Comparisons of Rain Estimates from Ground Radar 
And Satellite Over Mountainous Regions

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Abstract

A high-resolution rainfall product merging surface radar and an enhanced gauge network is used as a reference to examine two operational surface radar rainfall products over mountain areas. The two operational rainfall products include radar-only and conventional-gauge-corrected radar rainfall products. Statistics of rain occurrence and rain amount including their geographical, seasonal, and diurnal variations are examined using 3-year data. It is found that the three surface radar rainfall products in general agree well with one another over mountainous regions in terms of horizontal mean distributions of rain occurrence and rain amount. Frequency of rain occurrence and fraction of rain amount also indicate similar distribution patterns as a function of rain intensity. The diurnal signals of precipitation over mountain ridges are well captured and joint distributions of coincident raining samples indicate reasonable correlations during both summer and winter.

Factors including undetected low-level precipitation, limited availability of gauges for correcting the Z-R relationship over the mountains, and radar beam blocking by mountains are clearly noticed in the two conventional radar rainfall products. Both radar-only and conventional-gauge-corrected radar rainfall products underestimate the rain occurrence and fraction of rain amount at intermediate and heavy rain intensities. Comparison of PR and TMI against a surface radar-only rainfall product indicates that the PR performs equally well with the high-resolution radar-only rainfall product over complex terrains at intermediate and heavy rain intensities during the summer and winter. TMI, on the other hand, requires improvement to retrieve wintertime precipitation over mountain areas.
1. Introduction

Rainfall estimates over mountainous regions are known to have large uncertainties due to highly variable and complicated precipitation features associated with topography (e.g., Barros et al. 2000; Prat and Barros 2010; Yamamoto et al. 2011). As one of the main ground-based rainfall-measuring instruments over land, rain gauges are not only sparse over remote mountainous regions, but also suffer from calibration and representativeness errors. Ground radars can provide continual rain retrievals covering large areas, but their rainfall estimates may have large biases due to factors such as undetected low-level precipitation under the lowest radar beam elevation often caused by radar beam blocking by mountains. In addition, the lack of well-calibrated rain gauge data also severely limits bias corrections of the ground radar rainfall over mountainous regions. Therefore, the commonly-used surface rainfall reference data from conventional gauge and ground radar network have issues over mountainous regions and should be used with great care.

Satellite observations have been widely utilized to extract instantaneous estimates of rainfall information on the global scale, and provide a promising way to capture precipitation characteristics over mountainous regions at fine temporal and spatial resolutions. Among various remote-sensing instruments, microwave sensors that directly respond to the absorption and scattering of cloud hydrometeor particles are the backbone of space-based precipitation measurements. For example, the precipitation radar (PR) (Meneghini and Kozu 1990; Kummerow et al 1998; Iguchi et al. 2000; Kummerow et al. 2000) on board the Tropical Rainfall Measuring Mission (TRMM, Simpson et al. 1988, 1996) satellite provided the first space-borne rainfall retrievals from an active microwave
sensor. The recently-launched Dual-frequency Precipitation Radar (DPR) on board the Global Precipitation Measuring mission (GPM, Hou et al. 2014) core satellite has additional capabilities for measuring light rain and falling snow. Considering PR and DPR's active microwave sensing features, these radar data may serve as space-borne rain references for assessing other satellite rainfall retrievals and even surface measurements. In addition to the space-borne precipitation radars, passive microwave (PMW) radiometers and sounders, featuring wider ground track coverage, have been widely utilized to retrieve surface rainfall over land using high-frequency scattering-based algorithms.

Due to the sensitivity and spatial resolution of satellite instruments and retrieval algorithms, satellite rainfall products also have problems over mountainous regions due to topography and partial beam filling. For PMW retrievals, the highly variable land surface with different vegetation, snow and ice, and soil moisture (which may also change significantly with time) makes it difficult to distinguish rainfall against the complicated surface background (e.g., Wilheit 1986; Kummerow et al. 2000; Ferraro et al, 2005).

A major obstacle in assessing rainfall estimates over mountainous regions is due to the large uncertainties that surface measurements and satellite retrievals have at fine temporal and spatial scales: there are no perfect observations to serve as the “truth”. The National Mosaic and Multi-sensor QPE (NMQ, QPE: quantitative precipitation estimates) project at the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (NSSL) provides a number of experimental QPE products operationally. These QPE products, including radar-only and gauge-corrected radar...
rainfall estimates originally derived from about 140 WSR-88D operational radar with updated rain-reflectivity algorithms, cover the entire continental US at high spatial resolution (0.01°×0.01°) (Vasiloff et al. 2007; Zhang et al. 2011). These surface rainfall products have provided many valuable insights on weather analyses and severe storm forecasts over the continental US as well as providing a basis for satellite rain error estimates over land. Noting the uncertainty in gauge-corrected radar rainfall estimates over complex terrains, Tao and Barros (2013) further adjusted the hourly gauge-corrected radar rainfall product using the very dense rain gauge observations in the Pigeon River basin in the Southern Appalachian Mountains.

