A real-time algorithm for merging radar QPEs with rain gauge observations and orographic precipitation climatology

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1. Introduction

High-resolution, accurate real-time quantitative precipitation estimates (QPEs) are one of the most important inputs for hydrological predictions and for flood warnings. Rain gauges provide a direct measure of rainfall at a point, which is generally more accurate than remote sensing observations such as those from radar and satellite. However, high-quality rain gauges are expensive to maintain, and their distributions are often too sparse to capture small-scale storms that may produce flash floods. Radar provide precipitation observations with much higher resolutions than do rain gauges, although the radar variable, reflectivity, is an indirect measure of rainfall and radar QPEs are subject to errors in the reflectivity (Z) – rainrate (R) relationship. Further, radar QPEs are subject to range degradation and suffer from blockages in complex terrain, which often result in a poor sampling of orographically enhanced precipitation.

Figure 1 shows a gauge based and a radar based QPE products from the National Mosaic and QPE (NMQ) system (Zhang et al. 2011) for a convective storm event occurred in the central Unites States. Both QPEs are compared with independent 24-hr rainfall observations from the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS; www.cocorahs.org). The rainfall distributions are remarkably different in the two products where the radar-based rainfall showed much more small-scale structure than did the gauge field (Figs. 1a vs. 1c). The radar QPE compared well with the gauge observations (~10% underestimation and a 0.75 correlation coefficient) while the gauge QPE resulted in a significant underestimation (50% underestimation and a 0.3 correlation coefficient).

Figure 2 shows the same fields as in Fig.1 but for a cool season stratiform event in the Pacific Northwest. In this case both QPEs underestimated the rainfall (25% for radar and 21% for gauge QPE). The radar QPE suffered severe blockages due to the complex terrain. The gauge QPE appeared to be more continuous than the radar QPE, although the circular patterns around rain gauge locations may not be physical. A gauge and orographic precipitation climatology-combined product called "Mountain Mapper" (MM) (Schaake et al. 2004; Zhang et al. 2011) produced a better rainfall field (Fig.3) than both aforementioned QPEs, reducing underestimation to 9%. The bias ratio maps of the three QPEs (Figs. 4a, 4b, and 4c) indicated that major improvements in the MM field came from the precipitation climatology in the southwest coastal region of Oregon State (white/black circles in Fig.4). The radar QPE had worst underestimation in that area (Fig. 4a) due to poor coverage and beam overshooting cloud tops. The gauge QPE also had significant underestimation (Fig.4b) due to the sparseness of the hourly rain gauges (Fig.4d) used in the gauge QPE.

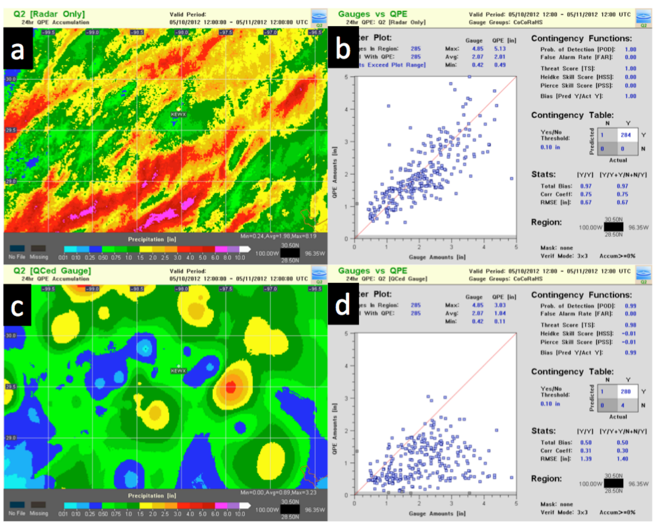

Fig. 1 Daily rainfall maps from the NMQ radar- (a) and gauge-based (c) QPEs and their comparisons with CoCoRaHS gauges (b and d, respectively). The data were for 24 hour ending at 12:00 UTC on 11 May 2012.

