Improving WSR-88D Radar QPE for Orographic Precipitation Using Profiler Observations

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ABSTRACT
Quantitative precipitation estimation (QPE) in the West Coast region of the United States has been a big challenge for Weather Surveillance Radar-1988 Doppler (WSR-88D) because of severe blockages caused by the complex terrain. The majority of the heavy precipitation in the West Coast region is associated with strong moisture flux from the Pacific that interacts with the coastal mountains. Such orographic enhancement of precipitation occurs at low levels and cannot be observed well by WSR-88D because of severe blockages. Specifically, the radar beam either samples too high above the ground or misses the orographic enhancement at lower levels, or the beam broadens with range and cannot adequately resolve vertical variations of the reflectivity structure. The current study developed an algorithm that uses S-band Precipitation Profiler (S-PROF) radar observations in northern California to improve WSR-88D QPEs in the area. The profiler data are used to calculate two sets of reference vertical profiles of reflectivity (RVPRs), one for the coastal mountains and another for the Sierra Nevada. The RVPRs are then used to correct the WSR-88D QPEs in the corresponding areas. The S-PROF-based VPR correction methodology (S-PROF-VPR) has taken into account orographic processes and radar beam broadenings with range. It is tested using three heavy rain events and is found to provide significant improvements over the operational radar QPE.

1. Introduction

In the National Mosaic & Multi-Sensor Quantitative Precipitation Estimation (QPE) system (NMQ; http://nmq.ou.edu; Zhang et al. 2011), an apparent vertical profile of reflectivity (AVPR) correction algorithm (Zhang and Qi 2010, hereafter ZQ10; Zhang et al. 2012, hereafter ZQKH12; Qi et al. 2013a,b,c; Qi and Zhang 2013) is used to derive surface precipitation from the Weather Surveillance Radar-1988 Doppler (WSR-88D) network. The AVPRs, one for each tilt, are range profiles of azimuthally averaged reflectivities in predefined brightband (BB) areas and in areas where the radar beam is above the melting layer. For cool season stratiform rain over flat lands, these spatially averaged AVPRs capture the main structure of the bright band very well and provide effective corrections to the BB-induced errors in radar QPEs (ZQ10). Such a profile (AVPR) automatically adapts to the WSR-88D beam propagation path and broadening

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effect with increasing range, prevents any discontinuities in the corrected radar QPE, and simplifies the correction procedure (ZQ10). This AVPR correction system has been running in real time for more than 3 yr, and it provides improvements in radar QPEs over those without the AVPR correction, especially in the cool season stratiform rain over the flat lands. In the complex terrain of the western Unites States, however, the performance of the AVPR correction is mixed.

Joss and Waldvogel (1990) stated that the major source of error in rainfall estimation lies not only in the often-researched area of the relationship between radar reflectivity and rainfall intensity but also in the heterogeneous nature of the vertical reflectivity profile (VPR). The VPR variability arises on a wide range of scales down to that of individual radar pixels (Kitchen and Jackson 1993). Nonuniform VPR is one of the major error sources for cool season radar QPEs, especially in mountainous areas. The error is due to two factors: one is that the radar beam samples too high above the ground and does not observe the orographic precipitation process at lower levels, and the other factor is that the radar beam broadens with range and cannot adequately resolve vertical variations of reflectivity structure at far ranges. Many studies (e.g., Koistinen 1991; Joss and Lee 1995; Germann and Joss 2002; Bellon et al. 2005) have tried to correct for these errors based on radar data observed at close ranges, which was close to the surface and of relatively high vertical resolution. In mountainous areas, however, the VPR structure can change significantly in space because of underlying topography. One mean VPR obtained from data close to the radar may not capture the microphysical processes in areas far away from the radar. This has been a major challenge for obtaining accurate radar QPEs in complex terrain (e.g., northern California).

Andrieu and Creutin (1995) proposed a sophisticated inversion scheme to filter radar sampling effects (i.e., beam broadening as a function of range) and to retrieve a mean VPR over the radar domain from two elevation angles. The scheme was later generalized by Vignal et al. (1999) to retrieve local VPRs over a small area of 20 km × 20 km using multiple elevation angles and was evaluated on Swiss (Vignal et al. 2000) and U.S. (Vignal and Krajewski 2001) radar data. Both evaluations showed that the local VPR approach provided more improvements in radar-derived QPE than the mean volume scan VPRs. However, the local VPR approach is relatively expensive computationally and is not easily implemented for operational applications.

