Radar Quality Index (RQI) – a combined measure for beam blockage and VPR effects in a national network

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Abstract The next-generation multi-sensor quantitative precipitation estimation (QPE), or "Q2", is an experimental hydrometeorological system that integrates data from radar, raingauge, and atmospheric models and generates high-resolution precipitation products on a national scale in real-time. The quality of the Q2 radar QPE varies in space and in time due to a number of factors, which include: (1) errors in measuring radar reflectivity; (2) segregation of precipitation and non-precipitation echoes; (3) uncertainties in *Z–R* relationships; and (4) variability in the vertical profile of reflectivity (VPR). In the current study, a Radar QPE Quality Index (RQI) field is developed to present the radar QPE uncertainty associated with VPRs. The RQI field accounts for radar beam sampling characteristics (blockage, beam height and width) and their relationships with respect to the freezing level. A national RQI map is generated by mosaicking single radar RQI fields. The radar quality information is useful to hydrological users and can add value in radar rainfall applications.

Key words radar QPE quality; beam blockage; VPR, national radar network

INTRODUCTION

The Next-Generation multi-sensor QPE ("Q2", Vasiloff *et al.* 2007; Zhang *et al.* 2011) is an experimental hydrometeorological system that integrates data from radar, raingauge, and atmospheric models and generates high-resolution precipitation products on the national scale in real-time. One of the Q2 products is the radar-based precipitation estimation (called "Q2rad" hereafter), which is generated by mosaicking precipitation fields derived from individual radars in the United States Weather Surveillance Radar – 1988 Doppler (WSR-88D) network. The Q2rad process includes reflectivity quality controls to remove non-precipitation echoes and a precipitation classification to segregate convective, stratiform, hail, tropical rain, and snow in radar reflectivity fields. Different Z-R relationships are applied for different precipitation types. The Q2rad products are generated for the Conterminous United States (CONUS) every 5-min and has a spatial resolution of ~1 km. The product suite contains precipitation rate, and 1- to 72-h accumulations.

The quality of the Q2rad product varies in space and in time due to a number of factors, which include: (1) errors in measuring radar reflectivity, e.g. the calibration bias; (2) contaminations from non-precipitation echoes, e.g. ground clutter due to anomalous propagations; (3) uncertainties in *Z–R* relationships; and (4) variability in the vertical profile of reflectivity (VPR). The radar QPE error due to factor (1) can be minimized through a close monitoring and vigorous maintenance of the radar network. Radar QPE errors due to factor (2) may be minimized with dual-polarization capabilities (e.g. Ryzhkov *et al.* 2005; Park *et al.* 2009). The uncertainty associated with Z-R relationships can be significant, and the understanding of this uncertainty requires observations of drop size distributions in different precipitation regimes. The error associated with Z-R uncertainties is expected to decrease with dual-polarization capabilities as well since additional radar variables can be used for hydrometeor classifications (e.g., Ryzhkov *et al.* 2005; Giangrande & Ryzhkov, 2008).

The radar QPE uncertainty associated with VPRs is closely related to sampling strategies of scanning radars and may not be reduced by the dual-polarization capabilities. Specifically, this uncertainty is related to the height and width of radar beams as well as their relationships with the vertical structure of precipitation. The current study attempts to develop a real-time national Radar QPE Quality Index, or RQI, that can represent relative qualities of the radar QPE in space and in time. One objective is to use the RQI field as a weighting factor when merging the radar QPE with other QPEs on the national scale. Previous studies such as Pellarin *et al.* (2002) had attempted to quantify radar QPE errors by modelling VPR effects. However, uncertainties still exist with the models given assumptions about the spatial uniformity of the VPR. For practical reasons of a real-time and national implementation, a simple mathematical formulation similar to Friedrich *et al.* (2006) is adapted in the current study.

The mathematical formulation of the RQI is described in the next section. Then example RQI fields and their relationships with the radar QPE accuracy in a national network are presented. A summary and discussions about the future work are provided in the last section.

METHODOLOGY

The dependency of radar QPE accuracies on VPRs is illustrated in Fig. 1. Assuming an idealized stratiform precipitation is horizontally uniform and produces the same amount of rainfall everywhere at the surface. Then the VPR (blue lines in Fig. 1) of the precipitation is also horizontally uniform. It has a negative dZ/dh slope in the ice region, a peak (bright band) near the freezing level and a zero dZ/dh slope below the bright band.