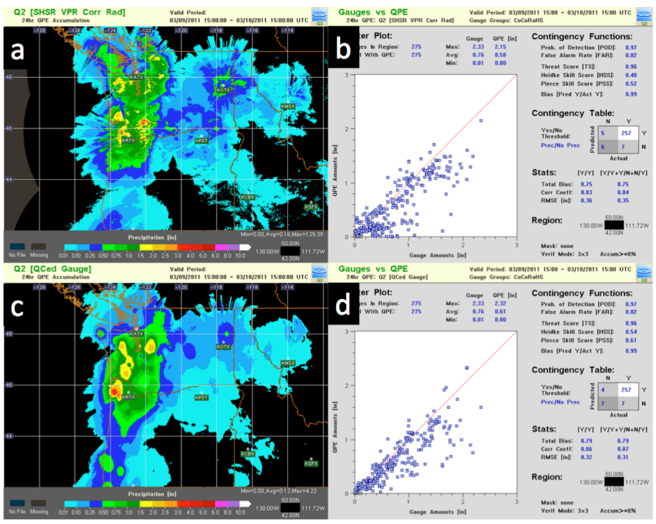

Fig. 2 Same as in Fig.1 but for 24 hour ending at 15:00 UTC on 10 March 201

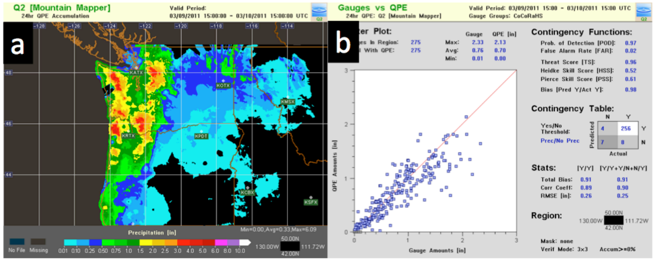

Fig. 3 Daily rainfall map (a) from the NMQ Mountain Mapper QPE and its comparison with CoCoRaHS gauges (b). The data were for 24 hour ending at 15:00 UTC on 10 March 2011.

The current study aims to develop a radar, rain gauge, and orographic precipitation climatology combined QPE within the NMQ system. It takes advantages of each component and provides a new product that's potentially superior to each individual QPEs. In the merged product, the radar QPE provides a high-resolution depiction of spatial precipitation distributions, rain gauges provide accurate measurements that can calibrate potential biases in the radar QPE. The orographic precipitation climatology, namely the monthly precipitation product from Precipitation-elevation Regressions on Independent Slopes Model (PRISM, Daly et al. 1994; www.prism.oregonstate.edu/), provides a background rainfall distribution where radar coverage is poor and where the orographic enhancement of precipitation is dominant. The merging methodology is based on error characteristics of each component, and the weighting scheme is based on radar quality index (RQI, Zhang et al. 2012), surface precipitation type, and freezing level height. The merging algorithm is fully automated and can be easily implemented in an operational system. The algorithm was tested on several heavy precipitation events in different areas of the United States and the two typical events are presented herein.