Kitchen et al. (1994) described a correction scheme in which observational data, combined with simple parameterizations of the bright band and low-level orographic growth, were used to construct an idealized reflectivity profile at each pixel. A linear relationship between the area of the brightband peak and the “background” reflectivity factor \( [t]he \) reflectivity in the rain just beneath the bright band, but above any low-level orographic growth (Kitchen et al. 1994, p. 1231) was fitted. Then the fitted relationship was used to correct radar QPE errors, and any correction based on the assumption that a linear relationship exists between the area of brightband peak and background values may incur significant bias errors, particularly where the ratio is very large. In their method, a climatological profile was assumed between the 0°C height and the observed cloud top. Although this assumption gave acceptable results in instances of widespread frontal precipitation similar to those from which the climatology was derived, it gave rise to large bias errors at long ranges if the observed profile deviated significantly from that assumed. The part of the orographic growth below brightband bottom is obtained by Hill (1983) from case studies of gauge data. Kitchen (1997) made some improvements to the correction scheme at long ranges by using radar data from several scan elevations.

ZOKH12 developed a radar-QPE VPR correction scheme for cool season precipitation over the complex terrain of northern California. This scheme includes multiple steps for identifying and removing nonprecipitation echoes, constructing the hybrid scan reflectivity, applying VPR corrections to the reflectivity, and converting the reflectivity into precipitation rates using adaptive Z–R relationships. However, several challenges/issues still remain for WSR-88D QPEs over the mountainous areas. One challenge is the horizontal variation of VPRs, and uneven topography may modulate the BB layer resulting in different BB heights across the radar domain. BB peak heights and intensities will be smeared in the AVPRs after the spatial averaging, and the AVPR correction may not effectively reduce QPE overestimations in BB areas. In other words, the ZOKH12 VPR correction scheme is not suitable for precipitation events where the horizontal variation of precipitation is comparable to or greater than the vertical variation. Another challenge is the underestimation for orographically enhanced precipitation processes. The existing WSR-88D cannot adequately resolve the orographic processes below the freezing level. The current study uses S-band Precipitation Profiler (S-PROF; Ecklund et al. 1999; White et al. 2000; Matrosov et al. 2006) observations from the National Oceanic and Atmospheric Administration (NOAA) Hydrometeorology Testbed 2006 (HMT06; http://hmt.noaa.gov) in the mountainous area of northern California and develops an S-PROF–based VPR correction methodology (S-PROF VPR) that takes into
account orographic processes and radar beam broadenings with range.

The S-PROF-VPR correction technique was tested using three heavy rain events in northern California during the period from 21 December 2005 to 1 January 2006. The S-PROF-VPR corrected radar QPE is compared with ZQKH2012. The new technique was found to provide consistent improvements over the ZQKH2012 QPE for the three heavy rainfall events. The next section describes the data used in the current study, and the S-PROF-VPR correction methodology is introduced in section 3. Case study results are presented in section 4, and section 5 provides a summary.

2. Data

Figure 1 shows the study domain, which extends from 38° to 40°N latitude and 123.5° to 119.5°W longitude, and locations of various observational facilities. During HMT06, three S-PROF radars were deployed in northern California as shown in Fig. 1. Because of hardware problems of the Colfax, California (CFC), profiler, only the data from Cazadero (CZD) near the west coast of California and from Alta (ATA) on the California Sierra Nevada were used in the current study. These profiler radars measure time evolutions of the reflectivity structure along a vertical column with high temporal (1 min) and spatial (60 m) resolution (e.g., White et al. 2000, 2003; Neiman et al. 2005; Kingsmill et al. 2006; Martner et al. 2008; Matrosov et al. 2006). For the WSR-88D QPE, four radars (KBHX, KDAX, KMUX, and KRGX) were used in the current study.

Hourly rainfall observations from the Hydrometeorological Automated Data System (HADS; www.weather.gov/oh/hads/) gauges and the special precipitation-gauge network deployed during HMT06 were used for the evaluation of radar QPEs. Manual quality control was performed to remove unreliable gauge data. The quality control procedures included checking spatial and temporal consistency between neighboring gauge observations. The consistency between time series of hourly gauge data and collocated radar reflectivities were also examined. Gauges with significant inconsistencies with its neighbors and with radar observations were removed from the validation.

