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Evaluation of NEXRAD Radar Precipitation Products for Natural Resource Applications

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Abstract

Timing and amount of precipitation are principal drivers of most rangeland processes, but the availability of rainfall-gauge data over extensive rangelands, particularly in the western United States, is limited. The National Weather Service (NWS), Department of Defense, and Federal Aviation Administration operate a network of Doppler radar stations that produce hourly rainfall estimates, at approximately 16-km^2 resolution, with nominal coverage of 96% of the conterminous United States. Internal utilization of these data by the three agencies is primarily for the detection and modeling of extreme weather events. The usefulness of these data for external hydrologic and natural resource applications is limited by a lack of tools for decoding and georeferencing digital precipitation data products. We modified NWS source code to produce decoding and georeferencing tools and used them to evaluate radar precipitation data for the Boise (CBX) radar relative to gauges in the Snake River Plain of southwestern Idaho for the period January 1998 to May 2004. The relationship between radar and gauge precipitation estimates changed after a revision of radar-processing protocols in 2002 and 2003. Cumulative radar precipitation estimates made prior to November 2002 underestimated gauge readings by 50%–60%. Subsequent radar data overestimated cumulative gauge precipitation by 20%–40%. The radar, however, detected precipitation during significantly fewer hours than were detected by the gauge network both before and after programming changes. Additional modification of NWS precipitation-processing procedures might improve accessibility and utility of these data for rangeland management and natural resource modeling applications. Currently available data can still be very useful for estimating high-intensity events that greatly affect processes such as soil erosion and flooding.

Resumen

La temporada y cantidad de precipitación son las causas primarias que afectan a la mayoría de los procesos del pastizal, sin embargo, la disponibilidad de información sobre la precipitación registrada en pastizales nativos, particularmente en el Oeste de los Estados Unidos, es limitada. El Servicio Nacional del Clima (NWS), el Departamento de la Defensa, y la Administración Federal de Aviación fungen como una red de las estaciones del radar Doppler que producen estimaciones de la precipitación cada hora con una resolución aproximada de 16 km^2 y cobertura nominal del 96% de los Estados Unidos. La utilización interna de estos datos por las tres agencias es principalmente para la detección y modelaje de acontecimientos climáticamente extremos. La utilidad de estos datos para usos hidrológicos y aplicaciones en recursos naturales es limitada por la carencia de herramientas para descifrar y georeferenciar productos digitales derivados de la precipitación registrada. Se realizaron modificaciones del código de fuente de NWS para producir herramientas que descifren y georeferencien. Estas herramientas se utilizaron para evaluar los datos de la precipitación registrada con el radar de Boise (CBX) en la planicie del Rio de la Serpiente al suroeste de Idaho desde enero de 1998 hasta mayo de 2004. La relación entre el radar y las estimaciones de la precipitación registrada cambió después de una revisión de los procesos del radar en los protocolos de 2002 y 2003. Estimaciones acumulativas realizadas antes de Noviembre 2002, subestimaron la precipitación registrada por el radar en 50%–60%. Los datos subsecuentes del radar sobrestimaron la precipitación acumulativa por 20%–40%. Sin embargo, el radar sensiblemente detectó la precipitación durante pocas horas de que ésta fuera detectada por la red antes y después de los cambios programados. La modificación adicional de los procedimientos de los procesos de la precipitación de NWS puede mejorar la accesibilidad y la utilidad de esta información para el adecuado manejo de los pastizales y el uso de aplicaciones en el modelaje de los recursos naturales. Los datos disponibles actualmente pueden todavía ser muy útiles para estimar los acontecimientos de alta intensidad que afectan grandemente procesos tales como inundaciones y la erosión.

Key Words: Doppler radar, meteorology, precipitation, watershed management, WSR-88D

INTRODUCTION

The National Weather Service (NWS), Department of Defense, and Federal Aviation Administration operate approximately 160 WSR-88D Doppler radar stations as part of a Next Generation Radar (NEXRAD) program that began implementation in 1991. These radar stations provide spatial rainfall estimates, at approximately 16-km^2 resolution, with nominal coverage of 96% of the conterminous United States (Crum et

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al. 1998). Effective coverage, especially in the western United States, might be much less due to beam blockage in areas of complex topography (Kingsmill and Huggins 1999; Westrick et al. 1999; Maddox et al. 2002).

