

COMPARISON OF GAGE VS MULTI-SENSOR (RADAR plus GAGE) PRECIPITATION ESTIMATES FOR MIDWESTERN UNITED STATES COUNTIES

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Abstract

An intercomparison of gage and radar-based precipitation estimates was undertaken for the Midwestern United States. Multi-sensor precipitation estimates (MPE) based on the Stage III/IV algorithm developed by the Office of Hydrology / NWS River Forecast Centers, National Weather Service quality-controlled cooperative gage (QC_Coop) data, and gage data from three high density networks in Illinois from February 2002 through August 2005 were examined.

Most differences in county-averaged monthly precipitation estimated by QC_Coop and MPE in nine Midwestern states were within +/- 25%, averaging 6%. The difference between gage and MPE monthly values decreased somewhat through the 41-month period of study. Data from three regional gage networks indicated that on a daily basis, averaged MPE and gage network data agreed to within about +/- 25%. Daily MPE values were often lower than the gage values for large precipitation amounts. When examining multiple gages within single MPE grid points, it was found that for very low daily precipitation amounts, MPE grid amounts were generally greater than gage, and for high daily precipitation amounts, MPE amounts were lower than gage amounts.

Introduction

For many purposes, real-time or near-real-time precipitation over a large area such as the central Midwest is desired. Sometimes daily data are required over small areas within counties, such as small watersheds. The National Weather Service's (NWS) Cooperative Observer Network is the core climate observing network of the U.S., with an average spacing between rain gages in the central U.S. of about 30 km. However, fully quality-controlled data are not available until several months after observations are taken. A small subset of these stations report observations to a local NWS office daily, and are distributed along with other NWS products. The spatial resolution of these real-time data is about one station every 70 km in the central U.S., often inadequate to identify local areas of anomalous conditions, particularly during the warm season when convective rainfall predominates.

Radar estimates of precipitation provide both dense spatial resolution (4 x 4 km grids) and coverage over large areas. Radars, however, have known problems related to the nature of the reflectivity-rainfall relationship, the location of the radar beam within the precipitating cloud, and problems due to calibration, hail, anomalous propagation and ground clutter. These errors often are not uniformly distributed over the radar coverage area, and vary within storms and with distance from the radar. Errors also may vary from radar to radar. Many studies have shown that adjusting radar with gages can improve precipitation estimates (e.g. Huff, 1967; Hildebrand et al., 1979).

A number of previous studies have compared gage precipitation and multi-sensor data (Stellman et al., 2001; Westcott and Kunkel, 2002; and Jayakrishnan et al., 2004). These studies examined observations made prior to 2002. In February 2002, a major upgrade was implemented by the National Oceanic and Atmospheric Administration's (NOAA) NWS Office of Hydrology and River Forecasting Centers, for computation of multi-sensor precipitation estimates (MPE), from the Stage III to the Stage III/IV MPE algorithm. It is the intent of this paper to examine MPE estimates for February 2002 through August 2005, in comparison with gage data.

Data and Analysis

Precipitation data were collected from several sources for this study: 1) daily gridded precipitation estimates based upon hourly gages and the WSR-88D radars obtained in near real-time from the National Centers for Environmental Prediction (NCEP) for the Midwest, 2) daily quality-controlled NWS cooperative raingage (QC_Coop) data from the National Climatic Data Center (NCDC)for the 9-state Midwest region (Fig. 1), and for a multi-county region encompassing the Fox River watershed in NE Illinois and SE Wisconsin, and 3) daily data from three dense gage networks managed by the Illinois State Water Survey (ISWS): the Cook County Precipitation Network (CCPN), the Imperial Valley Water Authority (IVWA) Precipitation Network (both with 10 km spacing in an approximately 2500 km^2 area), and the Boneyard Network (approximately 20 gages within a 95 km^2 area). The following describes these data sets.