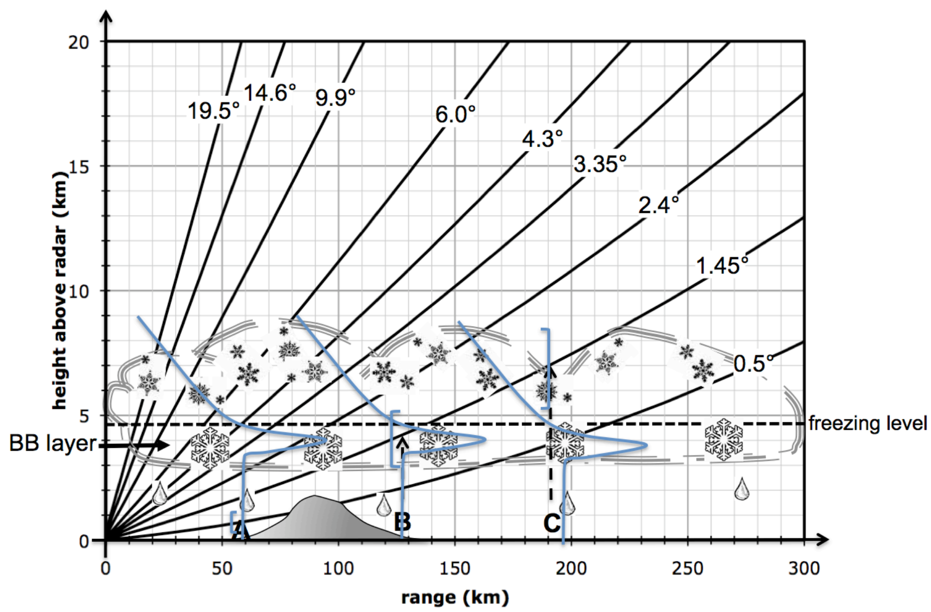

Fig. 1 Illustration of scanning radar sampling issues for stratiform precipitation in complex terrain. The blue lines represent the VPR of the precipitation. The radar is located at the origin, and the bold black lines represent axis of various radar tilts. The numbers denote the corresponding elevation angles. The blue square brackets represent the 3-dB beam widths of the 1st tilt at point A, and the 2nd tilt at points B and C.

Assuming a radar is located at the origin and scans in a mode with nine elevation angles (Fig. 1). At point A, radar data from the 1st tilt is used to estimate rainfall. At points B and C, radar QPEs are derived from the 2nd tilt because of a significant blockage in the 1st tilt at ~80–100 km range. Assuming an accurate Z-R relationship is applied to the unblocked radar reflectivity closest to the ground, the radar rainfall estimate at point A would be accurate. However, the radar QPEs at point B would be overestimating because the data was obtained within the bright band. At point C, the radar QPE would be underestimating due to (1) the decreasing of reflectivity in ice region and (2) the radar beam is partially overshooting the cloud top.

Partially blocked data are commonly used for radar QPEs if the blockage is not significant (e.g., data with up to 60% blockages are used in the operational WSR-88D radar QPE after a blockage correction is applied; see Fulton *et al.* 1998). The amount of blockages is usually pre-determined using static terrain data assuming a standard atmospheric refraction condition. When anomalous propagation occurs, the actual blockage can be much different than the pre-calculated and the radar QPE quality could be degraded.

Based on the discussions above, the RQI field is developed using two simple mathematical formulations:

$$RQI = RQI_{blk} \cdot RQI_{hgt} \tag{1}$$

$$RQI_{blk} = \begin{cases} 1; & blk \le 10\% \\ \left(1 - \dfrac{blk - 0.1}{0.4}\right); & 10\% < blk \le 50\% \\ 0; & blk > 50\% \end{cases} \tag{2}$$

$$RQI_{hgt} = \begin{cases} 1; & h_{0C} > D_{bb} \cap h_a < h_{0C} - D_{bb} \\ \exp\left[-\dfrac{(h_a - h_{0C} + D_{bb})^2}{H^2}\right]; & h_{0C} > D_{bb} \cap h_a \ge h_{0C} - D_{bb} \\ \exp\left[-\dfrac{{h_a}^2}{H^2}\right]; & h_{0C} \le D_{bb} \end{cases} \tag{3}$$

The variables in equations (1) to (3) are defined as: RQI_{blk}: RQI based on blockages (dimensionless); RQI_{hgt}: RQI based on radar beam height (dimensionless); h_a: height of the beam axis (in metres above radar level [m ARL]); h_{0C}: height of 0°C (in m ARL); D_{bb}: depth of the bright band layer (in meters; default = 700 m); *blk*: beam blockages (dimensionless; a value of 0.5 is equivalent to a 50% power blockage); *H*: a height scale factor (in metres; default = 1500 m).