The original intent of this network was to support operational objectives of the Departments of Defense, Transportation, and Commerce (Crum and Alberty 1993; Whiton et al. 1998a, 1998b; Anagnostou and Krajewski 1999a). Collection and interpretation of these data have been optimized for detection and mitigation of severe weather events, such as tornadoes and thunderstorms, that might result in flooding, destruction of property, and loss of life (Baeck and Smith 1998; Crum et al. 1998; Winchell et al. 1998; Witt et al. 1998a, 1998b; Anagnostou and Krajewski 1999a; Fulton 1999; Brown et al. 2000; Warner et al. 2000). The primary hydrologic application has been river and flood-forecast modeling by 13 NWS River Forecast Centers (RFC). Because each RFC is responsible for a large river drainage area, optimization of data processing and quality control are geared toward a relatively large spatial domain ($>$ 100 000 km^2; Anagnostou and Krajewski 1998; Seo et al. 1999).

Ideas for practical application of WSR-88D precipitation data to agricultural and natural resource management are easily derived, but have been slow to be implemented (Brandes et al. 1991; Nelson et al. 1996; Hunter et al. 2003; Jordan et al. 2003; Di Luzio and Arnold 2004; Hossain et al. 2004; Neary et al. 2004; Zhang et al. 2004). Previous studies have evaluated the utility of WSR-88D precipitation datasets as input to non-NWS hydrologic models but focused on parameter sensitivity and variability rather than the spatial accuracy of the data (Winchell et al. 1998; Koren et al. 1999; Carpenter et al. 2001; Hunter et al. 2003; Jordan et al. 2003; Di Luzio and Arnold 2004; Hossain et al. 2004; Sharif et al. 2004; Zhang et al. 2004). Utilization of WSR-88D precipitation data by the NWS-RFC system occurs in real time within the context of a custom programming/database/analysis system that is inaccessible to most external users (Anagnostou and Krajewski 1998). Digital, distributed precipitation radar products can be obtained from the NWS, but hourly precipitation files are stored in a binary-coded format for which there are no commercially available software or analysis tools. Georeferencing tools for comparing WSR-88D precipitation products with ground-based measurements also are relatively difficult to obtain and must be adapted for use outside of the NWS–RFC application domain. Development of tools to facilitate accessibility of radar precipitation products can result in product utilization in a larger number of applications than are currently supported (Hunter 1996; Crum et al. 1998; Steiner et al. 1999; Young et al. 2000; Snow and Scott 2003).

The purposes of this paper are 1) to describe the WSR-88D precipitation processing system; 2) to describe data format issues and data-decoding tools for assessing and manipulating WSR-88D Stage I, Level III spatial precipitation data; 3) to describe georeferencing tools for locating gauge sites relative to NEXRAD precipitation cells; 4) to compare NEXRAD and gauge estimates of cumulative precipitation for the Boise, Idaho (CBX) radar location; and 5) to propose modifications to existing data acquisition and management protocols to make these data more useful for rangeland and natural resource management applications.

THE WSR-88D PRECIPITATION-PROCESSING SYSTEM

The existing protocol for WSR-88D precipitation estimation consists of three processing stages (Anagnostou and Krajewski 1998; Fulton et al. 1998). Stage I occurs at the individual radar site and produces spatial rainfall estimates for a single radar domain. Stages II and III involve, respectively, multisensor bias adjustment and creation of a multiradar mosaic of precipitation estimates for areas with overlapping radar coverage.

Stage I, Level-I radar data are composed of raw analog output from the radar scanning process. Stage I, Level II processing produces reflectivity estimates for every radial volume scan (5, 6, or 10 min), in a polar grid with each of 82 800 bins representing 1° of arc and 1 km distance out to a radius of 230 km. The radar measures reflectivity in each bin at multiple elevation angles between 0.5° and 19.5° (Young et al. 1999). A computer program resident at the radar site selects an appropriate elevation angle for every bin based on a map of potential beam blockage for a given site location (Fulton et al. 1998). The resident computer program also conducts a number of error checking procedures and estimates precipitation rate (R) for each bin as a function of reflectivity (Z).