In this study, we use a similar gauge-enhanced high-resolution radar rainfall product as the reference to evaluate two operational surface radar and gauge-radar merged rainfall products (radar only and conventional gauge-adjusted). With a better understanding of the statistical characteristics including the strength and weakness of these radar rainfall products, satellite rainfall retrievals from both active and passive microwave sensors onboard the TRMM satellite, TRMM PR and TRMM Microwave Imager (TMI), are also coincidently examined against a 5-minute radar-only rainfall product over mountainous regions. Specifically, we intend to 1) quantitatively examine the rain detection and statistics as a function of rain intensity in different seasons over the mountains; 2) discuss strengths and limitations of ground-based radar-only and radar-gauge merged products in estimating rain occurrence and rain accumulation; 3) evaluate to what extent the current space-borne precipitation radar could help to improve rainfall estimates in mountainous regions. Section 2 introduces the dataset and analysis methodologies while Section 3 evaluates surface radar rainfall products against the reference dataset over the
mountainous region. Section 4 compares coincident satellite rainfall retrievals from TRMM PR and TMI against surface radar rainfall estimates. Finally, the conclusions of the study are presented in Section 5.

2. Data and Analysis Methods

2.1 The surface radar rainfall product

The NOAA NSSL, along with university research communities, provide two experimental Next Generation Multi-sensor QPE (Q2) hourly products covering the entire US continent at high spatial resolutions (0.01°×0.01°) (Vasiloff et al. 2007; Zhang et al. 2011): the WSR-88D radar-only-based rainfall product (Q2rad) and the conventional-gauge-corrected radar rainfall product (Q2rad_GC). Q2rad_GC is generated by applying radar-gauge bias fields calculated using hourly rain gauge observations to hourly Q2rad: comparisons show that Q2rad_GC in general performs better than Q2rad (Ware 2005; Zhang et al. 2011). However, it was also found that Q2rad_GC still underestimated rainfall significantly over the complex terrain of the Pigeon River basin in the Southern Appalachian Mountains (Tao and Barros 2013). Chen et al. (2014) compared Q2 products with gauge analysis and other rainfall products and also noticed large uncertainties over mountain regions. Thus, the hourly Q2rad_GC product was further adjusted by Tao and Barros (2013) in the Pigeon River basin in the Southern Appalachian Mountains using the very dense rain gauge observations.

Figure 1 shows the conventional WSR-88D radar sites covering the Pigeon River basin. The two ground radar sites (KMRX in Knoxville/Tennessee and KGSP in
Greer/South Carolina) lie in within 100 km of the Pigeon River basin, and at least 50 km
either side of the Southern Appalachian Mountains. Note the boundary of the basin is
coincident with the ridge lines, which causes the basin a land-lock region (blind-zone) for
the ground radars, implying that the rainfall spatial variability associated with orographic
modulation within the basin can hardly captured by the ground radars. Figure 2 details
the topography of the Pigeon River basin, located in Haywood County, North Carolina,
and the locations of rain gauges available from three different sources. There is 1 rain
gauge from the Environment and Climate Observing Network (ECONet) and 5 rain
gauges from Hydrometeorology Automated Data System (HADS). Both the ECONet and
HADS gauges are installed at low elevations or in valleys. It should be noted that the
HADS precipitation datasets are one of the major sources of rain gauge observations used
operationally to derive the multi-sensor QPE fields and adjust the Q2 product (Kim et al.
2009; Nelson et al. 2010; Seo 1998; Seo and Breidenbach 2002). The local-adjustment
for the Q2 (Q2rad) product at NSSL to produce the gauge-corrected Q2 (Q2rad_GC)
does not however always use all the HADS records probably due to data latency.
Considering that the locations of, and observations from conventional gauges used in
Q2rad_GC are very limited, as well as factors such as radar beam-blocking and beam
over-shooting, it is clear why considerable uncertainties still remain in the conventional-
gauge-corrected Q2 product over the mountainous region.