The simple linear and exponential functions are chosen because of their computationally efficiencies for real-time implementation in a national system. The formulations represent the general characteristics of the radar QPE errors (~0–1st order) associated with the blockages and VPR effects. At any given time, the errors are generally larger in areas with low freezing levels than those with high freezing levels, and the errors are generally larger in complex terrain (large blockages) than in flatlands (no blockages). However, the current RQI does not provide a direct quantitative measure of radar QPE errors. To obtain a quantitative relationship between the two, radar QPE error fields will be derived through comparisons with gauge observations. The error fields will be compared with the RQI fields and quantitative relationships are developed. The advantage of the RQI product is that it is generated every 5-min in real-time, and each radar precipitation rate field has an associated RQI field. Range-dependent bias maps derived from long-term VPRs may not be useful for such small time scales.

RQI PRODUCTS FROM A NATIONAL NETWORK

Radar QPEs are commonly calculated from the lowest radar bins that are not significantly blocked. Those bins constitute a 2-D polar grid called "hybrid scan" (O'Bannon 1997; Fulton *et al.* 1998). Figure 2 shows an example of such hybrid scan from KDAX radar located in northern California, USA. Due to the complex terrain (Fig. 2(a)) around the radar, there exist significant blockages on the lowest two elevation angles (Fig. 2(b),(c)) of the WSR-88D radar Volume Scan Pattern (VCP) #12 (http://www.ofcm.gov/homepage/text/pubs.htm: Federal Meteorological Handbook no. 11).

Thus the hybrid scan for VCP 12 (Fig. 2(d)) of this radar consists of data from the 1st to 3rd tilts.

Example RQI fields from a single radar (KDAX) are shown in Fig. 3. The RQI_{blk} (Fig. 3(a)) does not change with time as long as the radar scanning strategy remains the same. On the other hand, RQI_{hgt} can change from volume scan to volume scan because the freezing level height varies with time. A KDAX RQI_{hgt} field on the hybrid scan of VCP 12 and for a freezing level height of 3 km (ARL) is shown in Fig. 3(b). The corresponding *RQI* field (Fig. 3(c)) indicates that the KDAX radar QPE from this time has relatively good quality within 150 km of range along the northwest – southeast direction, which corresponds to the central valley region (Fig. 2(a)). To the east, the high quality range decreases to ~100 km due to some blockages in the region. The radar QPE quality to the west is much poorer than other areas because of severe blockages at ~ 40km west of the radar.

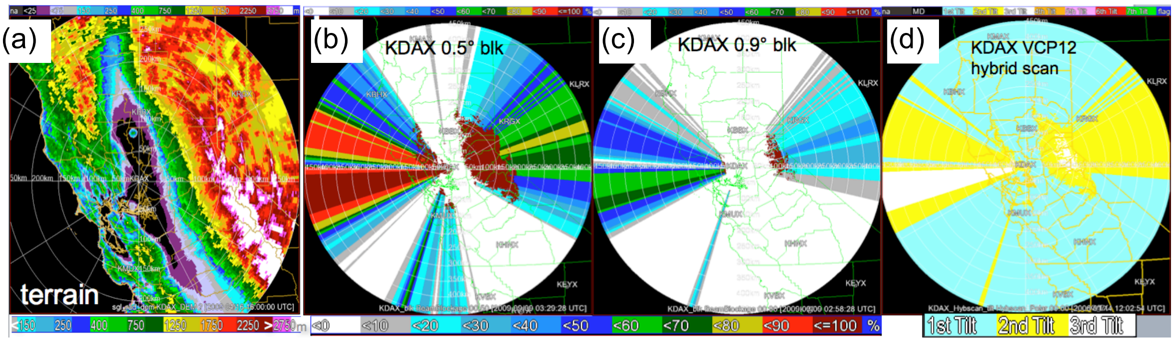

Fig. 2 Terrain height (a) around KDAX radar, and the radar's beam blockages at 0.5 (b) and 0.9° (c) elevation angles. The hybrid scan for VCP 12 is shown in panel (d). The radar site is located at the centre of each image.