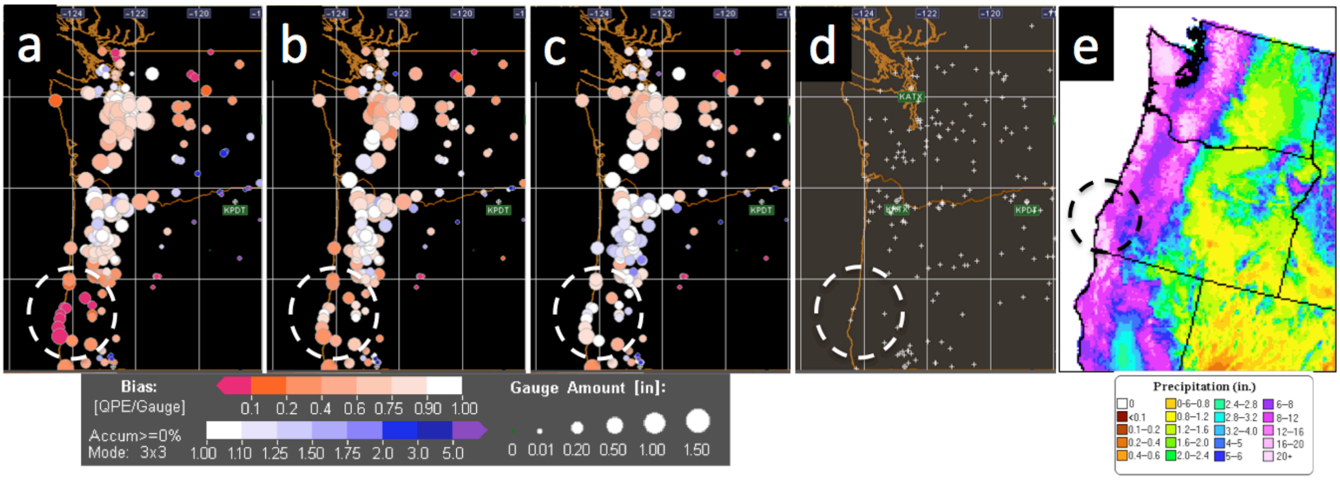

Fig. 4 QPE vs. gauge bias ratio maps from radar- (a) and gauge-based (b) QPEs and the MM (c). Both the gauge-based and MM QPEs used hourly gauge stations shown as the "+" in panel d. The PRISM December monthly precipitation climatology (used in MM) is show in panel e. The size of the circles in the bias ratio maps represents the 24-hr CoCoRAHS gauge amounts and the color represents the QPE bias (red means underestimation and blue means overestimation).

2. Methodology

The radar, gauge, and precipitation climatology merged product is derived by combining two existing hourly precipitation products from the NMQ system, one is the radar-based QPE ("Q2rad") and another the Mountain Mapper ("Q2MM"), both are described in Zhang et al. (2011). The original "Q2rad" has an automated precipitation classification scheme based on 3D reflectivity structure and atmospheric environmental data. At each grid cell precipitation was classified as one of five types: stratiform rain, convective rain, hail, tropical rain, and snow. Different Z-R relationships are applied pixel-by-pixel based on precipitation types to obtain an instantaneous precipitation rate field, and the rate fields are aggregated into hourly accumulations. In the current study, an enhanced version of Q2rad was used, in which a vertical profile of reflectivity (VPR) correction (Zhang and Qi 2010) was applied to mitigate errors associated with bright band and with the beam sampling above the melting layer.

Q2MM product was derived from hourly gauge observations from Hydrometeorological Automated Data System (HADS; www.nws.noaa.gov/oh/hads/WhatIsHADS.html) and monthly precipitation climatology from PRISM. At each gauge station the gauge/climatology ratio is computed, and the ratio is interpolated onto a regular 1-km x 1-km grid. The interpolated ratio field is multiplied by the climatology and a Q2MM hourly rainfall map is obtained.