Tao and Barros (2013) developed two simple methods based on linear regression to
enhance the hourly gauge-corrected Q2rad_GC by incorporating high-quality-controlled
rainfall dataset from the Great Smoky Mountains Rain Gauge Network (GSMRGN, also
a 1st phase of the Precipitation Measuring Mission rain gauge network). GSMRGN has
35 tipping bucket gauges which are installed at mid to high elevations along exposed ridges in the Southern Appalachians; 32 gauges are within the Pigeon River Basin (see Figure 2). Further study by Wilson and Barros (2014) indicated that in mountainous regions of moderate topography and humid climate such as the Appalachians, light rainfall could explain accounts for a significant fraction of the annual precipitation (up to 50% on average in the Appalachians) and exhibited persistent spatial and seasonal patterns. Consequently, a new bias-correction method was developed to solve the problem of nonlinearity between the rainfall estimates and gauge observations that is largely attributed to the different rainfall-intensity regimes. This new method utilizes the probability density function (PDF) and cumulative distribution function (CDF) of areal rainfall fields interpolated from rain gauge observations using IDW (Inverse Distance Weighting) method, to divide the whole study domain into a heavy rainfall domain and a non-heavy rainfall domain. Specifically, the empirical PDF and CDF are calculated first, and then the quantile of 0.9 (CDF_{0.9}) is estimated based on the CDF curve, which is used as a threshold for separating the region, i.e. the region with the rainfall above CDF_{0.9} is the heavy rainfall domain, while the region that below CDF_{0.9} is the moderate or light rainfall domain. Then, linear regression between rainfall estimates and gauge observations is applied separately in each domain, and the derived regression coefficients are retrospectively applied to each domain to adjust Q2rad_{GC} in the same manner as in Tao and Barros (2013), in such a way that the nonlinearity is resolved by separating the rainfall regimes. The new adjusting methods is used to adjust Q2rad_{GC} data (Jun. 2008 – Oct. 2011) in the Pigeon River Basin along with the methods discussed by Tao and Barros (2013). The computed RMSEs (Table 1) show that the Q2+_cdfThr generated by
this new CDF threshold-based method which resolves the nonlinearity between the
Q2rad_GC data and rain gauge observations, has the lowest overall RMSE,
outperforming all the other products. In this study, we therefore use this special gauge-
enhanced Q2 rainfall product adjusted by the CDF threshold over the Pigeon River basin
as the reference to evaluate the other two Q2 rainfall products (Q2rad and Q2rad_GC).
For simplicity, we will call this new Q2 rainfall product as Q2+ in the following sections.

2.2 Satellite rainfall retrievals

Past studies evaluating satellite rainfall retrievals were usually conducted at
relatively large temporal and spatial resolutions. In recent years, more and more emphasis
effort has been placed on hydrologic applications at finer scale with mesoscale
precipitating systems. Because the selected mountain area with the high-resolution gauge
network is relatively small (66 km x 61 km) and because the widths of ridges and valleys
are usually narrow, it is difficult to distinguish mountain ridges and valleys using
retrievals with large footprint sizes. We therefore in this study only examine satellite
rainfall retrievals from TRMM PR and TMI (the level-2 products: 2A25 and 2A12)

The TRMM satellite was launched in November 1997 to improve our understanding
of the temporal and spatial distributions of precipitation and latent heating in the Tropics
and subtropics (Simpson et al. 1988; Kummerow et al. 1998). TRMM’s orbit is circular,
with an inclination angle of 35° relative to the Equator. PR and TMI are two microwave
sensors onboard TRMM to retrieve precipitation and latent heat: the TMI is a 9-channel
passive microwave radiometer measuring radiances at five frequencies, while the PR is
the first quantitative space-borne Ku-band weather radar. Due to their differences in
swath (TMI: 878 km; PR: 247 km, boosted after August 2001), the TMI samples a given
area over the Tropics and subtropics about once per day, but at a different local time every day, while PR visits a given area on the average of about once every 3 days.

As described in Iguchi et al. (2000), the PR algorithm utilizes a globally averaged drop-size distribution (DSD) as the initial guess to obtain attenuation-corrected radar reflectivity-rain rate ($Z_e$-$R$) relationship that is consistent with the assumed DSD model: After taking into attenuation correction, the true effective reflectivity factor $Z_e$ is first estimated at 13.8 GHz at each radar resolution cell from the measured vertical profiles of reflectivity factor. The rainfall rate $R$ is then computed from the estimated $Z_e$. Several factors, as discussed by Iguchi et al. (2000) and Masunaga et al (2002), may affect the accuracy of the estimated rain rate: (1) assumptions in the DSD model; (2) uncertainties in the attenuation correction; (3) corrections for non-uniform beam-filling effects. The footprint resolution of a PR rain pixel is about 5 km at nadir and the minimum detectable rain rate is about 0.3-0.5 mm h$^{-1}$. The microwave rainfall retrievals used for TMI and many other imagers are essentially based on the most recent version of the NASA Goddard Profiling (GPROF version 7) algorithm (Kummerow et al. 1998; Olson et al. 1999; Kummerow et al. 2001; Olson et al 2006; Masunaga and Kummerow 2005; Kummerow et al. 2011). Over land, passive microwave sensors can measure the scattering effects of ice particles that later melt to form raindrops. Cloud ice water content is first retrieved (Zhao and Weng 2002; Weng et al. 2003) and surface rainfall is estimated based on empirical regressions established to match PR rainfall (Ferraro et al. 1998, 2000, 2005; Kummerow et al. 2011). The footprint resolution of a TMI rain pixel is about 5.1 km at 85.5 GHz and the minimum detectable rain rate is about 1.0 mm h$^{-1}$ in the GPROF algorithm.
2.3 Analysis methods

One of the main objectives of this study is to evaluate two experimental surface radar rainfall products over the mountainous region. Surface radar hourly rainfall products including the radar-only Q2 (Q2rad) and gauge-corrected Q2 (Q2rad_GC) are compared with the gauge-enhanced Q2+ data for the period from 1 January 2009 through 31 October 2011 over the Pigeon River basin (83.31°W to 82.66°W, 35.24°N to 35.84°N). The evaluation of surface radar rainfall products in terms of rain accumulation, frequency of rain occurrence and fraction of rain amount are conducted at their original temporal and spatial resolutions (0.01° x 0.01°, 1-h intervals).