Gridded Precipitation Fields

Gridded (4 x 4 km) daily (0600 - 0600 CST) precipitation estimates based on the NWS WSR-88D radar and on hourly rain gage observations are obtained in near real-time from NCEP. County averages are computed for the unadjusted radar (RDR), gage, and MPE fields for the central Midwest, and are stored for analysis. On average, there are twenty grid points per county. The gridded radar precipitation fields for the central Midwest are a composite of data from 30 WSR-88D radars. Fulton et al. (1998) provides a detailed description of the WSR-88D precipitation algorithm and a summary of possible radar and raingage errors. The Hydrometeorological Automated Data System (HADS) hourly gage data are employed to adjust the radar data. These gage data are automatically telemetered to NCEP and other locations in near real-time. Approximately 800 HADS gages are located within the analysis region, with the number increasing over the study period. The amount of real-time manual quality-control of the gage data performed at the individual River Forecast Centers prior to transferring the data to NCEP for processing for the 2002-2005 time period is unclear. The QC_Coop data employed in the Fox River Watershed analysis, and the gages located in the small networks are independent of the HADS and ASOS gages used by the MPE analysis. Aspects of the gridded MPE algorithms are described by Fulton et al. (1998) and Seo (1998).

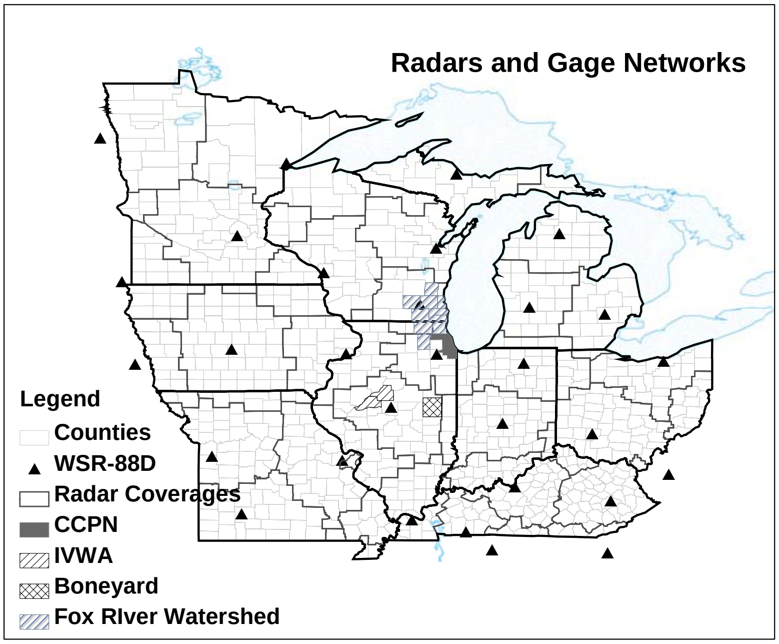

Figure 1. Study Area. Counties which host the Cook County, Fox River Watershed, Imperial Valley Water Authority and Boneyard Networks are indicated.

Stellman et al. (2001) indicated that for an area in Georgia, the algorithms employed in the Stage III MPE algorithm underestimated precipitation by about 38% over a two year period (June 1996 – July 1998) with the summer estimates being of a similar magnitude to the gage estimates, but with wintertime estimates considerably underestimating precipitation. Jayakrishnan et al. (2004) found a considerable underestimation of annual precipitation by MPE during 1996-1997 for Texas, but a trend towards overestimation of annual precipitation by the MPE compared to gages for 1998 and 1999. Westcott and Kunkel (2002) found for July 1997-1999 and 2001 that the county-averaged precipitation was underestimated by the MPE compared to the average computed with QC_Coop data in the early years of record, but with a significant improvement in 2001. During the winter of 2002, the NOAA's Office of Hydrology (OH), in conjunction with the NWS River Forecast Centers, implemented the Stage III/IV MPE algorithm that includes provisions for quality-controlling gage data (NWS Ofc. Hydro. Devel., 2005), and incorporates a new method of local bias-correction (Seo and Breidenbach, 2002). Other changes in radar precipitation processing are described at: http://www.nws.noaa.gov/oh/hrl/papers/papers.htm#wsr88d.

The closest 4 x 4 km grid points from Stage II RDR and the Stage III/IV MPE precipitation estimates are employed for comparison with QC_Coop gages in the Fox River Watershed, CCPN, IVWA and Boneyard precipitation amounts.