At each grid point, the merged hourly precipitation, called "Q2RM", is computed based on a set of heuristic rules (decision tree) as shown in Fig. 5. The merged Q2RM QPE is set to Q2MM in areas within a radius of gauge stations. The radius is a function of precipitation type. For instance, the default radius of influence is 10 km for stratiform precipitation and 5 km for convective. Q2MM also dominates Q2RM in areas where RQI is very low (e.g., less than 0.1) and where radar coverage is considered poor. On the other hand, the precipitation/no precipitation boundary is determined by Q2rad as long as RQI is greater than a threshold (default = 0.1), because radar provides a continuous spatial coverage of precipitation when it is not completely blocked. Away from gauges, the merged Q2RM QPE is set to Q2rad in areas of convective and tropical rain whenever the freezing level is relatively high. This is based on the fact that radar samples warm season deep-cloud precipitation quite well. "Q2rad" is also given a large contribution to the merged Q2RM QPE when the precipitation is frozen (snow, sleet), because majority of the HADS gauges used in Q2MM are not heated and can not provide realizable observations when the temperature is below freezing.

In areas far away from gauges and with moderate radar QPE quality, a weighted mean of the "Q2rad" and Q2MM is computed. The weights are a function of three longitudinal zones: west coast, Rocky Mountains, and eastern US. The west coast zone covers 125 – 115W. In this region, most of the precipitation falls in cool season and the heaviest is associated with large moisture influx from the Pacific, a phenomena known as the "atmospheric river" (e.g., Ralph and Dettinger 2012; Ralph et al 2004). The complex topography in this zone plays an important role in modulating the rainfall distribution, and such orographic influence is captured well in the PRISM precipitation climatology. The radar network, on the other hand, suffers from severe blockages in majority of the area. Many radars were placed on mountaintops to avoid blockages, although such siting choices resulted in radar beam overshooting cloud tops frequently. Based on these factors, the Q2MM component is given a dominant weight (default = 0.9) in this zone and the "Q2rad" is allowed a relatively small contribution (default weight = 0.1).

