7.2 RADAR PRECIPITATION ESTIMATES IN MOUNTAINOUS REGIONS: CORRECTIONS FOR PARTIAL BEAM BLOCKAGE AND GENERAL RADAR COVERAGE LIMITATIONS

Dennis A. Miller, David Kitzmiller, Shaorong Wu, and Robert Setzenfand
Office of Hydrologic Development
National Weather Service, NOAA
Silver Spring, Maryland

1. INTRODUCTION

NOAA/National Weather Service (NWS) is continually endeavoring to upgrade the hydrometeorological products and services it provides to the public. Among these are quantitative precipitation estimates (QPE) on local, regional and national scales, most often on timescales including hourly, 6-hourly and daily. Within NWS operations, these QPEs are crucial to hydrologic prediction on many time and space scales.

One of the principal components of NWS QPE is the estimates provided by radar. Operationally, these are contributed by a national network of more than 120 S-band (~10 cm wavelength) "Weather Service Radar-1998 Doppler" (WSR-88D) radars. Because of its potential to resolve precipitation at small time and space scales, radar QPE is especially important in hydrologic prediction for small basins prone to flash flooding, and in complex terrain (Smith et al. 2004b). In the WSR-88D, QPE is determined via temporal integration of instantaneous precipitation rates (R; mm/hr). Presently, R is derived from the single-polarized, base reflectivity field (Z; mm^6/m^3); however, the NWS is in the process of upgrading the WSR-88D from a single polarization to a dual polarization system (Ryzhkov et al. 2005a). Once this upgrade is completed and validated, R will be determined from several dual polarized fields, including differential reflectivity (Zdr) and specific differential phase (Kdp), as well as from the traditional Z. Which of these estimators (or combinations thereof) is used where will be determined by a preliminary assessment of the type of precipitation (light rain; heavy rain; hail; graupel; snow; etc.) occurring at any given time and location. Where the radar signal is unblocked by terrain or other obstacles or is not filtered or significantly refracted by atmospheric conditions, each unit can provide precipitation estimates to a nominal range of 230 km.

In NWS operations, QPE measures from the individual radars are mosaicked together and optimally combined with precipitation estimates from other sensors, such as rain gauges and satellites, in order to support regional applications such as hydrologic models used in the forecasting of river levels and streamflow rates. Such applications are run at NWS's 13 regional River Forecast Centers (RFCs) and 120+ Weather Forecast Offices, and at the National Centers for Environmental Prediction (NCEP)'s Climatological Prediction Center (CPC). At most of the RFCs, the primary application presently used is the Multisensor Precipitation Estimator (MPE). Another application currently under development at the NOAA/National Severe Storms Laboratory (NSSL) is the National Mosaic and Multi-Sensor Quantitative Precipitation Estimation (NMQ) system (Vasiloff et al. 2007; Zhang et al. 2009). In these and other multi-sensor applications, radar provides an important basis of the overall estimate; however, there are locations where gaps exist in the coverage provided by the individual WSR-88D units. This is particularly problematic in the U.S. mountainous west, where quantitative precipitation estimates are often hampered by terrain induced beam blockages (Vivekanandan et al. 1999; Lang et al. 2009), beam overshooting of precipitation from shallow cloud layers, and range limitations on coverage.

At the NWS Office of Hydrologic Development (OHD), we have recently concluded two studies seeking to improve the overall, NWS operational QPE process: one from the perspective of yielding better estimates at the individual radar units once the dual polar system becomes operational; the other from the perspective of improving the multi-radar/multi-sensor process; and both focused on improving the system's performance in mountainous terrain. The first study involved assessing the limitations on methods for correcting for terrain blockages. This was done by comparing four approaches to radar-based precipitation estimation: the first two based upon the traditional, horizontal polarization-based Z-R relationship, without and with enhancement of the reflectivity-power field (Zenh) to compensate, proportionally, for partial beam blockage (up to 90%); a third method based upon the dual-polarization, specific differential phase field (Kdp) that is, theoretically, insensitive to beam blockage (Zrnic and Ryzhkov, 1996; Friedrich et al.

2007); and a fourth approach that optimally combines the Zenh and Kdp methodologies. The second study explored a methodology for objectively defining radar data quality as a continuous field. A map of radar quality so defined could be used to determine where radar estimates should be blended with or replaced by estimates from other spatially-continuous sources, such as numerical prediction model forecasts or satellite estimates.

Other NOAA offices are working to improve algorithms for mitigating related terrain effects on radar QPE, particularly reflectivity profile effects (Matrosov et al. 2007), and investigating the impact of gap-filling radars (Gourley et al. 2009). Long-term plans involve the incorporation of such improvements within the WSR-88D Radar Products Generator itself and within the NMQ system, which is approaching operational readiness.

2. MOTIVATION

A primary motivation for the first study is that the WSR-88D radar is in the process of being upgraded from a single polarization to a dual polarization system. In anticipation, a new, Dual-Polar QPE algorithm has been incorporated into the latest-release WSR-88D code ("Build 12") and is presently being assessed for potential, national operational implementation. That algorithm, developed by staff of the NOAA/National Severe Storms Laboratory (NSSL), utilizes the Kdp field as the basis for precipitation estimates at places and times when a preliminary, hydrometeor classification procedure (Ryzhkov et al. 2005b) had determined the predominant hydrometeor type to be heavy rain or rain mixed with hail. The Kdp moment, which is determined as the first-order spatial derivative of the dual-polar, differential phase field (Φdp), is generally believed to be "insensitive to radar calibration, partial beam blockage, propagation effects, and system noise" (Brandes, 2000). Hence, it is expected to remain effective as a precipitation estimator even in the presence of rather substantial beam blockage. Despite this potential advantage over other radar fields used as the basis of QPE estimates, its use in the targeted, Dual-Polar QPE algorithm is anticipated to be limited to those situations mentioned above. One aspect of our investigation is to see whether Kdp may have more general advantages as a precipitation estimator in the presence of partial beam blockage.

Furthermore, in the single polarization-based "Precipitation Processing System" (PPS) algorithm (Fulton et al. 2005) that presently runs, operationally, in the WSR-88D, reflectivity-power enhancement is applied to compensate for partial beam blockage, but the upper limit of blockage at which that enhancement is applied rarely, in practice, exceeds the default threshold of 50% (resulting in 2x power enhancement by the PPS method; see equations in section 3c, below). Another aspect of our motivation was to determine whether enhancement of the horizontally-polarized reflectivity field to compensate for blockage beyond the 50% threshold might prove an effective approach to precipitation estimation. We compared the effectiveness of this approach against that of broader application of R(Kdp) (as discussed above) in performing radar-based QPE in areas of beam blockage up to 90% (corresponding to 10x power enhancement).