Quality Controlled Cooperative Data

The QC_Coop daily data, available approximately three months after the fact, were obtained from NCDC. The gages employed are mainly standard 8-inch non-recording gages. Only gages having 90 percent or more data reported during the period were used. There were approximately 1500 cooperative gages reporting during this period. About 775 of the 858 counties in the study region contained at least one quality-controlled raingage. This resulted in an average of about two gages per county in counties with gages, or about one gage per 800 km^2. The QC_Coop data were the reference standard for examining the utility of the NCEP gridded fields to provide similar quality monthly county precipitation measurements. Although the QC_Coop data are not without inaccuracies due to wind-dependent under catch, gage exposure, and observer errors, these errors are likely comparable to or smaller than radar errors, and smaller than errors in gage data not subjected to rigorous quality control. For all precipitation estimates, monthly totals of 0.0 mm were excluded.

Dense Gage Networks

The first study area covers the northern portion of the Fox River watershed that extends from NE Illinois to SE Wisconsin (Fig. 1). For the daily precipitation comparison, only gages which reported between 05:00 and 09:00 LST were used to attempt to avoid mismatch of days when precipitation fell between midnight and 06:00 LST. The gages range from about 2 to 80 km from the Milwaukee NWS radar in Sullivan, WI (KMKE).

The CCPN is operated by the ISWS for the United States Army Corps of Engineers (USACE). The study area covers most of Cook County, IL, and is just to the southeast of the Fox River Watershed study area, adjacent to Lake Michigan (Fig. 1). Weighing bucket gages are employed. Weighing bucket gages are generally comparable to the standard 8-inch gages (e.g., Allis et al., (1963). Gage data are recorded both on paper charts and data loggers, and are collected and quality controlled monthly. Hourly precipitation amounts are based upon data logger readings taken at 10-min intervals, with the charts used only if digital data are missing. Storm periods are delineated and analyzed for temporal and spatial consistency. Missing hourly values are filled employing a distance weighted interpolation program. For this analysis, hourly data are summed to obtain a daily total valid at 06:00 CST. The gages range from 15 to 75 km from the nearest NWS radar in Romeoville, IL (KLOT). The IVWA network is located in central Illinois (Fig. 1). This network is operated by the ISWS for the Imperial Valley Water Authority and employs weighing bucket gages, with data processed as above. The gages range from about 25 to 75 km from the nearest NWS radar in Lincoln, IL (KILX).

The fourth study area is centered on Champaign-Urbana, Illinois. The Boneyard Network, managed by the ISWS, is a dense volunteer precipitation network which consists of 2.5 x 2.5 inch wedge gages and two standard 8" non-recording gages. Wedge gages were found by Huff (1955) to compare satisfactory with the NWS standard 8-inch non-recording gages for measuring non-snow precipitation. Observations of precipitation, snow, and melted snow are taken daily at about 07:00 LST, and quality controlled by the network manager. The number of gages reporting varied from day to day. Generally about 20 gages reported within the six grid-point coverages included in this study, or about 1 gage / 5 km^2. This area is approximately 95 km east of the nearest radar, KILX.

County-Averaged Monthly Precipitation for the Midwest

Examining the Midwestern United States as a whole, the county-averaged MPE data and QC_Coop track very well (Fig. 2). Except for two months early in the record, February and May 2002, the median percent difference [((QC_Coop-MPE) / QC_Coop) x 100] in county precipitation is generally within +/- 25%, and after January 2003 between +/- 12.5%. Prior to 2005, the differences for all but two months were greater than zero, indicating that that the QC_Coop amounts were generally larger than the MPE averages. During four months in 2005, the median county-averaged MPE amounts are greater than the QC_Coop. This suggests a shift in the relationship between MPE and QC_Coop amounts. The median difference between the percent differences for the first 12 months and last 12 months decreased from 12.5% to 5.3% (Fig. 2), and this difference was statistically significant using the Mann-Whitney U Test. As the difference between the QC_Coop and MPE precipitation estimates decreased, the correlation between QC_Coop and MPE monthly county averages increased. Comparing the first 12 months and the last 12 months of data, the average correlation increased from 0.825 to 0.87, but this difference in correlations was not statistically significant.