The Rocky Mountains zone covers 115 – 100W. This zone has cool season stratiform precipitation similar to those in the west coast. But it also has convective precipitation in warm season such as those associated with the North America Monsoon (e.g., Adams and Comrie 1997). In this region, Q2MM is given a high weight (0.8) and Q2rad a low weight (0.2) for stratiform precipitation. Q2rad still dominates for warm season convective precipitation based on the heuristic rules mentioned above. The eastern US zone covers 100 – 60W. In this region, warm season deep convections, mesoscale convective systems, and tropical storms/hurricanes yield major portion of the annual precipitation. The topography is flat (except for the Appalachian Mountains) in this zone and radar can provide very good coverage for convective and tropical storms. Therefore Q2rad is given a dominant weight (0.9) and Q2MM's influence is minimized (default weight =0.1).

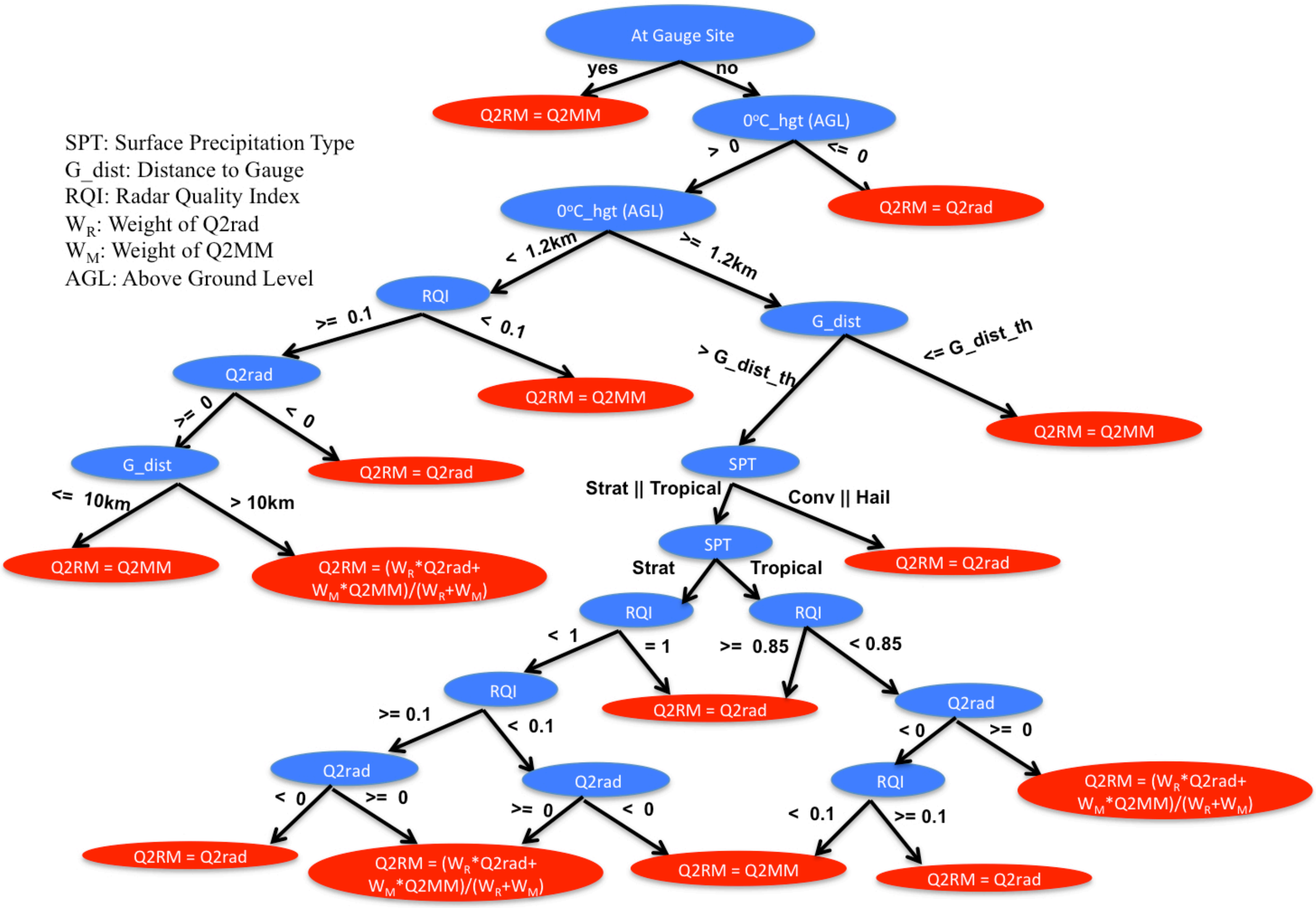

Fig. 5 Final decision tree for generating Q2RM.

3. Case Study Results

The new merged QPE algorithm was tested on several heavy rain events and two representative ones are presented here. Figure 6 shows Q2rad, Q2MM, and Q2RM QPEs for a winter event that occurred on 10 March 2011 in the Pacific Northwest. Q2rad had the largest bias (24% underestimation) and root mean square error (8.89mm) when compared with the daily CoCoRAHS gauge observations. The underestimation (red dots in Fig.6c_1) was most pronounced in areas with blockages and with beam overshooting cloud tops (Fig.6a$_1$). Further, beam blockages had resulted in many discontinuities in the Q2rad precipitation map (Fig.6a$_1$), which are non-physical and problematic for any hydrological applications. Q2MM had much less bias (+4%) and RMSE (5.89mm) than did the Q2rad. The merged product had slight improvements over Q2MM and provided a much more physically consistent rainfall distribution than Q2rad.