The default relationship between Z and R is based on a power function, $R = aZ^b$, where $a = 0.017$ and $b = 0.714$ (Young et al. 1999). Z–R coefficients have been shown to vary as a function of many factors, and it is not possible to derive a single equation that is accurate at every point in a given radar domain, and for every storm type and storm intensity (Austin 1987; Hunter 1996; Glitto and Choy 1997; Anagnostou and Krajewski 1999a; Ciach and Krajewski 1999; Ulbrich and Lee 1999). NWS radar operators, however, are permitted to select from several different Z–R relationships for an individual radar location and time period. Radar processing also involves selection of a precipitation detection function (pdf), which establishes a threshold reflectivity, below which radar rainfall estimates are set to zero (Anagnostou and Krajewski 1998; Fulton 1999; Kingsmill and Huggins 1999). Selection of appropriate Z–R and pdf coefficients can significantly affect the accuracy of Level III precipitation data but must be implemented at the Level II processing stage.

The WSR-88D precipitation processing system aggregates and remaps Level II radar data into Level III data, which are composed of hourly precipitation estimates that are spatially distributed on the Hydrologic Rainfall Analysis Project (HRAP) grid (Reed and Maidment 1999). The HRAP grid is a standardized grid, superimposed on the United States, with approximately 16-km^2 spatial resolution. Remapping of polar precipitation estimates on the HRAP grid, as Level III data, facilitates comparison and utilization of data for locations with overlapping radar coverage.

Three programming changes were made to the Boise (CBX) precipitation processing system during the time period studied: 5 November 2002; 15 May 2003; and 22 October 2003. Some of these software changes were initiated to correct errors in precipitation detection, and precipitation detection thresholds (Fulton et al. 2003; Istok et al. 2003). Subsequent analyses were conducted to separate these time periods to determine whether changes in radar gauge precipitation relationships were correlated to changes in the precipitation processing software on the radar. Data between November 1998 and May 2004 were evaluated in six 7-mo blocks (November–May) to optimize comparisons of precipitation detection subsequent to software changes.

DATA FORMAT AND DECODING PROCEDURES

Stage I, Level III, WSR-88D precipitation data are output as a series of Digital Precipitation Array (DPA) files, each containing the aggregate precipitation estimate for the previous hour in a binary-coded format (Fulton et al. 1998). Upon decoding, the DPA file consists of a header that contains radar site information, followed by precipitation estimates for 17 161 HRAP grid cells surrounding the radar location.

Individual hourly DPA files can be obtained from the NOAA National Climate Data Center (NCDC; http://hurricane.ncdc.noaa.gov/pls/plhas/has.dsselect). The US Department of Agriculture National Wildlife Research Center developed a computer program in the Perl programming language (Decode.pl), which we modified from the original source code obtained from the NWS Hydrologic Research Laboratory in Silver Springs, Maryland. Decode.pl converts binary-coded DPA files into ASCII-formatted files that contain a precipitation estimate, in mm, for every row and column within the 17 161-cell local HRAP grid domain. Current files are labeled DPA and have a different structure than older files that were labeled HDP (Hourly Digital Precipitation). A transition period also occurred when files with the new HDP format were labeled as DPA files. Decode.pl will decode older, newer, and transition files by calling specific subroutines, depending upon the nature of the file that it is tasked to decode. If no precipitation is detected during a given hour, the DPA file header contains a flag indicating that all of the precipitation values are zero.