The second study is designed to define a spatially continuous radar QPE quality field which could be used to weight radar QPE in a multi-sensor analysis in accordance with its quality It is presently focused on the mountainous, western United States during the cool season, October-March, where beam blockages and beam overshooting of precipitation lead to large coverage gaps (Wu and Kitzmiller, 2009; Maddox et al. 2002). Current interactive radar processing software within the NWS Advanced Weather Interactive Processing System utilizes binary radar coverage maps, defined subjectively, for each point in the radar umbrella. We wish to define such coverage maps objectively, and with a numerically-continuous quality index field. Gauge-radar correlations could serve as the basis for such a field; however, gauge coverage is often sparse in the mountainous, western U.S. Hence we sought a substitute, and ultimately found that the quantitative precipitation forecasts

(QPF) of the North American Mesoscale (NAM) model could serve as a suitable proxy.

3. DATA AND METHODOLOGY – APPROACHES TO CORRECTION OF PARTIAL BEAM BLOCKAGE

3a. Approach

Our basic approach was to prepare precipitation estimates via various methodologies from base data collected by an S-band, dual polar radar in a mountainous environment, and compare those, visually and statistically, against verification fields prepared from a combination of rain gauge and WSR-88D radar data. We utilized an in-house processing environment that employed the same core logic to generate the fundamental precipitation estimates as that employed in the new suite of WSR-88D, dual polar-based rainfall estimation algorithms (Ryzhkov et al. 2005a), though our environment did not necessarily contain all the detail and complexity of that system (i.e. we did not precede our analysis with a hydrometeor classification determination at all sample bin locations, nor did we process a multi-elevation "hybrid scan"; our assessment was confined to the 0.5 degree elevation angle).

3b. Base data

At the time of our study, little WSR-88D dual polar, base data were available from locations with significant terrain height and variability. We located suitable data from a field experiment conducted by the NCAR Earth Observing Laboratory (EOL) utilizing its dual polar, S-band unit ("S-Pol") in northeastern Colorado, near Boulder, during June-August 2006 (the Refractivity Experiment for H_2O Research and Collaborative Operational Technology Transfer, or REFRACTT; Roberts et al. 2008). The coverage umbrella of that radar site featured substantial sectors with partial beam blockage, in the south-southeast and north-northwest, as well as broad sectors with little blockage in the east and ones with almost complete blockage, even at low elevation angles, in the west (see Figure 1). An important advantage of this experiment relative to some others was the availability of "Stage4 IV" gridded gauge-radar estimates across the S-Pol umbrella, for use as verification (see section 3d, below). During the 161 hours of data collected over the study period, the predominant precipitation type was convective and, fortunately, we did find many instances of rainfall coincident with regions of partial beam blockage.

In order to determine percent terrain-blockage at individual sample bin locations for this siting, we employed the algorithm and digital elevation model used to generate beam blockage maps at WSR-88D sites, applying it, in our case, at the exact az/ran/height of the S-Pol location, east of Boulder. Figure 1 shows beam blockage, by percentage, at 0.5^0 for that S-Pol location after translation to the operational, ~4x4 km^2 HRAP grid.

3c. Radar QPE preparation

We employed the four methodologies, mentioned above, for preparing QPE estimates, as follows:

a) R(Z) or R(Z0):

We utilized the classic, Z-R relationship for estimating precipitation rate from reflectivity-power, incorporating the multiplicative and power-coefficients employed in the WSR-88D "Convective" relationship, i.e.:

R(Z) = (Z/a)**(1/b)

Where: Z is the (horizontally-polarized) reflectivity-power (mm^6/m^3); R is the instantaneous rainfall rate (mm/hr); a, b are the Z-R multiplicative & power coefficients (300.0; 1.4, respectively).

b) R(Zenh) or R(Z90):

We again employed the classic, Z-R relationship, as above, but this time after the reflectivity-power was enhanced proportionally to compensate for beam-blockage, in the manner of the WSR-88D Precipitation Processing System (PPS):

Blk_Fact = 1.0 / (1.0 - B)

$(B <= B_{threshold})$

Zadj = 10**(dBZ / 10.0) * Blk_Fact

R(Zenh) = (Zadj/a)**(1/b)

Where: B is the fractional beam blockage (to nearest 0.01) at a given sample bin location; $B_{threshold}$ is the upper threshold of beam blockage for which a correction is applied (i.e. 0.90); Blk_Fact is the blockage factor by which a bin's reflectivity power is enhanced; Zadj is the blockage-adjusted reflectivity power (mm^6/m^3); dBZ is the base reflectivity in decibel (log10) units; R(Zenh) is the enhanced rainfall rate after compensation for blockage (mm/hr); a, b are the multiplicative & power coefficients of the Z-R relationship (as above)

To determine B on a bin-by-bin basis we utilized the same methodology as used to determine blockage configuration files at operational WSR-88D sites, but applied it at the exact lat/lon/height of the S-Pol radar. Each bin's reflectivity-power is enhanced proportionally to B, though we cap B at 0.9. (Bins with greater than 90% blockage were not included in our analysis.) At the 0.9 threshold, note that the reflectivity power enhancement is equal to 10. Note: in our R_{enh} notation, 'enh' indicates the maximum blockage factor corrected for (e.g. R_{90}).

c) R(n-Kdp):

We utilized a rainfall estimation methodology based primarily on the specific differential phase field, Kdp, as described in the WSR-88D Dual Polarization Preprocessor and QPE algorithm documentation. This version determines rainfall rates from Kdp unless that field is negative (which we found to occur in 0.03% to 2.0 % of sample bins in our study), in which case we substitute a rainfall rate based upon the horizontally-polarized reflectivity field, i.e.:

R(Kdp) = ak * |Kdp|**bk * sign(Kdp)

```
IF R(Kdp) >= 0
THEN
    R(n-Kdp) = R(Kdp)
ELSE
    R(n-Kdp) = R(Zenh) = (Zadj/a)**(1/b)
ENDIF
```

Where: Kdp is the spatial derivative in the radial direction of the base, dual polar, differential phase field, Φdp; R is the instantaneous rainfall rate (mm/hr); R(Kdp) is the instantaneous rainfall rate dependent only upon the Kdp field (mm/hr); ak is the multiplicative coefficient of the R(Kdp) relationship (44.0); bk is the power coefficient of the R(Kdp) relationship (0.822); sign(Kdp) indicates that the rainfall rate maintains the same mathematical sign (+/-) as Kdp

d) R(Kdp-h):

Here we employed a "hybrid" version of precipitation estimation combining the R(n-Kdp) methodology of our part c, above, for heavier precipitation rates, with the R(Zenh) methodology of our part b, for lighter precipitation rates. To distinguish between the lighter and heavier rates, we employed a threshold (same as used in the WSR-88D Dual Polar QPE algorithm) below which R(Kdp) has been shown in operations to be less effective as a precipitation estimator, i.e.:

R(Kdp) = ak * |Kdp|**bk * sign(Kdp) (as in c, above)

R(Zenh) = (Zadj/a)**(1/b) (as in b, above)

```
IF R(Kdp) < 0  OR R(Zenh) < RRlgt-hvy
THEN
        R(Kdp-h) = R(Zenh)
ELSE
        R(Kdp-h) = R(Kdp)
ENDIF
```

Where: $RR_{lgt-hvy}$ is the threshold for light/heavy rainfall rate, namely 10.0 mm/hr, as estimated from R(Zenh).