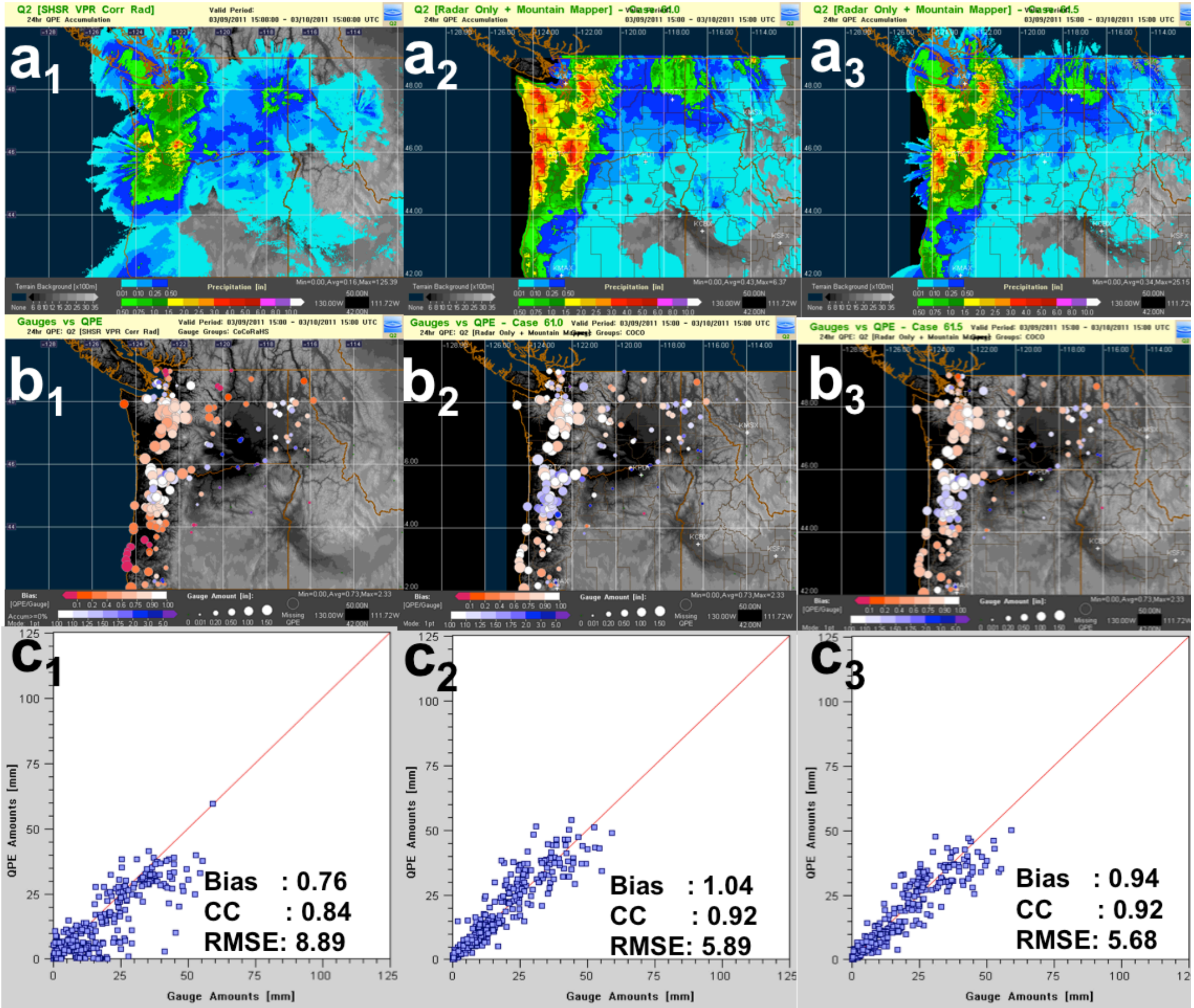

Fig. 6 Daily (a$_1$) Q2rad, (a$_2$) Q2MM and (a$_3$) Q2RM estimated precipitation accumulations ending at 1500 UTC 10 March 2011 in the Pacific Northwest. Bubble charts show bias ratios between (b$_1$) Q2rad, (b$_2$) Q2MM and (b$_3$) Q2RM QPEs and CoCoRAHS gauge observations, where the size of the circles represents the gauge-observed rainfall amount and the color shows the bias. Scatterplots show distributions of the 24-h (c$_1$) Q2rad, (c$_2$) Q2MM and (c$_3$) Q2RM QPEs vs. the gauge observations.

Figure 7 shows the same QPE products as shown in Fig.6, but for a warm season convective storm that occurred in central US on 9 Oct. 2011. For this event, Q2rad had 32% overestimation due to erroneous classifications of tropical rain. Q2MM had 17% underestimation due to insufficient gauge density to capture some heaviest but small scale convective precipitation. By merging the two products, the overestimation in Q2rad was corrected by the gauge component in Q2MM, and the gaps between gauges in Q2MM was filled with Q2rad. The merged product had much less bias (-3%) than that of Q2rad (+32%) and Q2MM (-17%) and retained high-resolution precipitation structure captured by Q2rad. It also resulted in less RMSE (9.92mm) than Q2rad (22.87mm) and Q2MM (21.02mm). Such improvements will greatly benefit hydrological predictions and flashflood warnings.