RADAR AND GAUGE GEOREFERENCING

The HRAP grid is a polar stereographic projection in which the United States is divided into discrete cells (Reed and Maidment 1999). These cells are designated by numbers indicating row (1 – 881) and column (1 – 1121), relative to a reference point west of Baja California (cell 1,1), and cover the 48 conterminous states (Fulton 1998). Each cell in the HRAP grid is approximately 4 km × 4 km but the exact size varies with distance from the reference point. DPA file data are georeferenced relative to a local HRAP grid, which is defined as a 131 × 131-cell subdomain of the national HRAP grid. As with the national-HRAP grid, row 1, column 1 of the local grid is located at the southern- and westernmost corner of the array. Row numbers increase moving north of row 1 and column numbers increase moving east of column 1. We developed a computer program in C programming language (Gauges_lh.exe) using code from existing NWS algorithms to georeference radar and gauge data relative to both the local and national HRAP grids. This program takes a specific radar location and list of gauge locations (latitude and longitude in decimal degrees) and outputs both the national and local HRAP row, column, and cell ID for the radar location and each gauge. The cell ID is a unique number corresponding to each row and column within the HRAP grid. Row 1, column 1 of the local HRAP grid has a cell ID of 1, progressing to row 131, column 131, which has a cell ID of 17161. The local HRAP location for a given radar is always within row 66 and column 66, which has a cell ID of 8581. All programs used for decoding and georeferencing DPA file data, for both Windows and UNIX operating systems, are available from the authors.

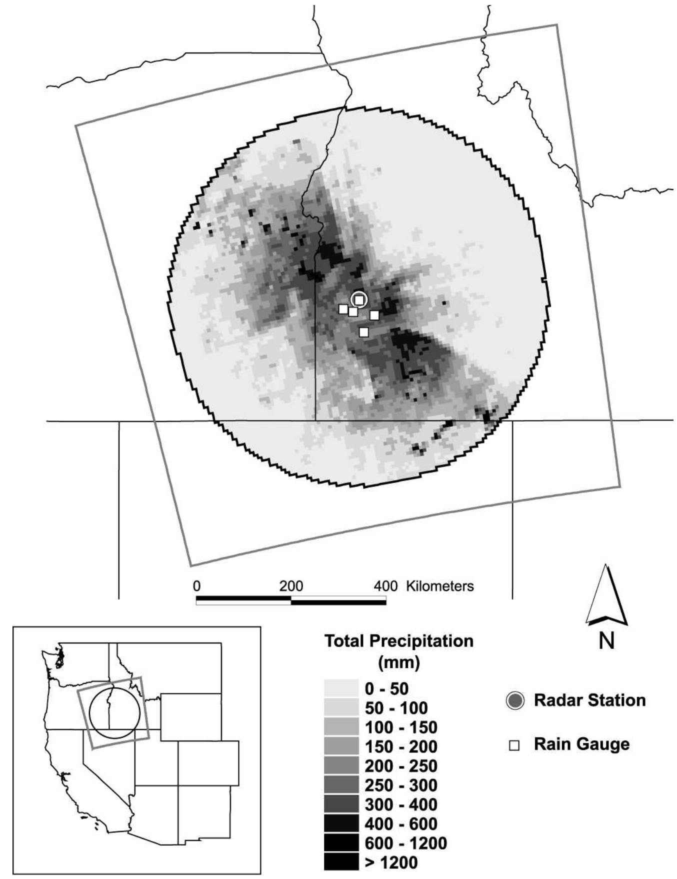

Figure 1. Three-year cumulative rainfall in the Boise (CBX) radar domain. Polygon represents row and column limits for local HRAP grid. Circle represents 230-km radius of coverage for the Level III data product.

COMPARISON OF RADAR AND GAUGE DATA

Four precipitation gauges in the Snake River Birds of Prey National Conservation Area were georeferenced relative to the Boise (CBX) radar, and the national and local HRAP grid. Precipitation was measured with shielded universal recording gauges with a 30.48-cm orifice at a height of 3.05 m aboveground. The shield was an Alter-type with the baffles constrained at an angle of 30° from vertical as described by Hanson et al. (1999). These gauges were all within 40 km of the CBX radar location (953 m above sea level [asl]) in relatively flat terrain and did not have any significant beam-blockage issues. A polygon connecting these gauge locations represents an area of approximately 435 km^2 with a total elevational range of 880–980 m asl. The gauges used in this study were well within the effective sensing domain of the CBX