3. Methodology

The main objective of the current study is to obtain accurate high-resolution QPEs in northern California, which is divided into three zones from west to east: coastal mountain, central valley, and the Sierra Nevada (Fig. 1). As discussed in ZQKH12, radar QPE errors include: 1) errors in measuring radar reflectivity (e.g., the calibration bias); 2) contamination from nonprecipitation echoes (e.g., ground clutter due to anomalous propagations); 3) uncertainty in radar reflectivity and rain-rate relationships; and 4) variability in the VPR. The
focus of the current study is the VPR-related uncertainties, namely error source. 5) Radar QPE errors associated with nonuniform VPRs include BB contamination (e.g., ZQ10; ZQKH12), radar beam overshooting (e.g., Joss and Waldvogel 1990; ZQKH12), and orographic enhancement (e.g., Kitchen et al. 1994). In ZQKH12, orographic enhancement effects were not accounted for and the VPR below the brightband bottom was assumed a constant. The VPR correction in ZQKH12 showed positive impacts in reducing radar QPE overestimation in the brightband area. It also mitigated the radar QPE underestimation in areas where the radar beam was sampling above the melting layer, although the improvement was small because of 1) less accurate VPR representations at the higher altitudes than within the bright band and 2) radar beam overshooting cloud tops, leaving insufficient information from which the VPR correction could start.

As mentioned earlier, one of the challenges for obtaining accurate WSR-88D radar QPEs in the West Coast region is the lack of high-resolution observations of orographically enhanced precipitation processes at the lower altitudes. S-PROF observations from HMT06 in northern California provided very high-resolution vertical profiles of precipitation process. The current study tries to extract representative vertical structures of orographic precipitation from these profiler data and create a set of “reference” VPRs for different rainfall intensities, then applies the reference VPRs in the WSR-88D QPE to obtain accurate rainfall estimates.

a. Reference VPRs from S-band precipitation profiler data

CZD and ATA S-PROF data from three heavy rainfall events during HMT06 were analyzed. Two events were from intensive operating periods (IOPs), that is, IOP3 (21–22 December 2005) and IOP4 (from 30 December 2005 to 1 January 2006), and one occurred during 27–28 December 2005. To account for potential spatial and temporal variations of precipitation, the S-PROF VPRs for each event are sorted into seven categories with different BB peak intensities varying from 25 to 60 dBZ (Table 1). Each category covers a 5-dB interval (e.g., 25–30, 30–35, and so on). One mean VPR is calculated for each category in the linear reflectivity unit (mm$^6$ m$^{-3}$) and then converted into the logarithm domain (dBZ as shown in Fig. 2). The mean VPRs are then used as the reference VPRs to correct the WSR-88D QPEs. Most of the standard deviations with respect to the mean VPRs are less than 2 dB, showing relatively high similarity of individual VPRs within each category. Mean VPRs are sometimes unavailable for the higher-intensity categories (e.g., the 55–60-dBZ category during 27–28 December 2005) because of insufficient data samples.

Table 1. Number of S-PROF observed reflectivity profiles used to compute the reference VPRs.

<table>
<thead>
<tr>
<th>Event summary</th>
<th>S-PROF</th>
<th>25–30 (VPR No.)</th>
<th>30–35 (VPR No.)</th>
<th>35–40 (VPR No.)</th>
<th>40–45 (VPR No.)</th>
<th>45–50 (VPR No.)</th>
<th>50–55 (VPR No.)</th>
<th>55–60 (VPR No.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOP3 ATA</td>
<td>178</td>
<td>142</td>
<td>256</td>
<td>217</td>
<td>90</td>
<td>37</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CZD</td>
<td>150</td>
<td>161</td>
<td>113</td>
<td>153</td>
<td>124</td>
<td>48</td>
<td>18</td>
</tr>
<tr>
<td>27–28 Dec 2005</td>
<td>ATA</td>
<td>300</td>
<td>211</td>
<td>258</td>
<td>367</td>
<td>158</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>CZD</td>
<td>347</td>
<td>264</td>
<td>145</td>
<td>132</td>
<td>160</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>IOP4 ATA</td>
<td>27</td>
<td>121</td>
<td>245</td>
<td>513</td>
<td>317</td>
<td>61</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CZD</td>
<td>86</td>
<td>127</td>
<td>209</td>
<td>392</td>
<td>305</td>
<td>63</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 2 shows mean VPRs with different BB peak intensities for the selected events. All three events showed evident BB features, even in the weak BB peak categories. ATA VPRs (Figs. 2a,c,e) showed very similar characteristics among three events at the BB peak but quite different below the BB bottom. In IOP4 (Fig. 2e), the negative VPR slope below the BB bottom was greater for the lower BB peak intensities than for the higher ones, with a maximum of 8 dB increase from the BB bottom to the ground for the 25–30-dBZ category (Fig. 2e). When the BB intensity is larger than 45 dBZ, the VPR slope below the BB bottom tends to become zero (Fig. 2a) or even positive (Figs. 2c,e).