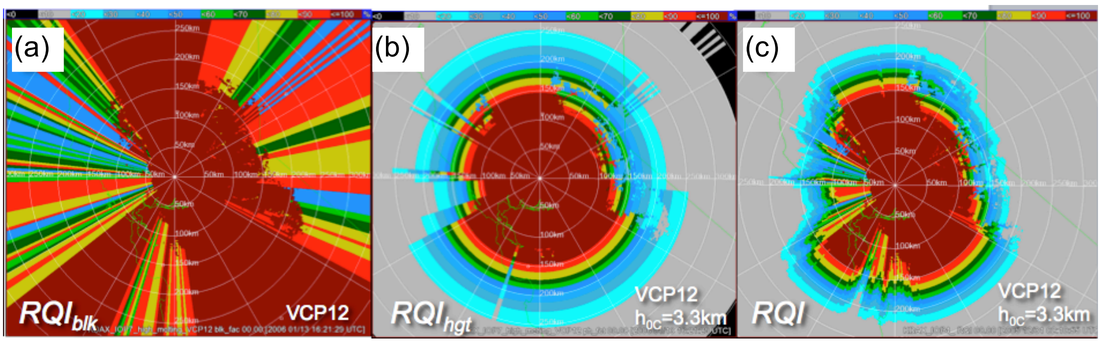

Fig. 3 KDAX RQIblk field for hybrid scans of VCP 12 and RQIhgt (b) for hybrid scan of VCP 12 with a 0°C height of 3.3 km ARL. The corresponding RQI field is shown in panel c, which is valid at 16:21 UTC on 13 January 2006.

Single radar RQI fields from the WSR-88D network are mosaicked in real-time to generate a national RQI product in the Q2 system (nmq.ou.edu). Figure 4 shows two real-time national RQI maps, one valid at 17:00 UTC on 28 August 2010 (Fig. 4(a)) and another at 17:00 UTC on 10 February 2011 (Fig. 4(b)). The corresponding surface temperature fields are shown in Fig. 4(c) and (d), respectively. The two maps clearly show that the radar QPE quality is better in the warm season than in the cool season. Further, apparent radar coverage gaps exist in the western US even in the warm season. The national RQI field is updated every 5-min and reflects the real-time radar QPE quality distributions across CONUS under different synoptic regimes, radar scanning strategies, and even radar outage situations.