Because mountain ridges and valleys usually have distinctly different diurnal variations of precipitation, the Shuttle Radar Topography Mission (SRTM) 0.01°×0.01° elevation data (derived from US Geography Survey’s SRTM30) are used to divide the mountain area into ridges and valleys. The grid points where SRTM elevation data are higher than 1200 m are defined as the ridge area, while the grid points along the Pigeon River where SRTM elevation data are lower than 1000 m are defined as the valley area. It should be noted that the ridge area as defined by the elevation data are mainly over the west side of Pigeon River Basin where most GSMRGN rain gauges are located.

Instantaneous satellite rainfall estimates can only be coincidentally compared against the gauge-corrected hourly surface radar data when the characteristics of rain events do not change much within an hour. Precipitation, however, can be highly variable over mountainous regions, particularly for those transient rain events which could develop and dissipate within a very short time. A number of sensitivity tests are carried out and the result suggests that the steady-state assumption is not a good assumption over the narrow
mountain ridge and valley area as shown in the Pigeon River basin. In order to compare coincident satellite rainfall retrievals and surface radar data, we will first take advantage of the comparison among the three surface radar rainfall products to get a better understanding of characteristics and weakness of Q2rad against Q2+. By assuming that the overestimation/underestimation for different rain event ensembles between Q2rad and Q2+ are similar at 5-minute and 1-h intervals, we collocated the original 5-minute Q2rad derived from radar Hybrid Scan Reflectivity (HSR) with instantaneous PR and TMI rainfall pixels to infer statistical characteristics of satellite rainfall estimation. Evaluation of PR and TMI data against Q2rad data are conducted at 5-km resolution as a function of rain intensity. The collocation is conducted by simply averaging high-resolution Q2rad data onto each sensor’s footprint pixel at 5-km resolutions.

3. Comparisons of surface radar products

Figure 3 compares the distribution of annual mean rainfall from Q2rad, and Q2rad_GC, with the reference data Q2+ over the Pigeon River basin. The Q2rad product, without any gauge corrections, shows a relatively uniform rainfall field within the basin while the Q2rad_GC displays slightly larger spatial variability. The Q2+ product, on the other hand, exhibits critical variability with apparent ridge-valley gradients. In addition, the Q2+ total indicates an area of high mean precipitation extending northwest to southeast, corresponding well with major mountain ridges of the Pigeon River basin as shown in USGS SRTM elevation data. Over the Pigeon River basin and the minor ridge area on the other side of the basin, the mean precipitation amount is generally low (below 3 mmd⁻¹). The radar-only Q2rad and the gauge-corrected Q2rad_GC underestimate with respect to the Q2+ product over the major mountain ridges. This underestimation may
result from a number of factors including the limited number of gauges available for correcting the Z-R relationship over mountains, undetected low-level precipitation under the radar beam, and radar beam blocking by mountains. This underestimation is similar to that found in Tao and Barros (2013) comparing operational Q2 rainfall products with individual GSMRGN gauges over the mountains. The Q2rad_GC result does, however, do a slightly better than Q2rad over the major mountain ridges, probably due to the inclusion of a few HADS gauge records used in the bias correction process. For example, the normalized underestimation of Q2rad against Q2+ is around 20-40% along the major ridges, but the underestimation is reduced to below 20% in Q2rad_QC. Similar patterns can also be observed during both summer and winter seasons (not shown), although the wintertime precipitation amount is much smaller. On the other hand, the differences of rain amount over the Pigeon River basin and the minor mountain ridges are generally small.

Although it is difficult to quantitatively estimate errors for each individual factors contributing to the conventional radar rainfall underestimation over the mountainous areas, potential error sources related to the undetected low-level precipitation beneath the ground radar beam can be examined. For instance, the local surface radar site KMRX in Knoxville, Tennessee (as shown in Figure 1) is about 80 km away from the center of the study area. According to the National Weather Service WSR-88D radar operational procedure, a radar performs volume scans at elevation angles of 0.5°, 1.5°, 2.5°, 3.5°, 4.5°, up to 19.5° in precipitation mode. Considering that the elevation of the major mountain ridge is about 1800 m which has a radar elevation angle of 1.7°, the lowest radar beam height (above the ground) is about 0.6 km at the northwest edge and 1.5 km at the center.
of the studied mountain ridge area after subtracting the radar elevation from the local
elevation and taking into account the curvature of the Earth. Therefore, many low-level
precipitation with echo tops below the distance-dependent radar beam elevation may not
be detected by the radar.