Reference VPRs derived from S-PROF CZD observations during the three events are shown in Figs. 2b, 2d, and 2f. An apparent difference was found in the BB peak intensity (i.e., reflectivity difference $\Delta R_z$ between the BB peak and bottom) of the 27–28 December 2005 event (Fig. 2d) compared to the other two. The mean reflectivity difference between BB peak and bottom was about 3–5 dB for the 27–28 December event, while such differences for IOP3 (Fig. 2b) and IOP4 (Fig. 2f) were 5–12 dB. The orographic enhancement of precipitation was apparent for the 27–28 December event, although the negative VPR slope below the BB bottom was relatively small, except for the 40–45 category. The average VPR slope below the BB bottom was about $-0.8$ dB km$^{-1}$.
Such slopes for IOP3 and IOP4 were significantly larger, especially for the reference VPRs of 35–40, 40–45, and 45–50 categories. On average, the reference VPR slopes below the BB bottom for IOP3 and IOP4 were about 2 dB km$^{-1}$, indicating a stronger orographic enhancement process than that in the 27–28 December event.

What could be the cause for the different lower-level VPR slopes? Mountain meteorologists have long recognized that when a deep, moist layer of air arises over a mountain barrier, precipitation amounts tend to increase sharply along the windward slope of the mountain (Hill 1881; Henry 1902, 1919; Peck and Brown 1962; Kitchen et al. 1994; Frei and Schär 1998; Houze and Medina 2005; Houze 2012). The increase in precipitation intensities at the lower slopes of mountains often seems surprisingly sharp because condensed moisture requires time to accumulate on particles and make them heavy enough to fall out. As pointed out by Panzieria and Germann (2010) through a study of 106 days of rainfall in the southern part of the European Alps, the upstream wind velocity has the largest impact on the frequency and intensity of the precipitation in the mountainous area, and the direction of the wind determines the spatial distribution and intensity of the precipitation. The air mass stability also determines the intensity of the...
precipitation, and usually unstable conditions cause more precipitation over a mountainous area than with stable conditions. Among these factors, the differences in airmass stability have a relatively minor impact on the precipitation intensity compared with wind direction and speed. Moisture is another fundamental element of orographic precipitation mechanisms (Browning et al. 1974; Hill et al. 1981; Alpert 1986; Ralph et al. 2004, 2005; Neiman et al. 2009). Hill et al. (1981) pointed out that the largest enhancement of rainfall occurred below 1.5 km above ground level (AGL) in association with high relative humidity and strong winds.

Figure 3 shows spatial distributions of wind speed and specific humidity at 800 m AGL during IOP3. At 0600 UTC 22 December 2005, a maximum humidity area of over 10 g kg\(^{-1}\) was located over the Pacific Ocean at \(\sim 34^\circ\)N, 130\(^\circ\)W (Fig. 3a). The moist air mass moved inland and was advected over the Sierra Nevada region with time. The specific humidity increased in the Sierra Nevada while the wind blew upward along the mountain slopes (Figs. 3b–d). The relative humidity in IOP4 was lower than that in IOP3, but the upstream wind was about twice as strong [Fig. 5 (described in greater detail below) versus Fig. 3]. The domain-averaged daily rainfalls from gauge observations for IOP3 and IOP4 were 49.7 and 75.6 mm, respectively. Panzieria and Germann (2010) indicated that the upstream wind speed had the largest impact on the frequency and intensity of precipitation over the mountains. Therefore, the significant difference in the 24-h rainfall totals and the lower-level VPR slopes between IOP3 and IOP4 was most likely a result of the large difference in the upstream winds. The 27–28 December 2005 event had a lower specific humidity than IOP3 and IOP4. The upstream wind velocity is larger than that in IOP3, but smaller than IOP4 (Fig. 4 versus Fig. 5). The 24-h rainfall for this event was 59.8 mm, which is between those of IOP3 and IOP4. This again seems to indicate that the upstream wind plays a dominant role in the orographic precipitation intensity and distribution.

b. VPR correction scheme

In the current study, two QPE techniques are tested: the first is the AVPR correction algorithm developed by ZQKH12, and the second is the new S-PROF–based VPR correction scheme developed in the current study.
1) AVPR CORRECTION ALGORITHM

Details of the algorithm can be found in ZQ10 and ZQKH12, but a brief introduction of the scheme is provided here for easy references. The AVPR correction contains three steps.