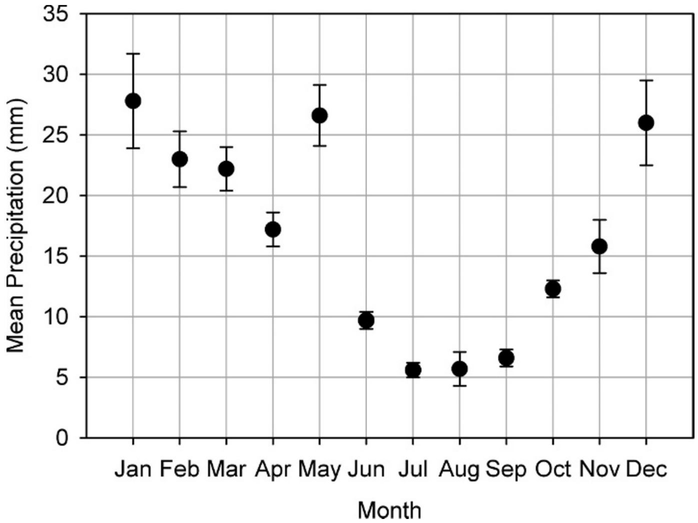

Figure 2. Mean monthly precipitation (± 1 SE) among gauge sites during the study period (January 1998–May 2004).

radar. Figure 1 shows the cumulative precipitation estimate for the CBX radar domain for a 3-yr test period. The general shape of the detected precipitation domain is very similar to that presented by Maddox et al. (2002) for the Boise radar location. Over the course of the study, approximately 80% of the annual precipitation during a given year, as measured by the gauge network, fell during the November–May time period in which data were evaluated for this study (Fig. 2).

Level III data files were obtained from NCDC for January 1998 through May 2004. These data were decoded and aggregated into a temporal and spatial database from which hourly precipitation estimates were derived for gauged cell locations. DPA files contain 1 hr of cumulative precipitation estimates, but these 1 hr accumulation periods do not necessarily coincide with the exact hour as measured by the rain gauge network. The Boise radar location (CBX) estimates cumulative hourly precipitation for the hour prior to each scan, which can be at intervals of 5, 6, or 10 min, depending upon atmospheric conditions within the radar domain. We selected the DPA file for the hour most representative of the gauge measurement interval. Radar data were not used for hours in which a DPA file was unavailable for the period ± 6 min from the top of the hour.

The radar record for the test period was incomplete. In addition to missing time periods, some radar files contained a flag noting insufficient data, bad data, or disk errors during a given hour. Valid DPA files were available for only 93% of the hours in any given year ($\pm 2\%$ standard error of the mean). Mean annual gauge precipitation during the periods when NEXRAD data were unavailable constituted 6% ($\pm 1\%$) of the total gauge precipitation measured during the study period.

Of the hours in which radar data were available, and for which there were no error flags, the total number of hours in which precipitation was detected by the radar was significantly less than the number of hours of precipitation detection by the gauge network (Fig. 3A). The relative number of hours in which the radar detected rainfall increased after October 2002, and again after October 2003, coinciding with radar reprogramming