3d. QPE Verification data

For our verification fields, we utilized "Stage IV" mosaicked, gauge-radar accumulation grids generated from the Multisensor Precipitation Estimator (MPE) application at the Missouri Basin River Forecast Center (MBRFC) and mosaicked at the National Centers for Environmental Prediction

(NCEP) (Lin and Mitchell 2005). In the region of our study, the WSR-88D radar input to the Stage IV product was primarily from the WSR-88D unit at Denver International Airport (KFTG), which has an unobstructed view of the S-Pol coverage area from the east. These verification fields were prepared on the ~4 km x 4 km, polar-stereographic, Hydrologic Research and Analysis Projection (HRAP) grid system often used in NWS operations. Finally, we translated the S-Pol accumulation fields determined from our four algorithms to the same HRAP grid system. Figure 2 shows one-hour accumulations determined by each of these methods for the one-hour period 2300-0000 UTC, 3-4 July 2006, as well as the corresponding Stage IV verification field.

3e. Statistical Evaluation and Analysis

We performed various statistical analyses upon the hourly accumulations determined from each of the four methodologies {$R(Z_0)$, $R(Z_{90})$, R(n-Kdp) and R(Kdp-h)} against the Stage IV verification data on the HRAP grid. Statistical fields determined included rainfall ratio, correlation coefficient, and error standard deviation. The criterion for including a given grid box for a given hour in the statistical analysis was that one among the measures from S-Pol or Stage IV had to be non-zero. All QPE values were determined from elevation 0.5^0; mean-field bias corrections were *not* applied; 48,428 boxes, in total, over 161 hours, were included

Figures 3-5 show statistical analyses, in the form of bar charts, of all the June-August, 2006 one-hour accumulations generated via the four QPE methodologies against the hourly Stage IV verification field, stratified by percentage of beam blockage into four groupings: 0-25%; 25-50%; 50-75%; and 75-90%. Each percentage-grouping had a fair number of samples (at least 4,100). Figs 3-5 depict the fields Radar/Stage IV Ratio; Correlation Coefficient; and Error Standard Deviation, respectively.

In Fig. 3, it is seen that the precipitation estimates from all the methodologies, when all blockage categories were aggregated together, were less than the Stage IV verification fields. When broken down by blockage percentage, the same was true except for a few instances: R(n-Kdp) slightly exceeded Stage IV when blockage < 50%; likewise did $R(Z_{90})$ in the blockage category 75-90%. Both $R(Z_{90})$ and R(n-Kdp) provided higher, overall estimates than the other two methods. One tendency of interest observed is that the estimates by all methods drop off, relative to Stage IV, once blockage exceeds 50%. This is true for our methodologies, R(n-Kdp) and R(Kdp-h), dependent (fully or partially) on the specific differential phase field, which is supposed to be unaffected by beam blockage unless nearly complete, as well as for our methodologies, $R(Z_0)$ and $R(Z_{90})$, dependent on horizontally-polarized reflectivity, which is known to be affected by such blockage. (Note, however, that $R(Z_{90})$, which compensates for partial beam blockage, recovers in the 75-90% category.)

In Fig. 4, it is seen that all the estimators have fairly similar correlation characteristics against the verification field, with $R(Z_{90})$ and R(Kdp-h) slightly outperforming the others overall and R(n-Kdp) performing slightly the worst. The correlations of all the estimators drop off in the 50-75% blockage percentile, with those dependent on Kdp doing so at about the same rate as the others. Interestingly, all the estimators largely recover in the 75-90% percentile.

The error standard deviation provides an estimate of the magnitude of random errors that cannot be corrected by simple bias adjustment. In Fig. 5, the estimators dependent on Z are seen to have the highest error standard deviation overall, while again, all the estimators perform worse in the 50-75% blockage percentile than in the lower and higher percentiles. For both correlation coefficient and error standard deviation, the estimator that performs ”best” overall – i.e. highest correlations; smallest random errors - is the “hybrid” methodology R(Kdp-h).

Overall, we find that the behavior of the R(n-Kdp) estimator is not consistent with what may be expected from the theoretical behavior of a field that is, theoretically, unaffected by the presence of partial beam blockage. In all our statistical categories, its performance falls off in the presence of beam blockage above 50%, and does so to a similar degree as our other estimators. Meanwhile, we get fairly good performance by correcting the traditional R(Z) field up to a higher percentage of blockage, 90%, than what is normally done in operational practice, 50%. The $R(Z_{90})$ estimator performs about similarly to, if not slightly better than, the R(n-Kdp) estimator, overall as well as in the higher blockage categories. Our estimator which performs the best, R(Kdp-h), is the one most analogous to that employed in the WSR-88D Dual Polar QPE algorithm that is presently under assessment for operational implementation.

4. OBJECTIVE QUANTIFICATION OF SPATIAL VARIATIONS IN RADAR QPE QUALITY DUE TO TERRAIN, BEAM OVERSHOOTING, AND PRECIPITATION CLIMATOLOGY

Multi-sensor merging, such as gauge-radar or satellite-radar, depends on accurate knowledge of coverage limitations, particularly for radar. Radar estimates are affected not only by radar site elevation and precipitation climatology, whose effects on precipitation detection are generally spatially continuous, but also by terrain and other beam-blocking objects, which can cause large horizontal gradients in the radar QPE field. This property of radar QPE means that its quality can range from excellent to very poor within the space of a few kilometers. Over mountainous regions, there are presently no known methods of reliably interpolating radar QPE quality measures, based on point data from sites with rain gauge reports.

In the NWS Multi-sensor Precipitation Estimator (MPE; Seo 1998; Seo et al. 1999; Fulton 2005; Glaudemans et al., 2008), radar coverage boundaries are accounted for through a set of subjectively-derived binary grids depicting long-term radar detection efficiency around each radar (known as the “misbin” grid, see Fulton, 2005). In multi-radar or multi-sensor QPE analysis, areas outside the coverage zone of one radar are either covered by another radar or by rain gauge or satellite estimates.

In an attempt to define the quality of radar coverage objectively, and in terms of a continuous measure that might enable application of compromised but useable radar input, we correlated the radar QPE to a gridded, continuous, reference rainfall field. The reference field we chose is daily 24-hour accumulations from the North American Mesoscale (NAM) model (Black et al. 2005), which provides a spatially-continuous estimate of rainfall that, in the mean, accurately represents terrain-dependent features of local precipitation climatology. The 24-hour NAM precipitation ending at 1200 UTC was taken from the sum of the 12 h forecasts from the previous 1200 and 0000 UTC runs. Radar QPE was taken from the NCEP Stage II product (Lin and Mitchell 2005). We used the product-version designated “radar-only”. It was discovered recently that this data in fact included a mean-field gauge/radar bias adjustment during our study period (Ying Lin, personal communication). However, this adjustment has limited effects on our overall results, since it is only an umbrella-wide multiplicative factor.