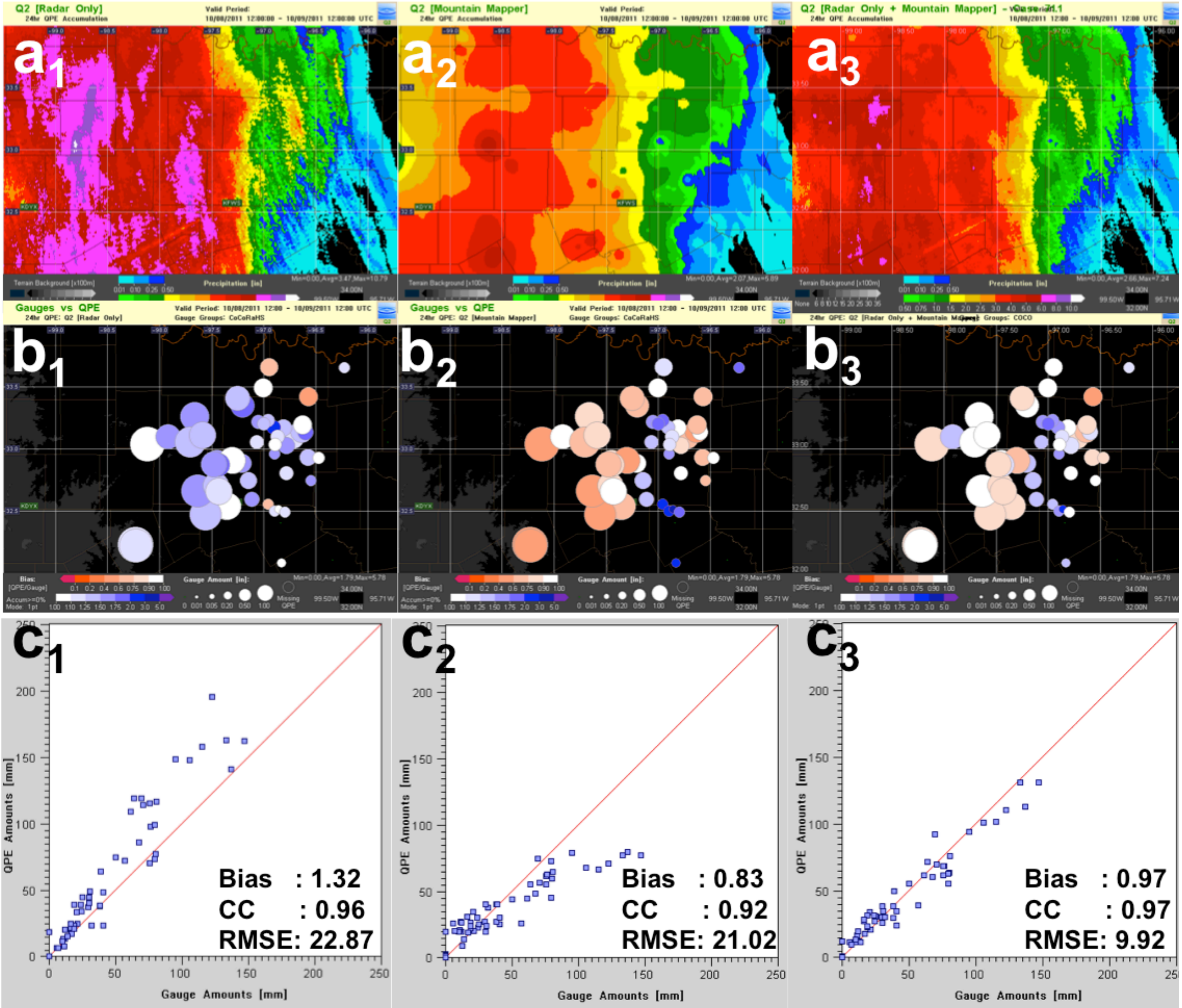

Fig. 7 Same as in Fig.6 except for 24-hr rainfall ending at 1200 UTC 09 Oct 2011 in the central US, and Q2rad instead of Q2rad.

4. Summary

A radar, gauge, and orographic precipitation climatology combined QPE product was developed. The new product was based on the NMQ hourly radar QPE and the Mountain Mapper QPE. A set of heuristic rules was developed to merge the two QPEs at each grid point every hour. The merging rules and weighting functions are based on the error characteristics of each component. For instance, the MM QPE has higher weights than does the radar QPE in complex terrain and in areas where the radar beam is severely blocked or is much higher than the freezing level (overshooting). The MM also has higher weights in the close vicinity of gauge stations. The radar QPE has dominant weights in flat lands and in warm season convective rain.

The new algorithm was tested for several heavy precipitation events from different areas of the US, and the merged product showed improvements over the individual QPE components. In the Pacific Northwest, the merged product reduced the underestimation in the radar QPE and provided a spatially continuous rainfall map without the blockage discontinuities. In the central US, the merged product reduced the radar QPE overestimation due to inaccurate tropical rainfall identification while retained the small-scale structure of convective storms. The current weighting function is based on longitudinal zones. Future work will include refining the weighting scheme based on topography. The new algorithm is fully automatic and computationally efficient. It will be implemented in the real-time NMQ system for evaluations over conterminous United States and southern Canada for all seasons.

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