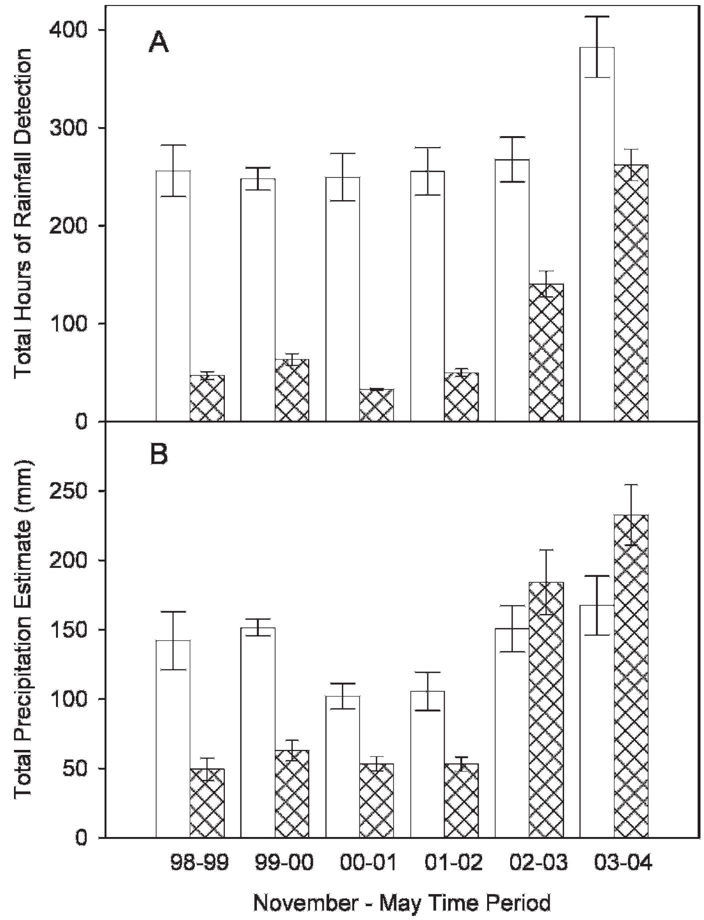

Figure 3. Total hours of detected rainfall (**A**) and total estimated precipitation (**B**) for rain gauges (solid bars) and radar (hatched bars) during the six November–May test periods. Error bars represent ± 1 standard error of the mean.

events (Fig. 3A). Simultaneous precipitation detection by the gauge network and the radar was more likely to occur during higher-intensity events. Hourly rainfall rates for gauges, across all locations and sites, averaged only 0.34 (± 0.05) mm $\cdot$ h^{-1} during periods when only the gauges were detecting rainfall events, but averaged 0.98 (± 0.08) mm $\cdot$ h^{-1} during periods when both the radar and gauges were detecting rainfall events. The ratio of radar to gauge precipitation amount is frequently used as an estimate of radar gauge bias (Glitto and Choy 1997; Anagnostou and Krajewski 1998; Anagnostou et al. 1998; Seo 1998; Ciach and Krajewski 1999; Seo et al. 1999; Steiner et al. 1999; Ulbrich and Lee 1999; Ciach et al. 2000; Seo et al. 2000). This ratio was less than 54% during the first four test periods, but rose to between 123% and 141% subsequent to programming changes in 2002 and 2003 (Fig. 3B).

Mean monthly precipitation estimates for both radar and gauges are plotted in Figure 4 for the period prior to May 2002, and during the subsequent two November–May test intervals. Correlation of radar and gauge estimates during the first two periods (Figs. 4A and 4B) was very low, but improved during the final time period (Fig. 4C). Radar precipitation estimates were significantly lower than gauge estimates prior to May 2002 (Figs. 3B and 4A), indistinguishable from gauge estimates between November 2002 and May 2003 (Figs. 3B