An initial experiment (Wu and Kitzmiller, 2009) was conducted for the northwestern conterminous United States (CONUS), which features sharp gradients in climatic precipitation and numerous terrain features causing radar beam blockages. To determine whether the radar-NAM correlation is an effective proxy for radar-rain gauge correlation, we compared the two sets of statistics at several hundred individual daily-reporting sites in this region (Fig. 6). Each point in the figure represents the radar-NAM and radar-gauge correlation over the cool seasons 2007-2009 for one gauge site. We found that the radar-NAM correlation explains almost 80% of the variance in the radar-gauge correlation; therefore we feel confident that we can infer the overall quality of radar QPE data from its correlation to NAM precipitation simulations, at least in the cool season in mid-latitudes.

The process of calculating radar-NAM correlations was repeated for all individual boxes within the HRAP grid over the western United States. For areas beyond the 230-km umbrella of any radar unit, the correlation was set to 0; otherwise, it was determined on a continuous scale 0-100. The spatial distribution of the correlation coefficients (Fig. 7) clearly indicates many known characteristics of radar coverage. These include gaps in the network (central Idaho, central Nevada) and major terrain-induced beam blockages (the radial patterns over northeastern Washington and southeastern Arizona). Since this pattern of correlation coefficients is based on a mosaic of data from multiple radars, range degradation is evident primarily where large areas are covered by only one radar (e.g., western Colorado and eastern Utah, northeastern Montana).

A similar assessment of effective radar coverage in the warm season is being prepared. However, due to uncertainties in QPF in the warm season as a consequence of convection, a new reference precipitation field must first be developed, this time, likely dependant upon satellite infrared estimates and possibly rain gauge information, Moreover, for effective use in the MPE package, the analysis must be extended to individual radar umbrellas. Finally, in an upcoming joint project among NOAA/Office of Hydrologic Development and NSSL, we aim to apply statistical methods to determine how best to merge radar and other remote-sensor information or gauge reports, using this information.

5. SUMMARY AND PRELIMINARY CONCLUSIONS

The results from our Colorado S-Pol experiment indicate that unenhanced precipitation amounts derived from horizontal polarization were substantially underestimated in areas of large beam blockage, as might be expected. However, augmenting the returned power proportionally to the amount of blockage yielded fairly reliable estimates, even in sectors with significant blockage (up to 90%). This finding suggests that, within any one local sector affected by terrain blockage within some limited percentage interval, the time history of precipitation can be reliably retrieved from uncorrected Zh, even though the blockage introduces a low bias in the resulting rainfall estimates.

Our estimates based primarily on the Kdp field appeared to become biased low in areas of partial beam blockage, suggesting sensitivity to terrain blockage, as well. This finding is in contrast to prevalent thinking regarding the behavior of the R(Kdp) field. It is possible that this result was due in part to application of the algorithm to all hydrometeor types; current plans are to use the R(Kdp) operationally only in large-drop or rain/hail situations.

Our estimator that performed the best in terms of correlation coefficient and error standard deviation, R(Kdp-h), is essentially similar to that employed in the WSR-88D Dual Polar QPE algorithm. This is encouraging, in light of the fact that this algorithm is presently under evaluation for national operational implementation.

These findings could have some practical implications, since the current operational practice for the WSR 88D precipitation processing system is to ignore reflectivity data collected wherever beam blockage exceeds 50%. For such locations, reflectivity from the next higher, unblocked antenna elevation is used, instead, in the QPE determination process, even though the radar may be overshooting the precipitation at this higher altitude, or providing an estimate less indicative of what is actually occurring at the ground. These results indicate that further investigation is warranted to determine if the blockage limitation on precipitation estimates determined from the Z-R relationship should be extended to a higher percentage, perhaps as much as 90%.

Our results on quantifying radar QPE quality based on correlation to a spatially-homogeneous reference precipitation field (North American Mesoscale model forecasts) suggest that the radar/NAM correlation effectively indicates quality of radar coverage, on a scale of good-to-suspect. Such a continuous, radar quality index field could be particularly beneficial for use in determining where, or perhaps what percentage-weight to place on, radar precipitation estimates in mosaicked, multi-sensor precipitation fields such as MPE or the National Mosaic and Multi-Sensor Quantitative Precipitation Estimation (NMQ) system (Zhang et al. 2009). It is likely that in order for this analysis to be extended to the warm season, a new reference precipitation field based on satellite rainfall estimates must be employed. Finally, approaches to using the radar/NAM correlation information in estimating the relative weights of radar and other data in a multi-sensor QPE algorithm will be tested

6. ACKNOWLEDGEMENTS

We are indebted to staff of the NCAR Earth Observing Laboratory, particularly Scott Ellis and John Hubbert, for assistance in interpreting the S-Pol data used in the execution of these tasks.

Stage IV precipitation data was retrieved from archives maintained by the NCAR Earth Observing Laboratory.

Ron Guenther, NWS Office of Operational System Radar Operations Center, provided the beam blockage estimates for the Oregon and Colorado S-Pol sites.

Work on mitigation of radar partial beam blockage was supported by the National Weather Service Radar Operations Center. Work on radar coverage patterns was supported by the NWS Advanced Hydrologic Prediction Service initiative.

7. REFERENCES

Black T. L., M. Pyle, and H.-Y. Huang, 2005: The operational WRF-NMM at NCEP. *Preprints, 21st Conf. on Weather Analysis and Forecasting/17th Conf. on Numerical Weather Prediction*, Washington, DC, Amer. Meteor. Soc., **4B.4**. [Available online at: http://ams.confex.com/ams/pdfpapers/94734.pdf]

Brandes E.A., 2000: Dual-polarization radar fundamentals and algorithm prospects, Report on Next Generation Weather Radar Program – Operational Support Facility, WSR-88D Commerce-Defense-Transportation, May 2000.

Friedrich, K., Germann, U., Gourley, J., Tabary, P., 2007: Effects of Radar Beam Shielding on Rainfall Estimation for the Polarimetric C-band Radar. *J Atmos. and Ocean. Tech*., **24**, 1839-1859.

Fulton, R., J. Breidenbach, D.-J. Seo, D. Miller, and T. O'Bannon, 1998: The WSR-88D rainfall algorithm. *Wea. Forecasting*, 13, p377–395.

_____, 2005: Multisensor Precipitation Estimator (MPE) Workshop. [Available from http://www.nws.noaa.gov/oh/hrl/papers/wsr88d/MPE_workshop_NWSTC_lecture2_121305.pdf]

Gourley, J.J., D.P. Jorgensen, S.Y. Matrosov, and Z.L. Flamig, 2009: Evaluation of incremental improvements to quantitative precipitation estimates in complex terrain. *J. Hydrometeor.*, **10**, 1507–1520.

Glaudemans, M., P. Tilles, and B. Lawrence, 2008: Interactive quality control and operational product generation of hourly multi-sensor precipitation estimates in the NWS. *Preprints 23rd Conference on Hydrology*, New Orleans, Amer. Meteor. Soc., 5B.3.