One possible reason for differences between MPE and QC_Coop may be in the number of gages used in computing QC_Coop monthly averages. A comparison was made between averages made using 1, 2, and 3 or more gages. Correlations between monthly MPE and QC_Coop county averaged precipitation improved slightly when more gages were used in the computation of county averages. In the more convective months of April to September, there were consistent but small improvements in the correlation between MPE and QC_Coop estimates when more gages were employed. Considering all July county precipitation estimates, for example, the correlation improved from 0.84 to 0.87. From October to March, when non-convective precipitation is more predominant in the Midwest, little or no improvement was found when incorporating 3 or more gages into the average. November and January had consistently high correlations (0.95) no matter how many gages were included in the averaging calculation. The bias in MPE vs. QC_Coop data was found regardless of the number of gages used in averaging. An examination of differences in MPE vs. QC_Coop by areal coverage per gage was also performed for coverages from $<500km^2$/gage to $>2500km^2$/gage ($500km^2$ increment). The MPE underestimated precipitation compared to the QC_Coop by a similar amount for all area categories $<2500\ km^2$.

Precipitation is most critical in the Midwest during the agricultural growing season. For the March to August periods of 2002 to 2005, monthly precipitation was summed for each county. By county, most MPE growing season totals fall within +/- 25% of the gage amount: 88% in 2002, 93% in 2003, and 96% in 2004 and 2005. The percent differences evidenced in individual counties changed somewhat from year to year and a visual inspection (not shown) indicated that the differences varied somewhat by geographical region and perhaps by individual radar coverage areas.

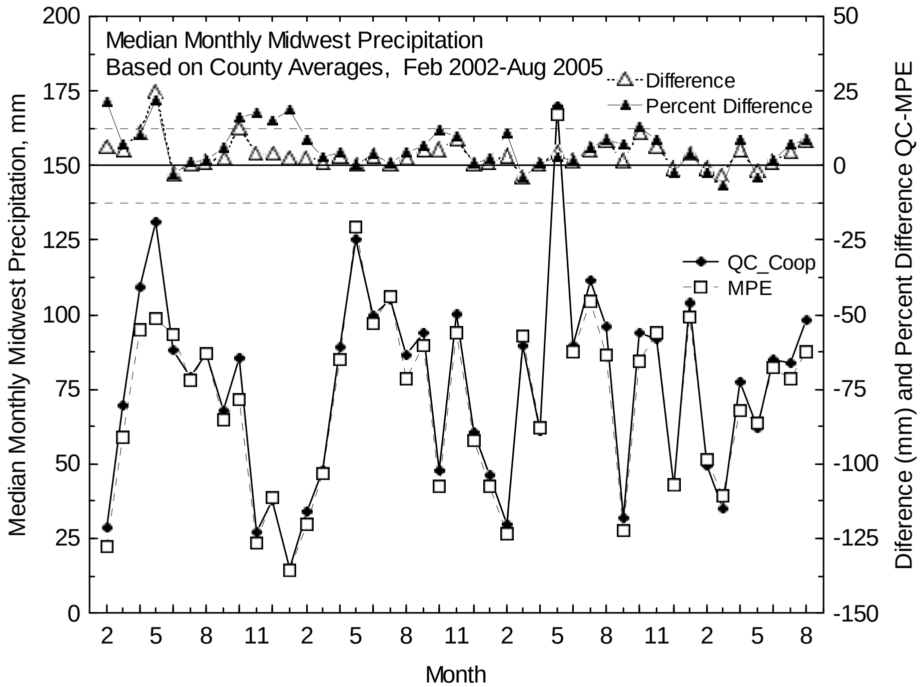

Figure 2. Comparison of QC_Coop and MPE county-averaged monthly precipitation totals for the 9-state region for the period February 2002 to August 2005.