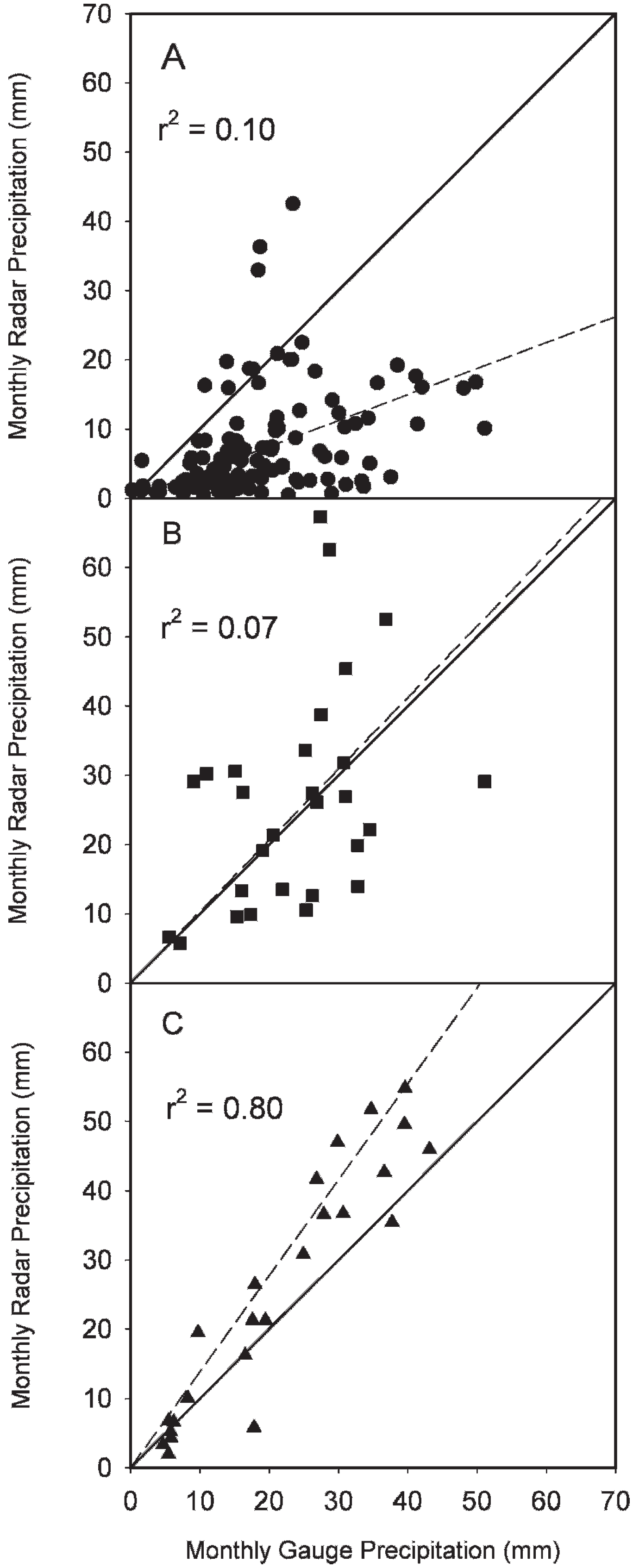

Figure 4. Monthly radar precipitation estimates vs. monthly gauge precipitation estimates for the four test periods before May 2002 (**A**), the 2002–2003 test period (**B**), and the 2003–2004 test period (**C**). The dashed lines represent the linear regression relationships for the data.

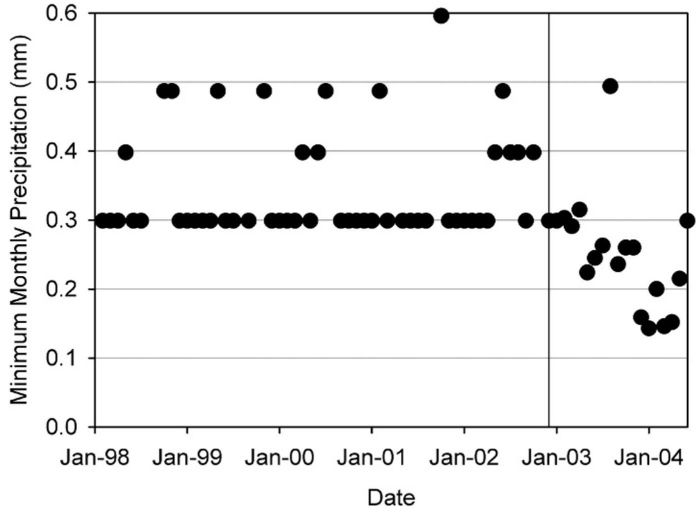

Figure 5. Minimum hourly radar precipitation estimates (mm) for each month within all gauged cells for the entire measurement period. Vertical line represents November 2002, after which all software changes were made at the radar.

and 4B), and significantly greater than gauge estimates after November 2003 (Figs. 3B and 4C).

The precipitation detection function determines the minimum reflectivity at which the radar acknowledges a precipitation event. This function should define the minimum value returned by the radar for precipitation estimation during a given hour. Figure 5 shows the minimum hourly radar precipitation detected by the radar among all gauged cells as a function of time. This figure shows that the radar detected some lower-intensity storm events subsequent to radar programming changes in 2002 and 2003, resulting from utilization of a lower precipitation detection function.