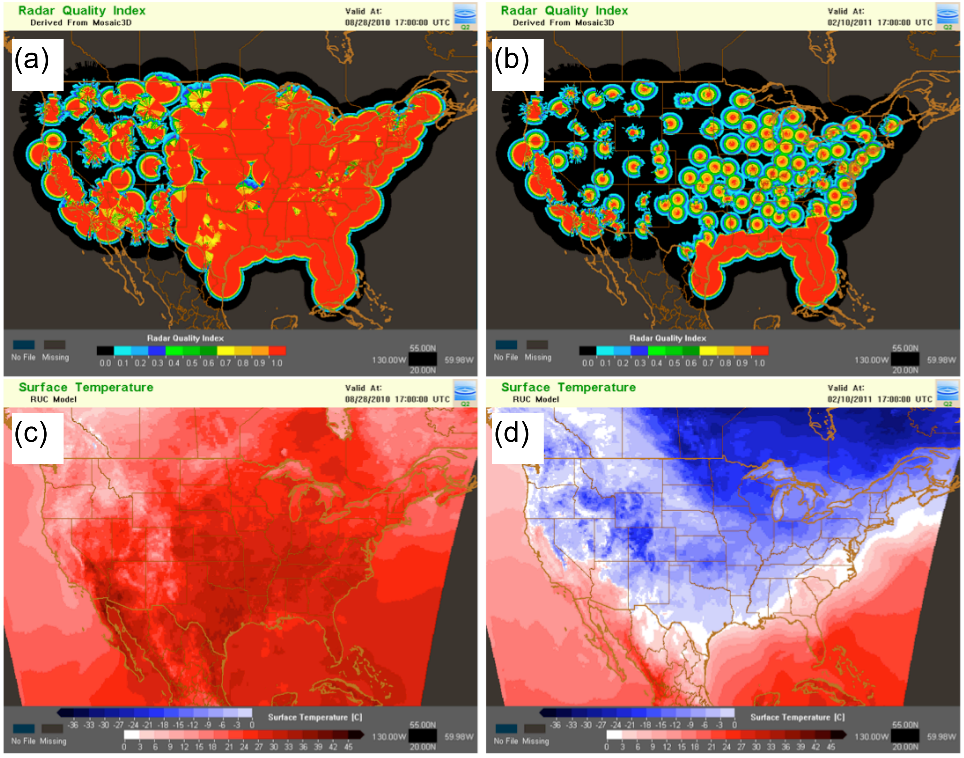

Fig. 4 National RQI fields valid at 17:00 UTC on 28 August 2010 (a) and 17:00 UTC 10 February 2011 (b). The corresponding surface temperature fields are shown in panels (c) and (d), respectively.

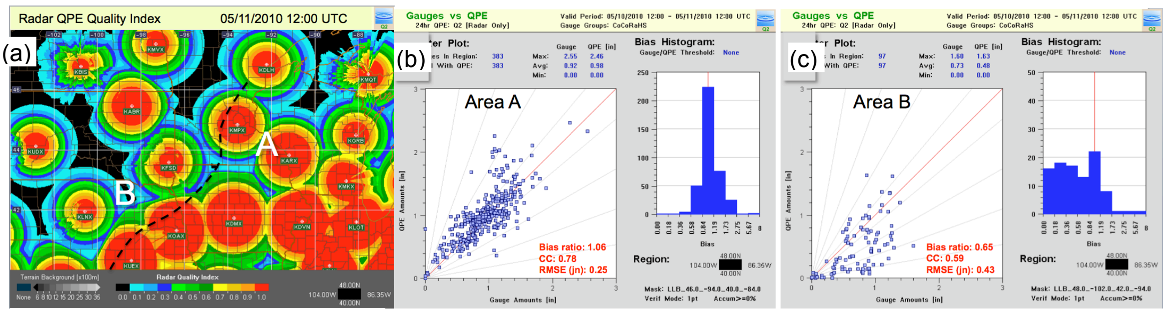

Fig. 5 National RQI field valid at 12:00 UTC on 11 May 2010 (a) and scatter plots of the 24-h radar QPEs ending at 12:00 UTC on 11 May 2010 in areas A (b) and B (c) *vs* gauge observations.

A preliminary evaluation of the Q2 radar QPE accuracy under different RQI distributions indicated a good correlation between the accuracy and RQI. Figure 5(a) shows the RQI field in north central US region during a storm event on 10–11 May 2010. RQI values in the southeast half of the domain (area "A", Fig. 5(a)) are apparently higher than those in the northwest half (area "B", Fig. 5(a)). The difference in the RQI field is reflected in the radar QPE accuracy when the 24-h radar rainfall estimates from the two areas are compared with gauge observations. For area A, the radar QPE average was within 6% of the gauge observed mean, and had a correlation coefficient of 0.78 and a root-mean-square-error (RMSE) of 0.25 in (Fig. 5(b)). For area B, the radar QPE had a 35% underestimation (Fig. 5(c)), and a much lower correlation coefficient (0.59 *vs* 0.78) and larger RMSE (0.43 *vs* 0.25 in) than in area A. Further studies are underway to refine the RQI product and to develop quantitative relationships between the RQI and the radar QPE errors over the CONUS domain.

SUMMARY AND FUTURE WORK

A Radar QPE Quality Index, or RQI, field was developed in an attempt to show relative qualities of the Q2 national radar QPE in different seasons and different regions. The RQI field accounts for radar beam sampling characteristics and their relationships with respect to the atmospheric freezing level. A national RQI map is generated in real-time with 1-km resolution and 5 minute frequency. The RQI field reflects the real-time radar QPE accuracies associated with synoptic environments, radar scanning strategies, and even radar outage situations. It also shows radar coverage voids and provides guidance for the deployment of gap-filling radars.

Future work will include the development of a quantitative relationship between the RQI and the Q2 radar QPE errors. Rainfall data from a national gauge network will be quality controlled and radar QPE errors with respect to the gauge observations are derived. The error distributions will be compared with the RQI fields and quantitative relationships between the two will be developed. The error-related RQI field will provide added values for radar QPE product users. Additionally, the real-time RQI can be used as a weighting factor for the radar QPE when it is merged with QPEs from different sensors (e.g. satellite).

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