The frequency of rain occurrence, calculated as the ratio of the number of raining
samples to the total number of samples, is another way to examine the climatology of
rainfall characteristics. Figure 4 examines mean frequency of rain occurrence derived
from the three surface radar rainfall products using data from 2009 to 2011. The gauge-
enhanced Q2+ data show a maximum on the northwest corner and a lesser maximum in
the southeast corner of the domain. Both Q2rad and Q2rad_GC underestimate Q2+ over
most of the mountain area, with greater underestimation near the above two corners and
along the major mountain ridges. Q2rad_GC again performs better than Q2rad when
comparing against Q2+.

In order to further examine the contributions of rain samples within different rain
intensity ranges to the difference in total rain occurrence and total rain amount, the region
was divided into ridges and valleys according to the SRTM elevation data, and rainfall
event statistics evaluated as a function of rain intensity. Since the major mountain ridges
on the west side of the Pigeon River basin consistently showed large differences among
the different Q2 rainfall products and most GSMRGN gauges are located near the major
mountain ridges, our analysis focused on the area of major mountain ridges.

Figure 5 shows the frequency of rain occurrence over mountain ridges (SRTM
elevation >1200 m) as a function of rain intensity for the three surface radar rainfall
products. During the summer, the mountainous region usually features large contributions
from vigorous convective precipitation. Both Q2rad and Q2rad_GC appear to underestimate the frequency of intermediate and heavy rain occurrence (rain intensity larger than 3 mm$h^{-1}$), but overestimate light rain occurrence (rain intensity smaller than 3 mm$h^{-1}$). This phenomenon may be associated with the underestimation of rain intensity in Q2rad and Q2rad_GC over mountain ridges: Some of the intermediate and heavy rain events shown in Q2+ may be classified in Q2rad and Q2rad_GC as rain events with lighter rain intensities. Another possible explanation for the overestimation of light rain events is that radar rain retrieval algorithm used during summertime is not able to handle convection over mountain ridges. The limited conventional rain gauge data utilized in Q2rad_GC are mainly located in low-elevation areas where annual rain accumulation is small. The distinctly different precipitation characteristics between ridges and valleys during the summer may not help to correct bias near mountain ridges. For very heavy rain events, the three rainfall products tend to agree well in terms of frequency of rain occurrence.

During the winter, persistent, light stratiform precipitation provides large contributions to the total precipitation (Wilson and Barros 2014). The frequency of heavy rain events is significantly reduced in all three radar rainfall products. Both Q2rad and Q2rad_GC significantly underestimate the incidence of light rain events and moderately underestimate incidence of intermediate rain events. This suggests a problem in the detection of wintertime precipitation resulting from the radar retrieval algorithm. It is interesting to notice that Q2rad_GC appears to agree slightly better with Q2+ than Q2rad for rain events with intensities above 3 mm$h^{-1}$, possibly due to some bias correction
effects from rain gauges located in low-elevation areas (i.e. HADS) which may have
similar rain characteristics to those over ridges.

Figure 6 compares fraction of rain amount as a function of rain intensity over
mountain ridges from the three radar rainfall products. During the summer, some
intermediate and heavy rain samples are identified as lighter rain samples in the Q2rad
and Q2rad_GC. The Q2rad and Q2rad_GC therefore slightly overestimate the total of
light rainfall but greatly underestimate the total at intermediate and heavy rain intensities.
The largest rain amount underestimation occurs with rain rates between 5 and 20 mm$h^{-1}$,
with about 30% underestimation. During the winter, Q2rad underestimates Q2$+$ rainfall
total throughout all the rain intensity ranges. Q2rad_GC also underestimates Q2$+$ rainfall
total for light rain events and some intermediate rain intensities (rain rates less than 6
mm$h^{-1}$). For rain intensities greater than 6 mm$h^{-1}$, the Q2rad_GC appears to agree better
with Q2$+$ than Q2rad, indicating some influence of bias-correction from a limited number
of conventional gauges at low-elevations.

The above comparisons of the rain occurrence and fraction contribution to the rain
amount illustrate the collective impact of factors such as the limited number of gauges
available for correcting the Z-R relationship over the mountains, undetected low-level
precipitation under radar beam elevation, and radar beam blocking by the terrain. Figure
7 shows the joint distribution of coincident rain occurrence between the Q2$+$ and the
other two radar rainfall products during summer and winter over mountain ridges. This
kind of plot is similar to scatter plots but instead of showing the collocated raining
samples, it displays the accumulated distribution of coincident sample numbers. Both the
Q2rad and Q2rad_GC data generally agree with the Q2$+$ during both summer and winter.
However, careful examination indicates that the collocated Q2rad data appear to slightly overestimate rain intensity for very light rain events and underestimate rain intensity for intermediate and heavy rain events. Small improvements can be noticed in the Q2rad_GC data especially for heavy rain events and very light rain events. The bias correction, although coming from gauges some distance away from mountain ridges, does help to obtain better rainfall estimates over the data-sparse ridge area if the two areas feature similar rain characteristics.