1) The first step is computing azimuthal-mean reflectivity from predefined precipitation areas with potential BB contamination and with radar sampling in the ice region. The areas are delineated according to the following criteria: (i) vertically integrated liquid (VIL; Greene and Clark 1972) is less than 6.5 kg m\(^{-2}\); (ii) blockage is less than 50%; (iii) for BB areas (i.e., when height is within the apparent BB layer, where the apparent BB layer was determined using a procedure developed in ZQ10), the reflectivity value is larger than 15 dBZ and the composite reflectivity (i.e., the maximum reflectivity in the vertical column) is larger than 30 dBZ; and (iv) for the ice region (i.e., when height is above the apparent BB top), the reflectivity value is larger than 0 dBZ. These criteria are chosen to include as much reflectivity data as possible in the ice region, so that the AVPR structure in the ice region can be accurately represented.

2) The second step is deriving an idealized VPR by fitting the mean observed AVPR with a linear model (Fig. 3 in ZQKH12). BB top, peak, and bottom are identified and slopes (\(\alpha, \beta, \gamma\)) of the linear VPR model are computed from the mean observed AVPR.

3) The final step is applying AVPR correction to reflectivity pixels, and the reflectivity observations are adjusted based on the parameterized VPR to obtain the corresponding values for rainfall estimation at the ground (Fig. 4 in ZQKH12). The adjusted reflectivity pixels should meet the following criteria: (i) the height of the reflectivity bin is above the apparent BB bottom; (ii) VIL is less than 6.5 kg m\(^{-2}\); (iii) for the BB area, the reflectivity value is larger than 20 dBZ; and (iv) for the ice region, the reflectivity value is larger than 5 dBZ. The correction uses one parameterized VPR for each tilt, and adjustments are made to the hybrid scan reflectivity, assuming a horizontally invariant VPR and a constant reflectivity below the BB bottom.

2) S-PROF–BASED VPR CORRECTION SCHEME

The ZQKH12 scheme uses one AVPR for each tilt, assuming a horizontal uniformity of the vertical precipitation structure across the radar domain. It also assumes a constant reflectivity below the BB bottom. Such assumptions work relatively well when the vertical
gradient of precipitation is much greater than the horizontal variation, for example, in stratiform precipitation over flat lands. In a complex terrain, rough landform may modulate the BB layer, leading to different BB heights across the radar domain. Also, the orographic enhancement may cause increasing reflectivity with decreasing height below the BB bottom, which violates the constant reflectivity assumption. The S-PROF–based VPR correction scheme tries to address these two deficiencies by using spatially varying and intensity-dependent VPRs calculated from profiler radar observations (ATA and CZD). The reference VPRs derived from CZD are used for West Coast mountains and the western half of the central valley (i.e., the region west of the solid green line in Fig. 1). For the Sierra Nevada and the eastern half of the central valley, the reference VPRs from the ATA site were used. The S-PROF VPR correction algorithm includes two parts that are presented below.

(i) VPR matching for each radar pixel

At any given bin (azimuth, range) in the radar domain, an optimal reference VPR is selected as follows: 1) determine the lowest elevation angle without severe blockages (i.e., the hybrid scan as shown in Fig. 11 of ZQKH12), 2) calculate the equivalent WSR-88D observed reflectivities $Z_{\text{smhl}}$ from the reference S-PROF VPRs (in Fig. 2) based on the radar bin location and the corresponding event, 3) calculate the differences $\Delta z$ between the WSR-88D radar observation $Z_{\text{obs}}$ at the hybrid scan bin and the equivalent reflectivities ($Z_{\text{smhl}}$) for each reference VPR, and 4) the optimal reference S-PROF VPR is identified as the one with the minimum $\Delta z$.

(ii) VPR correction for each radar pixel

Once the optimal reference S-PROF VPR is found, the corrected reflectivity $\hat{Z}(h_0)$ is obtained by

$$\hat{Z}(h_0) = Z_{\text{obs}}(h) - 10 \cdot \log_{10} \int_{x=h-\Delta h}^{x=h+\Delta h} \rho(x) \cdot f^4(x) \cdot dx,$$

(1)

where $h_0$ is a low-level reference height (the ground level) and $Z_{\text{obs}}(h)$ is the hybrid scan reflectivity from a WSR-88D radar. The variable $h$ is the height at the hybrid scan bin center, and $\Delta h$ is the half beamwidth. The variable $f^4(x)$ is the two-way radar antenna gain function, and $\rho$ is the normalized VPR expressed as

$$\rho(h) = Z(h)/Z(h_0),$$

(2)

where $Z(h)$ and $Z(h_0)$ are reflectivities (mm$^6$ m$^{-3}$) in the reference VPR at the heights of $h$ and $h_0$, respectively. The 4/3 Earth radius model is assumed for the beam propagation path.
4. Case study results

Two sets of QPEs were generated for each case; one uses the S-PROF VPR correction scheme, and the other uses the ZQKH12 algorithm. The two QPEs were assessed through comparisons with the hourly HADS gauge observations as well as the special gauges deployed during HMT06. The temporal resolution of gauges is hourly, and the spatial resolutions of HADS (~30 km) and HMT06 (~10 km) gauges are different. All the gauges were manually quality controlled before the statistics calculation. The quality control was based on subjective assessments of temporal and spatial consistencies of the gauge observations, and only gauges with very high confidence were retained for the evaluation of radar QPEs. The performance of each algorithm is quantified using the following statistics.