Lin, Y., Mitchell, K.E., 2005. The NCEP Stage II/IV hourly precipitation analyses: Development and applications. *Preprints, 19th Conference on Hydrology.* San Diego, Amer. Meteor. Soc., **1.2**.

Lang, T. J., S. W. Nesbitt, and L. D. Carey, 2009: On the correction of partial beam blockage in polarimetric radar data. *J Atmos. and Ocean. Tech*., **26**, 943-957.

Maddox R. A., J. Zhang, J. J. Gourley, and K. W. Howard, 2002: Weather radar coverage over the contiguous United States. *Wea. Forecasting*, **17**, 927–934.

Matrosov, S.Y., K.A. Clark, and D.E. Kingsmill, 2007: A polarimetric radar approach to identify rain, melting-layer, and snow regions for applying corrections to vertical profiles of reflectivity. *J. Appl. Meteor. Climatol.*, **46**, 154–166.

Roberts, R.D., F. Fabry, P.C. Kennedy, E. Nelson, J.W. Wilson, N. Rehak, J. Fritz, V. Chandrasekar, J. Braun, J. Sun, S. Ellis, S. Reising, T. Crum, L. Mooney, R. Palmer, T. Weckwerth, and S. Padmanabhan, 2008: REFRACTT 2006. *Bull. Amer. Meteor. Soc.*, **89**, 1535–1548.

Ryzhkov, A.V., S.E. Giangrande, and T.J. Schuur, 2005a: Rainfall Estimation with a

Polarimetric Prototype of WSR-88D. *J. of Appl. Meteor.*, Vol. **44**, No. 4, pp. 502—515.

Ryzhkov, A., Schuur, T., Burgess, D., Heinselman, P., Giangrande, S, and Zrnic, D., 2005b: The Joint Polarization Experiment: Polarimetric Rainfall Measurements and Hydrometeor Classification. *Bull. Amer. Meteor. Soc*. **86**, 809-824.**Y -** Seo, D.-J., 1998: Real-time estimation of rainfall fields using radar rainfall and rain gauge data. *J. Hydrol.*, 208, 37-52.

_____, J. Breidenbach, and E. Johnson, 1999: Real-time estimation of mean field bias in radar rainfall data. *J. Hydrol*., 223, 131-147.

Smith, M.B., Seo, D.-J., Koren, V.I., Reed, S., Zhang, Z., Duan, Q.-Y., Cong, S., Moreda, F., Anderson, R., 2004b. The distributed model intercomparison project (DMIP): motivation and experiment design. *J. Hydrology*, 298(1-4), 4-26.

Vasiloff, S.V. and Coauthors, 2007: Improving QPE and very short term QPF: An initiative for a community-wide integrated approach. *Bull. Amer. Meteor. Soc.*, **88**, 1899–1911.

Vivekanandan, J., Yates, D., and Brandes, E., 1999: The influence of terrain on rainfall estimates from radar reflectivity and specific propagation phase observations. *J Atmos. and Ocean. Tech*., **16**, 837-845.

Wu, W., and D. Kitzmiller, 2009: Evaluation of radar precipitation estimates from NMQ and WSR-88D digital precipitation array products: Preliminary results. Preprints 34th Conference on Radar Meteorology, Williamsburg, Amer. Meteor. Soc., **P14.4**.

Zhang, Y et al, 2009: National Mosaic and QPE (NMQ) System – Description, Results and Future Plans. *Extended Abstract, 34th Conference on Radar Meteorology Hydrology.* Williamsburg, VA., Amer. Meteor. Soc., **7A.1**.

Zrnic, D., Ryzhkov, A., 1996: Advantages of Rain Measurements Using Specific Differential Phase. *J of Atmos and Ocean Tech*., **13**, 454-463

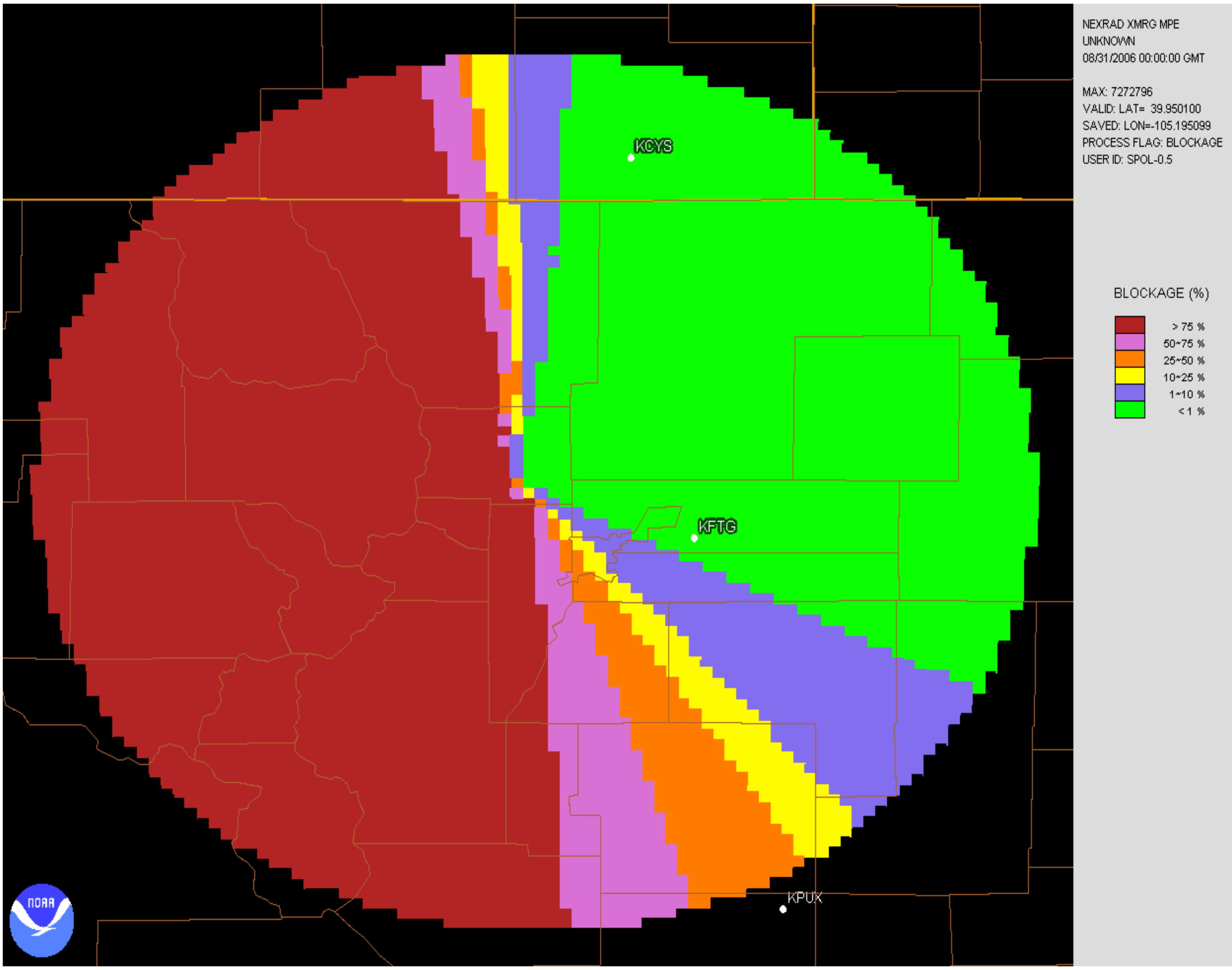

Figure 1. Beam blockage at 0.5^0 for **Colorado** on ~4x4 km^2 HRAP grid centered at S-Pol site east of Boulder.