Large mountain ridges and valleys usually have distinctly different diurnal variations of precipitation (e.g., Astling 1984; Riley et al. 1986). During the warm season, mountain ridges warm up quickly during the day due to the dominant daytime boundary layer heating, and strong convection usually occurs in the afternoon. On the other hand, mountain valleys cool much more slowly than ridges during the night, and the local ridge-valley circulation usually leads to late night precipitation in valleys. Figure 8 compares diurnal variation of precipitation features over mountain ridges during the summer from the three radar rainfall products. Consistent with earlier studies, the occurrence of and contribution to the total rainfall all indicate a single peak in the afternoon between 13 and 15 LST over mountain ridges. The Q2rad_GC appears to have very similar diurnal signals as the Q2+ in terms of frequency of rain occurrence while Q2rad overestimates rain occurrence from early afternoon to late evening. This overestimation in the Q2rad may be associated with light rain detection from the unadjusted radar retrieval scheme. On the other hand, the Q2rad and Q2rad_GC agree very well in terms of diurnal variation of rain amount and both of them underestimate the Q2+ from morning to afternoon. This underestimation, as discussed earlier, may come
from underestimated rain intensity from intermediate and heavy rain events. The narrow
valley area in the Pigeon River basin is strongly modulated by convection on the
mountain ridge. All three radar rainfall products exhibit a similar diurnal precipitation
pattern as the ridge with a single rainfall peak in the afternoon (not shown). However, for
extensive valley areas which may show a distinctly different diurnal rain features, using
gauge data in valley areas to perform bias corrections over the data-scarce ridge areas
could lead to even larger uncertainties, especially for transient small- and mesoscale
precipitating systems.

In summary, the statistical evaluations of two experimental surface radar rainfall
products against a gauge-enhanced radar rainfall product over mountain regions show a
reasonably good agreement among these surface radar rainfall data in terms of rain
occurrence and rain amount. The diurnal signals of precipitation over mountain ridges
are well captured and joint distributions of coincident raining samples agree well. The
rain intensity bias and light rain detection associated with the radar retrieval schemes and
the impact of the mountains are clearly noticed. Comparing with the reference Q2+ which
merges both enhanced gauge data in high-elevations areas and conventional gauge data in
mid- to low-elevation areas, the Q2rad tends to underestimate rain occurrence and rain
amount at intermediate and heavy rain intensities, and during summer it also
overestimates rain occurrence and rain amount for light rain intensities. The Q2rad_GC,
which merges limited conventional gauge data located in mid- to low elevation areas, to
some extent may help to improve rainfall estimations over data-sparse areas but the result
is highly dependent on the similarity of precipitation characteristics between gauge
locations and the remote mountain areas.
4. Comparisons with satellite rain retrievals

Analyses in Section 3 provide many statistical characteristics for hourly surface radar rainfall products over mountainous regions, particularly the difference between the Q2rad and the Q2+ products. Although surface radar-gauge merged rainfall products currently do not have temporal resolutions less than 1 hour, we can coincidently compare the original Q2rad at 5-minute intervals with instantaneous satellite rainfall retrievals to meet the requirement of collocation at the satellite rainfall product resolution.

Figure 9 examines the distribution of summertime mean satellite rainfall retrievals vs. the sensor swath-sampled Q2rad on a 0.1°x0.1° grid. Although the data are accumulated for three summers, the satellite revisit numbers are still not sufficient to compare with fully-sampled rainfall distributions similar to that shown in Figure 3. Since the PR and TMI have different swaths, their sample sizes are different, consequently we can only compare retrievals from each sensor with the sensor-sampled Q2rad product. The spatial distributions of PR and PR-sampled Q2rad rainfall show similar patterns with a maximum near the southeast corner of the domain and a minimum on the northwest side. Except for a small area near the right hand side of the domain showing some overestimation, the Q2rad in general underestimates compared to the PR over most of the mountain areas, with the largest underestimation located near the main mountain ridge. The TMI and TMI-sampled Q2rad products indicate similar spatial rainfall distributions with a maximum on the northwest part of the domain but also with a few discrepancies. As discussed in many earlier studies (e.g., Wilheit 1986; Kummerow et al. 2001; Ferraro...
et al. 2005), passive microwave rain estimates over land are still largely empirically retrieved from scattering-based algorithms and have significant uncertainties. Not only is the scattering of microwave radiation highly dependent on the poorly known details of the ice-size distribution, but also the precipitation estimate is primarily related to frozen hydrometeor aloft which has a less direct relationship with surface rain rates. Highly variable land surface such as mountain ridges and valleys further make it difficult to distinguish rainfall pixels over complicated and varied surface backgrounds.