1) Bias ratio is

\[
\text{Bias} = \frac{\bar{R}}{\bar{G}},
\]

where

\[
\bar{R} = \frac{1}{N} \sum_{k=1}^{N} r_k
\]

and

\[
\bar{G} = \frac{1}{N} \sum_{k=1}^{N} g_k.
\]

A bias ratio greater (less) than 1.0 indicates that the radar has overestimated (underestimated) the rainfall assuming the gauge report is accurate. In this work, all the gauge reports have been manually quality controlled before statistics calculations. The quality control was based on subjective assessments of temporal and spatial consistencies of the gauge observations, and only gauges with very high confidence were retained for the evaluation of radar QPEs.

a. IOP3

During this event, a maximum of 146 mm of rain was reported east of Alta, California, over a 24-h period ending at 2300 UTC 22 December 2005 (Figs. 6a, top; 6b, top). For IOP3, heavy rainfall over the high terrain was not captured well by the WSR-88Ds. The S-PROF-VPR correction performed well in the West Coast and the higher terrain of the Sierra Nevada (Fig. 6a, middle versus Fig. 6b, middle) compared with ZQKH12. Through

\[
\bar{G} = \frac{1}{N} \sum_{k=1}^{N} g_k
\]

Here $\bar{R}$ and $\bar{G}$ are the averaged 24-h (or hourly) radar and gauge precipitation, respectively; $r_k$ and $g_k$ represent a matching pair of the radar-derived and gauge-observed rainfall; and $N$ represents the total number of matching gauge and radar pixel pairs in the entire domain. A matching radar–gauge pair is found if 1) the gauge location is within the boundary of a 1 km × 1 km radar pixel and 2) both the radar estimate $r_k$ and the gauge observation $g_k$ are greater than zero. The variable $q_k$ is an average radar rainfall in a 5 km × 5 km box that is centered at the corresponding gauge.

2) Root-mean-square error (RMSE) is

\[
\text{RMSE} = \left[ \frac{1}{N} \sum_{k=1}^{N} (r_k - g_k)^2 \right]^{1/2}.
\]

3) Correlation coefficient (CC) is

\[
\text{CC} = \frac{\left[ \frac{1}{N} \sum_{k=1}^{N} (r_k \cdot g_k) \right] - \left( \frac{1}{N} \sum_{k=1}^{N} r_k \right) \cdot \left( \frac{1}{N} \sum_{k=1}^{N} g_k \right)}{\left[ \left( \frac{1}{N} \sum_{k=1}^{N} r_k^2 \right) - \left( \frac{1}{N} \sum_{k=1}^{N} r_k \right)^2 \right] \cdot \left( \frac{1}{N} \sum_{k=1}^{N} g_k^2 \right) - \left( \frac{1}{N} \sum_{k=1}^{N} g_k \right)^2}^{1/2}.
\]

103 R–G pairs, the radar QPE with the ZQKH12 VPR correction underestimated the rainfall by ~47% (Fig. 6a, bottom). The S-PROF-VPR correction greatly reduced the underestimation to ~18% (Fig. 6b, bottom), and the improvement was most significant for rainfall amounts between 50 and 100 mm (Fig. 6b, bottom vs Fig. 6a, bottom). The RMSE was reduced by 21.6% (29 vs 37 mm), and the CC was improved from 0.41 to 0.42. The improvements with S-PROF-VPR correction algorithm have passed 0.001 Student’s $t$ tests compared with ZQKH12. The Student’s $t$ test statistical significance indicates whether or not the difference between two groups’ averages most likely reflects a ‘real’ difference in the population from which the groups were sampled. The residual underestimation came from two areas: one was ~20 km northeast from ATA (area B in Fig. 6b, middle) where the heaviest rain (>100 mm in the 24-h period) fell, and another was along the middle California–Nevada border (ridge areas of Sierra Nevada). Detailed investigations indicated that the
precipitation during this event was relatively scattered and nonuniform in space (Fig. 7). For instance, at ~1325 UTC 22 December 2005, the precipitation at ATA was much lighter and the cloud much shallower than that in the heaviest rain area (B in Fig. 7a). The vertical variations of reflectivity at ATA did not represent those in area B even though they were only about 20 km apart. Similarly, there were horizontal variations...
of precipitation structure in the coastal mountains. CZD is located on the windward slope of the coastal mountains where the moist Pacific air mass was blown inland. On the leeside (e.g., green circle in Fig. 6b, middle), the precipitation intensities were not as strong as the windward side because of downdrafts, and applying a VPR correction based on the CZD S-PROF VPRs resulted in some overestimations (green circle in Fig. 6b, bottom). For this type of precipitation, additional high-resolution local VPRs such as those from the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) satellites may provide further improved VPR corrections for WSR-88D radar QPEs.