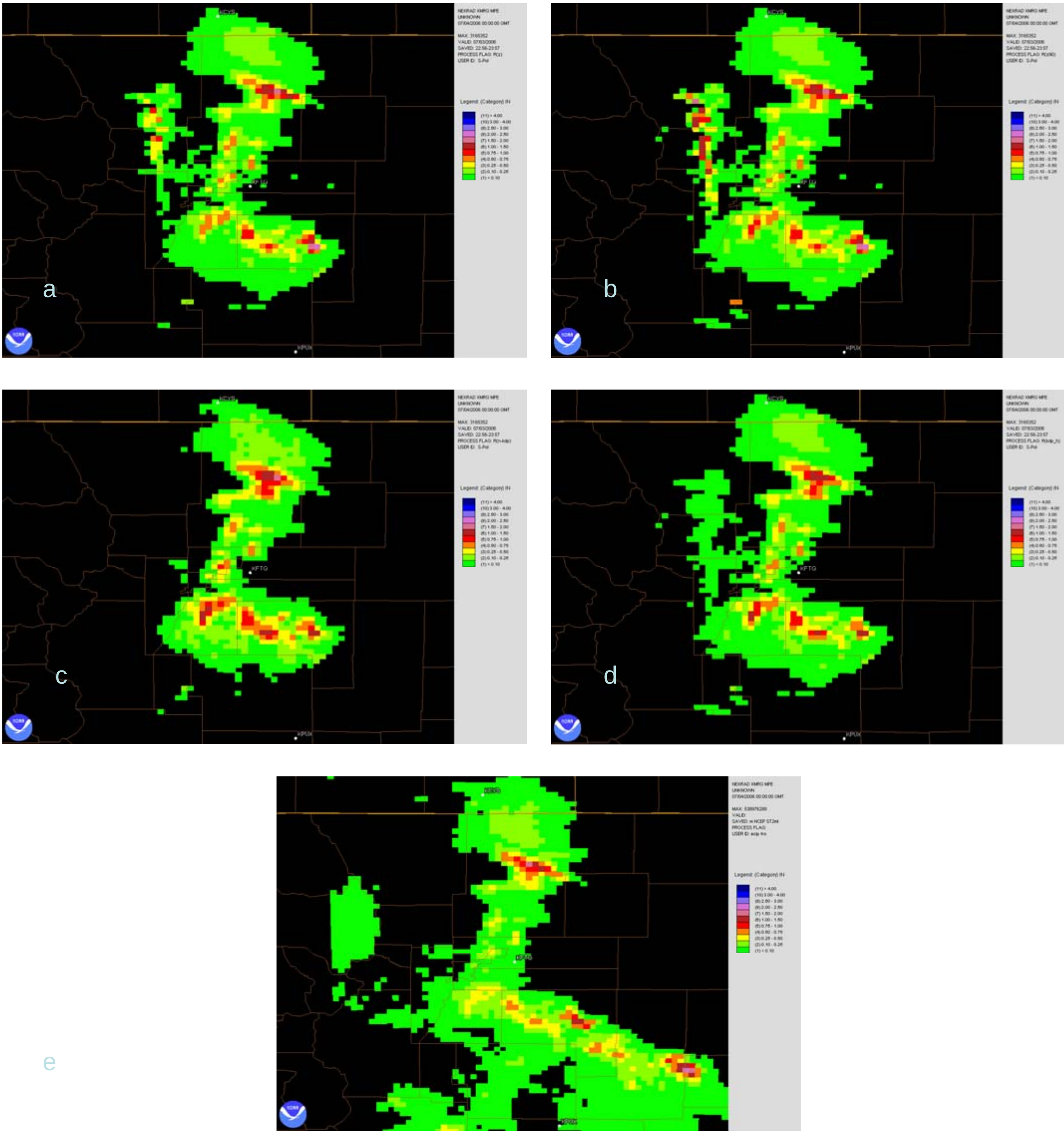

Figure 2. 1-hour accumulations at 0.5^0 for **Colorado** on ~4x4 km^2 HRAP grid centered at S-Pol site east of Boulder, ending 07/04/2006, 00z: a) $R(Z_0)$; b) $R(Z_{90})$; c) $R(n\text{-}k_{dp})$; d) $R(K_{dp}\text{-}h)$*;* also e) Stage IV (verification).