During the wintertime (Figure 10), except near the southwest corner where the PR clearly overestimates, the PR and PR-sampled Q2rad indicate a similar distribution with maxima in northwest and southeast corners. Over other parts of the domain, the Q2rad tends to overestimate compared to the PR. The TMI-sampled Q2rad also shows a rain distribution similar to the PR-sampled Q2rad. However, the TMI has significant problems in retrieving wintertime precipitation over mountainous regions with very small rain amounts across the whole domain. It is likely the current empirical retrieval algorithm has difficulties retrieving precipitation over snow-covered regions and solid or mixed precipitation.

Figure 11 shows the frequency of rain occurrence as a function of rain intensity over mountain ridge. During the summer, the PR significantly underestimates the occurrence of light rainfall compared to the PR-sampled Q2rad, mainly due to PR’s detection capability (PR’s minimum detectable rain rate is 0.5-0.7 mmh⁻¹). For intermediate and heavy rain intensities, PR generally overestimates the rainfall occurrence compared to the Q2rad product. Considering Figure 5 which shows the Q2rad suffers less rain occurrence over mountain ridges, the PR data may be closer to the
reference in observing intermediate and heavy rain intensities. The TMI also has large
underestimates for light rain intensities since the minimum detectable rain rate for the
TMI GPROF algorithm over land is about 1 mm h\(^{-1}\). For intermediate and heavy rain
events, the TMI detects more rain occurrences than the Q2rad, which is consistent with
the PR data. During the winter, the PR cannot detect most light rain intensities below 1
mm h\(^{-1}\), but can still detect more rain occurrence than the Q2rad for rain events with rain
intensities above 4 mm h\(^{-1}\). The TMI however, shows a distinctly different pattern in the
occurrence of rainfall since it cannot detect any rain intensities below 1.0 mm h\(^{-1}\), and
above 6 mm h\(^{-1}\). This issue reflects the fact that the current GPROF algorithm over land
has significantly large space for improvement to retrieve wintertime precipitation over
mountain areas.

The contribution of rain intensities to the total rainfall amount is shown in Figure
12. This indicates that during the summer both PR and TMI tend to overestimate with
respect to the corresponding Q2rad at intermediate and heavy rain intensities and
underestimate Q2rad at light rain intensities. These are similar to the statistical features
shown in Figure 6 which compared Q2+ to Q2rad. During the winter, the PR also
indicates similar features as in the summer but the TMI has retrieval problems and can
only provide rain estimates within a very narrow range of rain intensities. Joint
distributions of coincident raining sample numbers (Figure 13) also suggest that the PR
agrees well with the Q2rad during both summer and winter, and the PR generally
overestimates compared to the Q2rad at intermediate and heavy rain intensities at the 5
km footprint scale. The TMI product is similar to that of the Q2rad during the summer
with small overestimates but can only retrieve rain estimates between 1 and 4 mm h$^{-1}$ during winter.

5. Summary

Due to the highly variable precipitation features associated with topography and the limitation of sensors in their coverage and measuring capabilities, accurate estimations of precipitation over mountain areas at fine temporal and spatial resolutions has been a challenging task. Although the commonly-used surface rain reference data from conventional gauge and ground radar network have provided many insights in weather analysis and forecast, they have large biases over mountainous regions and therefore cannot be used as a perfect reference. Satellite rainfall retrievals also have significant uncertainties over land, particularly over complicated mountainous regions such as the Appalachians (Prat and Barros 2010; Duan et al. 2015). Following Tao and Barros (2013) a new hourly surface radar rainfall product merging a conventional gauge-adjusted radar rainfall product (Zhang et al. 2011) with the very dense rain gauge observations has been developed over the Pigeon River basin in the Southern Appalachian Mountains.

In this study, the gauge-enhanced rainfall product is used to evaluate the performance of two operational surface radar rainfall products (radar-only Q2rad and conventional gauge-adjusted Q2rad_GC). Relative to the 5 conventional gauges which are located in the low-elevation river basin area, the enhanced gauge stations are mainly installed in high-elevation regions, and provide a good opportunity to evaluate rainfall estimates over mountain ridges. Rain detection and statistical differences of these three
surface radar rainfall products are examined as a function of rain intensity in different seasons. By defining each data at 0.01°x0.01° horizontal resolutions and 1-h temporal resolutions as an individual precipitating/non-precipitating sample, statistics of rain occurrence and rain amount including their geographical and seasonal variations is documented over a 3-year period between 2009 and 2011.

The results show that there is a reasonably good statistical agreement among these surface radar rainfall data over mountainous regions in terms of horizontal mean distributions of rain occurrence and amount. The fraction of rain occurrence and fraction of rain amount also indicate similar distribution patterns as a function of rain intensity. The diurnal signals of precipitation over mountain ridges are well captured and joint distributions of coincident raining samples indicate similarities during both summer and winter.