Spatial variations of precipitation were likely a contributor to the remaining underestimation in the S-PROF-VPR corrected QPE along the middle California–Nevada border, because this area is far away from the ATA site. Furthermore, the QPE in this area was mostly from the KDAX observations, which is about 6–7-km above the radar level (ARL). Because the cloud top of the IOP3 storm system was about 6 km ARL, the radar observations were partially or completely overshooting the precipitation in this region. The overshooting resulted in a biased $Z_{\text{obs}} h$ and subsequently a biased $Z_{\text{corr}}$ and QPE underestimation. Adding gap-filler radars in these areas would help capture the lower-level microphysics processes and provide more accurate QPEs than the current operational radar network.

b. The 27–28 December 2005 event

The 27–28 December 2005 event had a maximum rainfall of 132.84 mm (Alta, California) during 24-h period. Figures 8a (top) and 8b (top) show 24-h radar rainfall accumulations ending at 2300 UTC 28 December 2005 with ZQKH12 and S-PROF-VPR correction, respectively. The S-PROF-VPR correction also performed well in the West Coast and the higher terrain of the Sierra Nevada (Fig. 8a, middle versus Fig. 8b, middle) compared with ZQKH12. Through 107 $R-G$ pairs, the 24-h radar QPE with ZQKH12 VPR correction was significantly lower than the gauge observations throughout the domain (as orange to red colored bubbles shown in Fig. 8a, middle), and the bias ratio of the radar QPE over gauge was 0.38 (a 62% underestimation). The 24-h QPE from the S-PROF-VPR correction agreed with the gauge observations much better than did the ZQKH12 (as shown by the white to light-orange bubbles in Fig. 8b, middle), with a lesser bias of 0.72 (or 28% underestimation). The CC score was improved from 0.4 to 0.55, and the RMSE error was reduced from 48 to 32 mm (Figs. 8a, bottom; 8b, bottom). The improvements with S-PROF-VPR correction algorithm have passed 0.001 Student’s $t$ tests compared with ZQKH12.

More rain fell along the West Coast during this event than it did in IOP3 (larger circles along the coast in Fig. 8a, middle than those in Fig. 6a, middle). Applying the S-PROF-VPR correction reduced the radar QPE underestimation bias (Fig. 8b, middle versus Fig. 8a,
middle), although the extent of improvement varies from place to place because of spatial variabilities of vertical precipitation structure and relatively poor radar coverage in the region (Maddox et al. 2002). For instance, the moisture advection was stronger in area “D” than in areas to the south, given the stronger wind and higher moisture content upstream (Figs. 4a,b). The stronger moisture advection resulted in a more intense orographic enhancement and heavier rain that were not fully captured by the CZD VPRs. In addition, the WSR-88D radars cannot “see” below 2 km AGL in this region (Maddox et al. 2002). Hybrid scan reflectivities of KBHX and KDAX (both running VCP21) in this area were from 1.45° (see Figs. 11d and 11h of ZQKH12) and were well above the melting layer (marked by the bright band of yellow-shaded reflectivities) and even partially overshooting the cloud tops (Figs. 9b,d). Similar deficiency of radar sampling is found in the area around...
CZD, where the first tilt was completely blocked beyond ~120-km range (Fig. 9c). A gap-filler radar (e.g., at 150–200 km south of KBHX at the coast) is needed to improve the radar coverage and subsequently the quality of radar QPEs in this area.