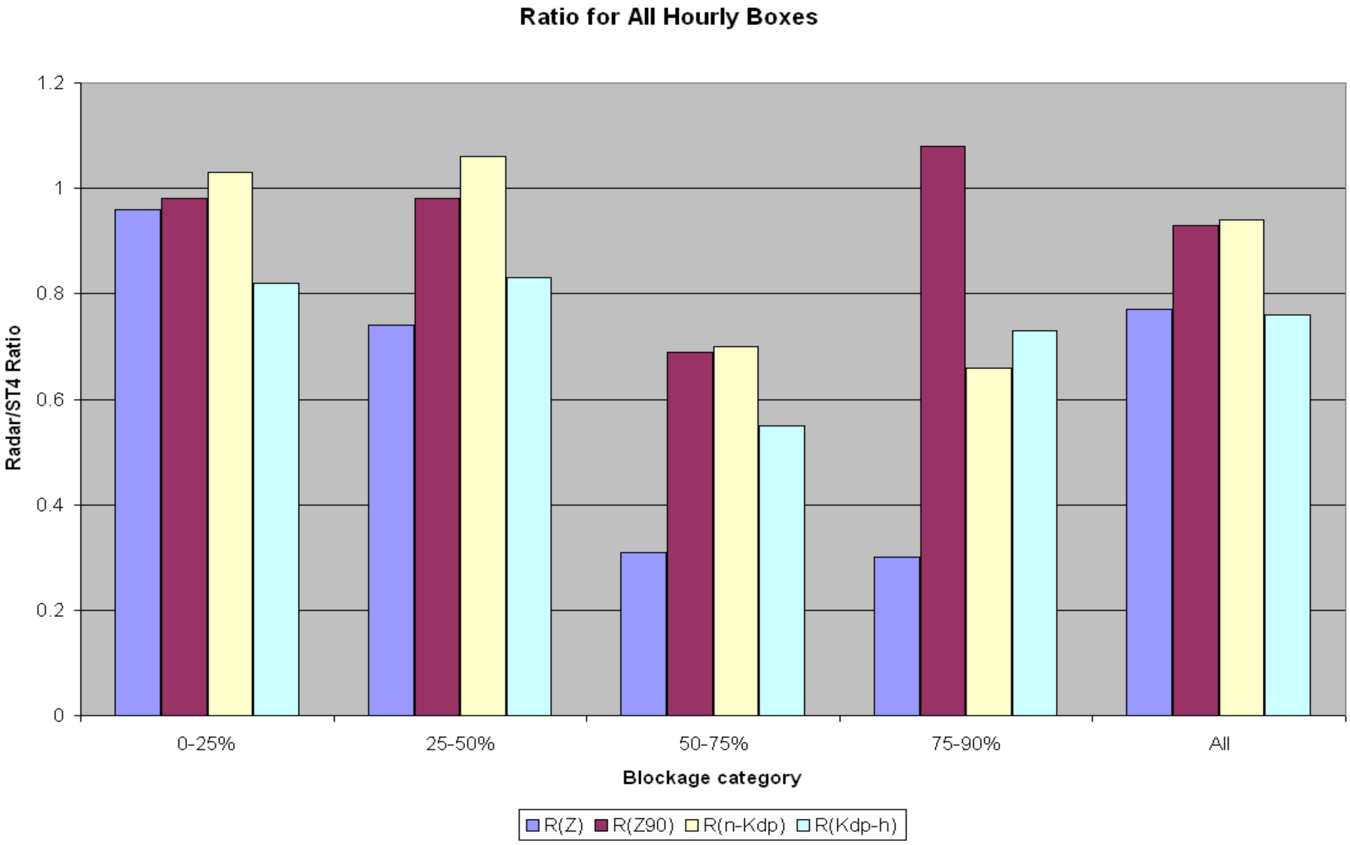

Figure 3. Statistical comparison **(Radar/Stage IV Ratio)** of 1-hour accumulations by different methodologies (blue: $R(Z_0)$; red: $R(Z_{90})$; yellow: $R(n\text{-}k_{dp})$; turquoise: $R(K_{dp}\text{-}h)$) vs. Stage IV verification, for all June, July & August 2006 **Colorado** cases (at 0.5^0) with non-zero accumulation. Stratified by blockage percentage: (0-25%: 30,728 HRAP grid boxes; 25-50%: 5,006 boxes; 50-75%: 8,587 boxes; 75-90%: 4,107 boxes) and all cases considered together (48,428 boxes).

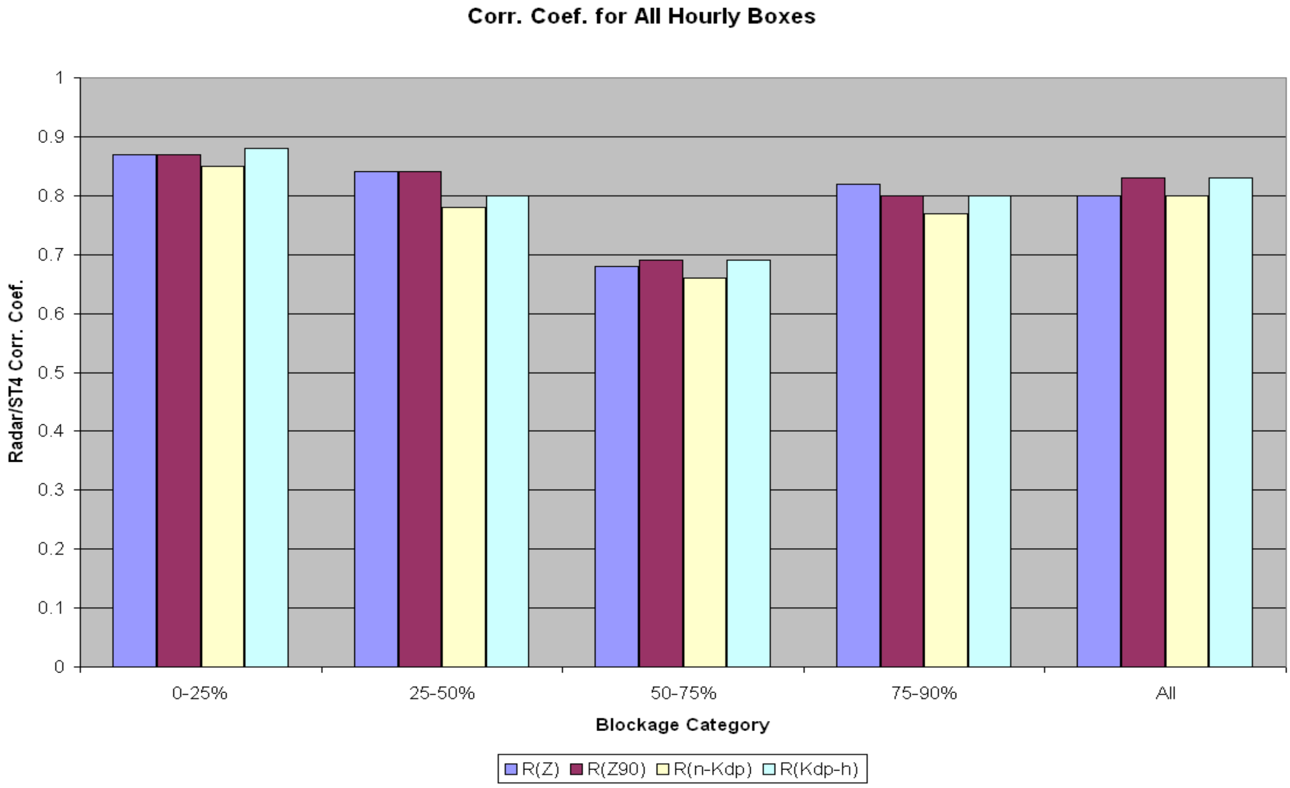

Figure 4. Same as Fig. 3 but for **Correlation Coefficient**.