Daily Precipitation Over Small Areas

Both individual gage and network averaged comparisons were made employing QC_Coop data and data from small regional networks. The 20 QC_Coop gages within the Fox River watershed were averaged together to form a “network” daily average. The closest grid point to each gage also was averaged for the radar-only (RDR) and for the MPE data. The daily averaged RDR values in comparison to the QC_Coop average values are generally centered about the 1:1 line, but with large positive and negative deviations (Fig. 3a). In contrast, differences between the MPE and QC_Coop averages are smaller (Fig. 3b), and there is a tendency for the MPE values to be smaller than the QC_Coop values. MPE values fall more frequently within 25% of the QC_Coop values, but often are less than the QC_Coop values. The median percent difference is 14%.

A similar analysis was preformed employing the CCPN and IVWA gages, with similar results (Fig. 3c, Fig. 3d). Again, large differences in the daily gage and RDR averages were found (not shown). The gage and MPE daily averages were more similar, but the MPE averages are often lower than the gage averages. The median percent difference in gage and MPE amounts is 6% for CCPN and -4% for IVWA.

Daily Values at Individual Gages

Heavier precipitation amounts will have a greater immediate impact on the hydrologic system. Gage values of >2.54 cm (1 inch) were examined to determine how well MPE algorithm performed on a daily basis for larger precipitation amounts. During the February 2002 – August 2005 period, there were 84 days when at least one CCPN gage exceeded 2.5 cm, with each CCPN gage having 19-32 days with >2.5 cm of