However, biases in rain intensity, frequency of occurrence, and rain detection are also clearly noticed. The rain uncertainties are the collective result from a number of factors including the limited number of gauges available for correcting the Z-R relationship over mountains, undetected low-level precipitation under radar beam elevation, and radar beam blocking by mountains. Comparing with the reference Q2+ (which has enhanced gauge observations in high-elevation areas), both the Q2rad and the Q2rad_GC tend to underestimate rain occurrence and rain amount at intermediate and heavy rain intensities and overestimate rain occurrence and rain amount at light rain intensities during the summer. Some of the intermediate and heavy rain intensities shown in Q2+ may be classified in the Q2rad and Q2rad_GC as rain events with lighter rain intensities. The Q2rad_GC product may help to improve rainfall estimates over data-
sparse mountainous areas but the result is highly dependent on the similarity of precipitation characteristics at the gauges and the rainfall regimes in remote mountainous areas. Over the Pigeon River basin, for example, a limited number of conventional gauge stations are installed in low-elevation areas for hydrologic purposes. However, even as this number is small, because the valleys occupy a relative small fraction of the inner mountain region, and despite significant differences between rainfall on adjacent ridges and valleys on an event basins (e.g. Wilson and Barros, 2014; Duan et al. 2015), the use of low elevation gauges to correct radar rainfall estimates proves to be useful from the point of view of the bulk statistics examined here. Over large mountain areas where there are distinctly different diurnal precipitation features over ridges and valleys, using conventional gauge data observed near the valley to correct radar rainfall bias on the ridge could incorporate more uncertainties in rainfall estimates than the original radar-only product, and the diurnal rainfall signals could even be erroneously modified. Great care should be taken with the representativeness error when using the conventional gauge-adjusted radar rainfall product over mountain areas.

With a better understanding of surface radar hourly rainfall products over mountain areas, we coincidently compared the original Q2rad at 5-minute intervals with instantaneous satellite rainfall retrievals from TRMM PR and TMI at their rain footprint resolutions. By assuming that the 5-minute and 1-hour Q2rad data suffer similar topographical impacts over mountain areas, we can indirectly infer some statistical features of satellite rainfall retrievals, especially the one derived from the PR data.

It is found that the horizontal mean rainfall distributions of the PR and PR-sampled Q2rad have similar patterns during both summer and winter. The PR
overestimates rainfall compared to the Q2rad rainfall near mountain ridges in a similar way to the Q2+, especially during the summer. The TMI and TMI-sampled Q2rad show similar horizontal rainfall distributions during the summer but with large differences. During the winter, the GPROF7 PMW rain algorithm has problems in retrieving precipitation over mountainous regions, resulting in very low rain amounts across the whole domain. This reflects a fact that the current empirical retrieval algorithm is not able to handle light rainfall which is dominant in the Appalachians in the cold season, as well snow-covered mountainous regions and solid precipitation.

Comparisons of PR and Q2rad indicate that the PR and PR-sampled Q2rad are in reasonably good agreement in terms of the frequency of rain occurrence and fraction of rain amount. The PR significantly underestimates incidence of light rain intensities compared to the PR-sampled Q2rad, mainly due to PR’s detection capability (PR’s minimum detectable rain rate is 0.5-0.7 mm h\(^{-1}\); see Duan et al. (2015) for a detailed study of PR error characteristics in the Southern Appalachians). The recently-launched DPR on board the GPM core satellite has a minimum detectable rain rate around 0.3 mm h\(^{-1}\), it is therefore expected that light rain intensities can be better retrieved in DPR. For intermediate and heavy rain events, the PR in general overestimates rain occurrence and rain amount compared to that of the Q2rad product. Considering that the Q2+ also overestimates compared to that of the Q2rad product in rain occurrence and rain amount, the PR data appears to be statistically more close to the reference in detecting and estimating intermediate and heavy rain intensities.

Satellite microwave rainfall retrievals have been widely used to provide rainfall estimates on the global scale. Among these microwave instruments, space-borne
precipitation radars have long been expected to serve as space-borne rain references for assessing other satellite rainfall retrievals and even some surface measurements. In this study, we have showed the potential that PR may perform equally well and sometimes better than the high-resolution radar-only rainfall product over complicated terrain for intermediate and heavy rain intensities. After careful calibration and with good reference data, space-borne precipitation radars will indeed be able to serve as a “flying rain gauge” to assess not only other satellite rainfall retrievals, but also surface measurements over data-sparse regions (Hou et al. 2014).
Acknowledgements.

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<table>
<thead>
<tr>
<th>QPE</th>
<th>RMSE (mm h(^{-1}))</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>GSMRGN</td>
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<tr>
<td>Q2 (Q2rad, GC)</td>
<td>0.64</td>
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<td>Q2+ All*</td>
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<tr>
<td>Q2+ H/L*</td>
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<tr>
<td>Q2+ cdfThr</td>
<td>0.30</td>
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</tbody>
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* Q2+ All and the Q2+ H/L are generated using the methods developed in the study of Tao and Barros (2013)
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