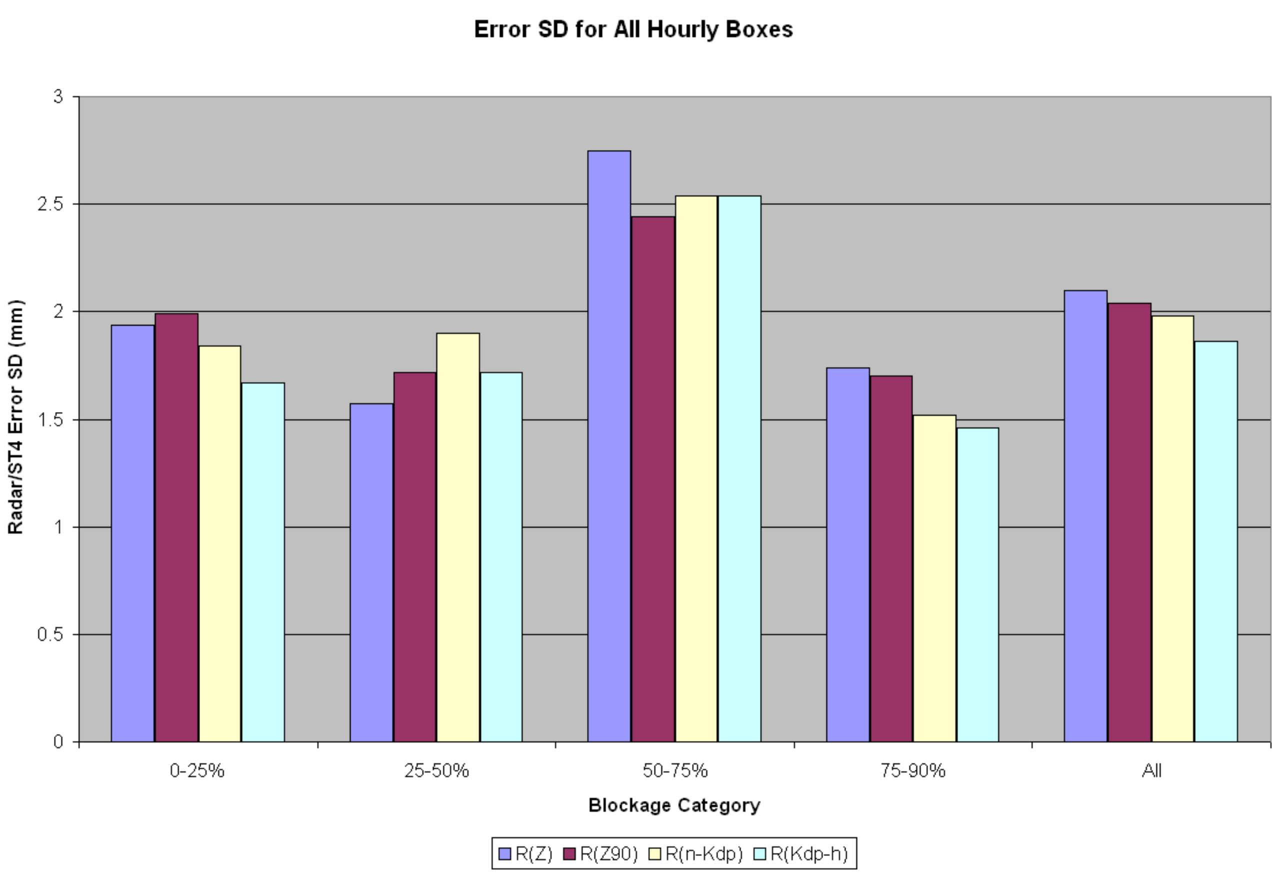

Figure 5. Same as Fig. 3 but for **Error Standard Deviation**.

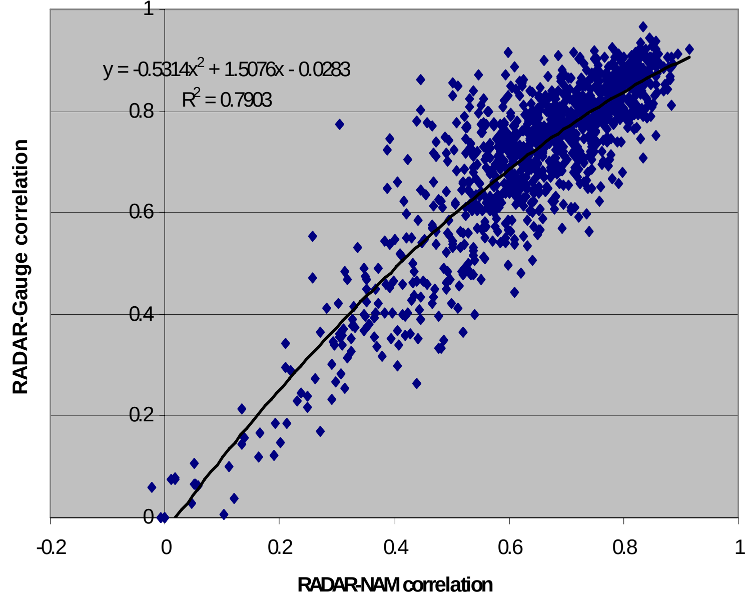

Figure 6. Relationship between Radar-NAM precipitation correlation and radar-gauge correlation for 24-h amounts over the northwestern United States, October-March 2006-2009.

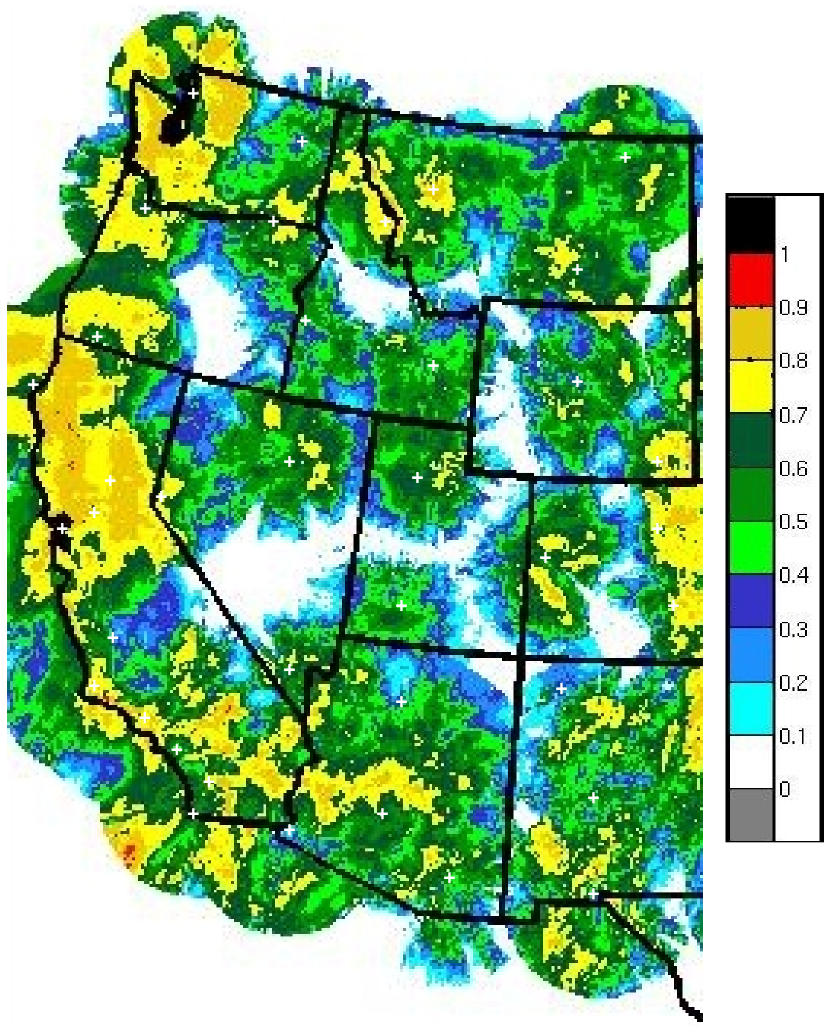

Figure 7. Linear correlation between 24-h precipitation amounts as estimated by radar and simulated by NAM, October-March 2006-2009. White crossmarks indicate WSR-88D sites.