surface rainfall estimates in areas where radar beam overshoots the melting layer;

3) a winter surface precipitation type classification; and

4) to improve the radar QPE for snow.

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