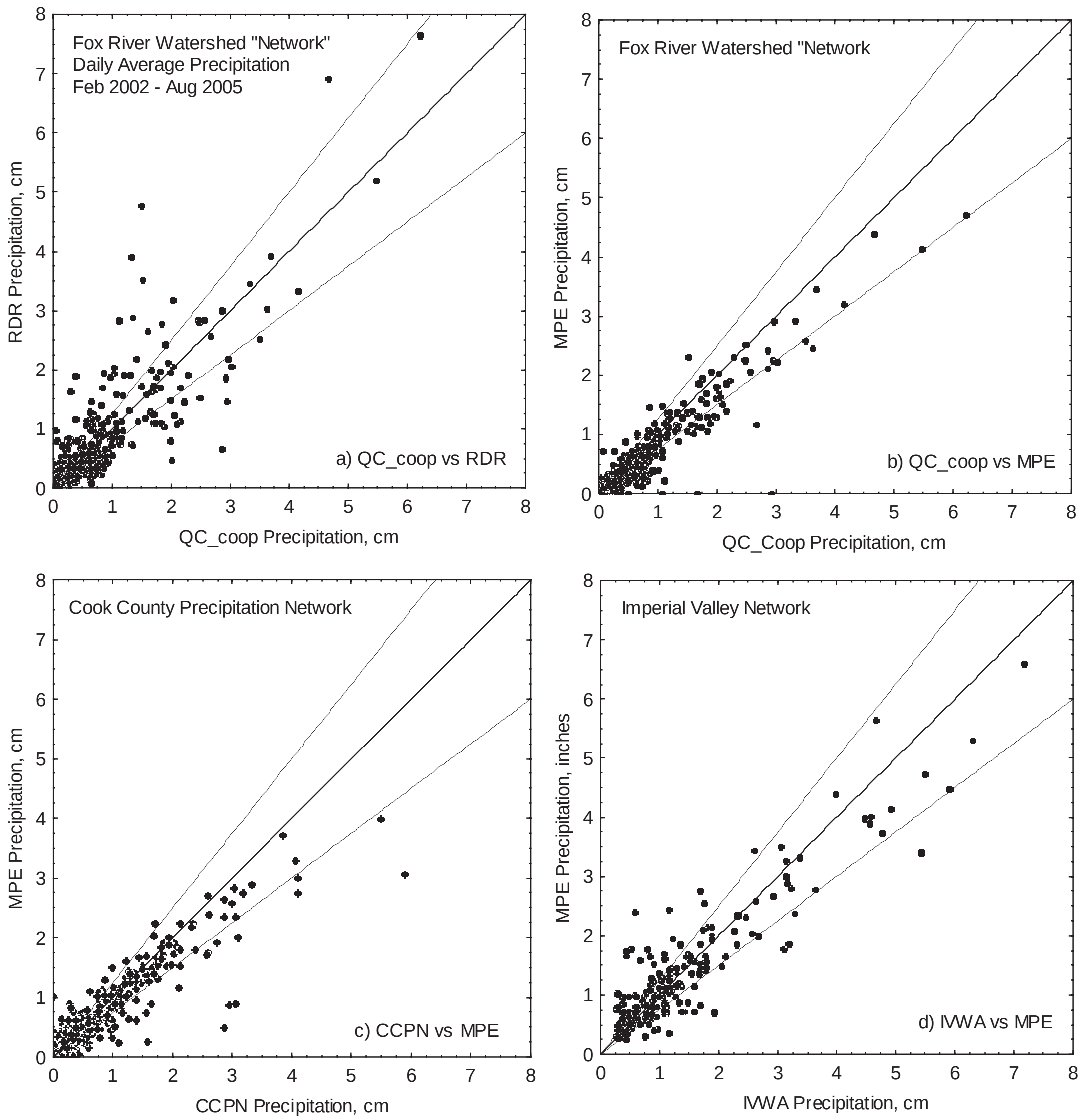

Figure 3. Daily network-averaged precipitation based on QC_Coop gages in the Fox River Watershed and the nearest grid points for a) RDR and b) MPE estimates, and c) the CCPN gages, and d) the IVWA gages vs. the nearest grid points for MPE estimates. The solid line indicates a 1:1 slope and the dashed ones are +/- 25% lines.

precipitation. It was found that the median difference was about 25% for both the Fox River Watershed QC_Coop gages (not shown) and the CCPN gages (Fig. 4). The median differences between the gage and corresponding grid point closest to the KLOT radar (13 km, Fig 1) and the KMKE radar (<2 km), however, were on the order of 50%, much greater than the median difference for all other gages. The RDR estimates also were low compared to the gage values at these near-radar sites, perhaps because of ground clutter filtering. One might speculate that the MPE algorithm was not able to compensate for the very low RDR values at these locations. Gage-MPE differences did not appear dependent on distance from the radar in any other way for the CCPN gages, Fox River Watershed QC_Coop gages, or for IVWA gages. For larger precipitation amounts in the IVWA (not shown), it was found that the median difference ranged from about 7% to 22% with a median of 16%. The largest errors, both positive and negative, were found on days with low precipitation, when only a few gages had amounts over 2.54 cm (1 inch).

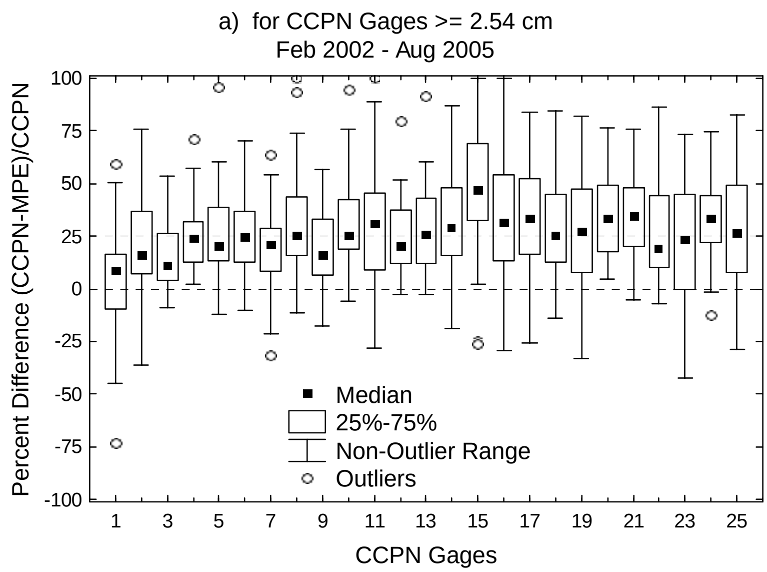

Figure 4. Median percent difference in daily precipitation between each CCPN gage and the nearest MPE grid for February 2002 to August 2005 for gage amounts ≥2.54 cm.