c. IOP4

IOP4 was a relatively high freezing-level event with different precipitation periods (see White et al. 2003; Martner et al. 2008). The current study focuses on the
relatively uniform precipitation period of 48 h from 1200 UTC 30 December 2005 to 1200 UTC 1 January 2006. For IOP4, heavy rainfall over the high terrain was dominated by the orographic enhancement process, which was not captured well by the WSR-88Ds. The S-PROF VPR correction has largely reduced the underestimation in the West Coast and the higher terrain of the Sierra Nevada (Fig. 10a, middle versus Fig. 10b, middle) compared with ZQKH12. Figure 10 shows the 48-h rainfall accumulations ending at 1200 UTC 1 January 2006 with ZQKH12 (Fig. 10a, top) and with S-PROF VPR correction (Fig. 10b, top). Through 101 R–G pairs, ZQKH12 had a significant underestimation throughout the domain except in a few places around the central valley (Figs. 10a, middle and bottom), resulting in a radar–gauge 48-h rainfall bias ratio of 0.54 (~46% underestimation) (Fig. 10a, bottom). The S-PROF VPR correction algorithm greatly improved the radar QPEs and essentially removed the underestimation with a radar–gauge bias ratio of 1.14. The improvements

![Figure 10](image-url). As in Fig. 6, but for 48-h radar rainfall accumulations ending at 1200 UTC 1 Jan 2006.
with S-PROF VPR correction algorithm have passed 0.001 Student’s t tests compared with ZQKH12. The slight overestimation mainly came from an area on the eastern or leeward side of the coastal mountains (green circles in Figs. 10b, middle and 10b, bottom), due to the fact that CZD was on the windward side of the coastal mountains and the reference VPRs were not representative of the vertical precipitation structure on the leeward.

Compared to the previous two events, improvements to the radar QPE by the S-PROF-VPR correction were remarkable in the Sierra Nevada zone (Fig. 10b, middle versus Figs. 10a, middle; 8b, middle; and 6b, middle), except for the very high elevations along the middle California–Nevada border. The improvements were attributed to two factors: 1) the horizontal uniformity of the precipitation and 2) the high vertical resolution of KDAX data during this event. The KDAX radar was running Volume Coverage Pattern 12 (VCP 12; http://en.wikipedia.org/wiki/NEXRAD) in IOP4 but VCP 21 in IOP3 and during 27–28 December 2005. Figure 11 shows KDAX base reflectivities (at ~1427 UTC 31 December 2005) on 0.5° (Fig. 11b) and 0.9° (Fig. 11c) and a vertical cross section (Fig. 11a) through ATA and the same point B as in Fig. 10b, middle. The precipitation system in IOP4 was more horizontally uniform than in IOP3, and the cloud top height was taller (Fig. 11a versus Fig. 7a). The vertical precipitation structure across the Sierra Nevada zone was more uniform than it was in IOP3 and in the 27–28 December event, and the reference VPRs from ATA were very representative of such structure. In all three events, KDAX reflectivities from the second tilt (1.45° for IOP3 and 27–28 December and 0.9° for IOP4) were used in the WSR-88D radar QPE because the first tilt (0.5°) was more than 50% blocked. Radar data at 0.9° for IOP4 were about 0.5–1-km lower than those at 1.45° for IOP3 and were better correlated with the ground-level precipitation processes than the latter. More representative VPRs and lower-level WSR-88D reflectivities resulted in a VPR correction that more effectively removed underestimation biases in the Sierra Nevada for IOP4 (Fig. 10b, bottom versus Fig. 10a, bottom) than for the previous two events.

5. Summary

For surface rainfall estimation, radar-based techniques are subject to overestimation errors when the lowest radar beams sample the bright band and underestimation errors when the beams sample in the ice region. Furthermore, radar QPEs can underestimate rainfall in complex terrain when the lowest radar observations are above the levels where orographic precipitation enhancement is occurring. ZQKH12 developed an automated technique to correct radar QPEs for errors associated with the first two issues but not the orographic enhancement. The current study focuses on the latter and a new (S-PROF) VPR correction algorithm is developed, and the S-PROF–based VPR correction methodology (S-PROF-VPR) has taken into account
orographic processes and radar beam broadenings with range.

The new technique uses very high resolution reference VPRs derived from S-band precipitation profiler data to correct the WSR-88D radar QPE errors associated with the bright band and the orographic precipitation enhancement in the complex terrain. The S-PROF VPR correction was examined on three heavy rainfall events in northern California and showed consistent improvements over the radar QPEs computed from the ZQKH12 approach. The results demonstrated a good potential of combining high-resolution reference VPRs (e.g., those from precipitation profilers or from spaceborne radars) with ground radar observations to obtain more accurate high-resolution QPEs than using the ground radar only, especially in the complex terrain. The new scheme has limited impacts when the ground radar observation is too high above the ground and overshoots precipitation clouds and when there are large horizontal variabilities in the precipitation distribution.

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