In summary, the MPE precipitation estimates were found to be a considerable improvement over the RDR estimates during the period February 2002 – August 2005, in comparison to the QC_Coop, the CCPN and the IVWA gage data. The MPE data on average are lower than the gage data. The individual gage results confirm the county-averaged comparisons, that is, the lower grid point vs. daily gage amounts translate into lower county averages.

Comparison of Daily Gage Data within a Grid Point Coverage

The variability of precipitation within individual 4 x 4 km grid points is determined here by examining gage data from the Boneyard Network located within Champaign County, Illinois (Fig. 1). Most gages in the network are located within six MPE grid points. Daily gage and MPE data were compared for the February 2002 – August 2005 time period when one or more gages reported precipitation within the coverage of the corresponding grid point, and when the average-gage precipitation and the MPE precipitation both exceeded 0.254 cm (0.1 inch).

When examining multiple gages within single MPE grid points, including more gages in the averaging computation, though improving the agreement between MPE and averaged-gage amount, did not eliminate the bias in MPE vs. gage amount. When the data were grouped by precipitation amount, it was found that for larger precipitation amounts, the bias increased more than the range in gage values within the MPE grid point (Fig. 5). For the lowest precipitation amounts, it was more common (55%) for the

MPE value to exceed the maximum gage amount, and as the precipitation amount increased, there was a strong tendency for the MPE value to be less than the minimum gage value (>60% for precipitation > 2.54 cm; 1 inch). The large number of MPE values lower than the minimum gage amount suggests that the MPE algorithm may systematically underestimate higher precipitation amounts at individual gages. This was found even though overall, the MPE values slightly overestimated precipitation in the Boneyard Network (median percent difference -2%).

Although the percent difference in MPE vs. gage data vary for these three network, from +14% for the Fox River watershed to -4% for IVWA, still as precipitation amount increases, MPE precipitation is more likely to underestimate precipitation in comparison to gage amounts.

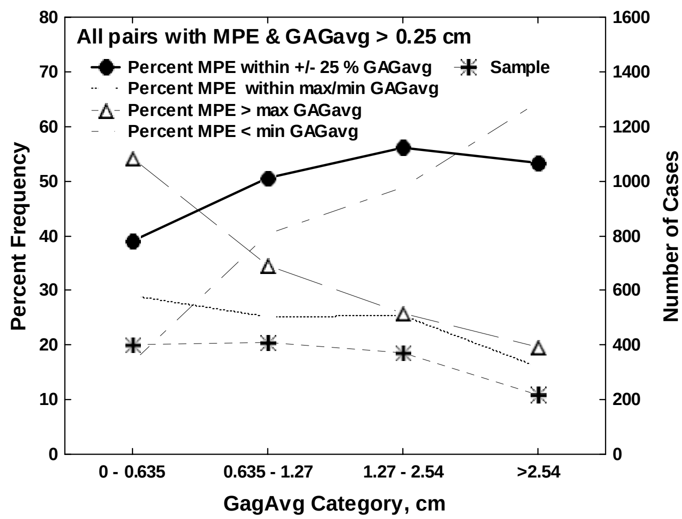

Figure 5. Comparison of MPE and Boneyard averaged-gage (GAGavg) daily precipitation data when both MPE and the averaged gage value were > 0.254 cm, stratified by the average-gage precipitation amount, for Feb 2002- Aug 2005.

Summary and Conclusions

An intercomparison of multi-sensor estimated precipitation at monthly and daily temporal resolutions and county and grid cell spatial resolutions were undertaken for the Midwestern United States for the period February 2002 through August 2005. Examining differences in county-averaged monthly precipitation in nine Midwestern states, differences of +/- 25% were most common, averaging 6%. The difference between gage and MPE monthly values decreased somewhat through the 41-month time period and the mean correlation increased. However, a lower monthly MPE compared to gage bias was present. The bias in gage vs. MPE precipitation was not uniform across the Midwest region.

Data from small regional networks indicated that on a daily basis, averaged MPE and gage network data also agreed to within about +/- 25%. When examining multiple gages within single MPE grid points for a small gage network in central Illinois, it was found that at low precipitation rates (<0.25" or 0.625 cm) the MPE overestimated precipitation and at higher precipitation rates, the MPE underestimated precipitation compared to gages.

Acknowledgements

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