DISCUSSION

Radar data products are subject to three types of error that affect the accuracy of precipitation estimates: mean field systematic bias, range dependent systematic error, and random error (Hunter 1996; Seed et al. 1996; Smith et al. 1996; Anagnostou and Krajewski 1998; Anagnostou et al. 1998; Anagnostou and Krajewski 1999a; Ciach and Krajewski 1999; Steiner et al. 1999; Young et al. 1999; Young et al. 2000). Gauge data can be used to improve the accuracy of WSR-88D radar precipitation estimates in two ways: in development of more accurate model coefficients, such as *Z–R* relationships and pdf values, for Level II data processing; and in postestimate bias correction of Level III DPA data (Glitto and Choy 1997; Anagnostou and Krajewski 1998; Anagnostou et al. 1998; Seo 1998; Ciach and Krajewski 1999; Seo et al. 1999; Steiner et al. 1999; Ulbrich and Lee 1999; Ciach et al. 2000; Seo et al. 2000). Error detection and optimization of radar precipitation products is almost always conducted by comparing radar-precipitation estimates with ground-truth gauge data (Smith et al. 1996; Anagnostou and Krajewski 1998, 1999a; Anagnostou et al. 1998, 1999; Seo 1998; Fulton 1999; Seo et al. 1999, 2000; Steiner et al. 1999; Morin et al. 2003; Neary et al. 2004).

For our data, range dependent systematic errors were probably not a factor because the gauge locations were relatively close together, were not subject to beam blockage and were well within the maximum range of precipitation detection. Random errors would be expected to increase the variability in radar and gauge rainfall estimates but would not be expected to affect mean values over time. We attribute the majority of the discrepancy between gauge and radar estimates in this study to mean field systematic bias. Specifically, the majority of gauge events appear to have occurred below the detection threshold set by the pdf function. We infer this from two types of evidence: mean hours with positive gauge measurements during the November to May test period far exceeded hours in which the radar detected precipitation (Fig. 3B); and mean rainfall intensity measured by the gauge-network when the radar was not detecting rainfall (0.34 ± 0.05 mm · h^{-1}) was significantly less than measured for hours in which the radar was also detecting precipitation (0.99 ± 0.08 mm · h^{-1}). There were some periods where only the radar detected precipitation, but the mean number of hours that this condition occurred was an order of magnitude smaller (20 ± 8 h · yr^{-1}) than the mean number of hours during the test period where only the gauges were detecting rainfall (197 ± 14 h · yr^{-1}). The relative number of hours of radar rainfall detection, and ratio of radar-detected to gauge-detected precipitation increased after radar programming changes in 2002 and 2003 (Fig. 3).

Xie et al. (2006) found similar patterns of radar detection errors for two NEXRAD locations in New Mexico. Xie et al. (2006), however, were comparing gauge estimates to radar estimates from Stage III data, which had already gone through multisensor bias adjustment. Current methods for postprocessing bias adjustment might be inappropriate for estimating cumulative precipitation for radar locations where the majority of gauge events occur below the detection threshold set by the pdf function. This type of systematic threshold detection error might be underrepresented in the literature as most radar gauge comparisons focus on storm totals for higher intensity events or specifically ignore lower intensity events that occur during the test periods (Austin 1987; Klazura and Kelly 1995; Anagnostou and Krajewski 1998; Baeck and Smith 1998; Brandes et al. 1999; Fulton 1999; Steiner et al. 1999; Ulbrich and Lee 1999; Seo et al. 2000). Stage I, Level III radar data from the Boise location, therefore, might not be suitable for long-term water balance and natural resource modeling applications that require estimates of total annual rainfall. Because both gauges and radar were more likely to detect rainfall at the same time during higher-intensity storm events, these data could still be very useful for applications such as flood forecasting and modeling debris flow and erosion events during thunderstorm activity. Indeed, the correlation of gauge and radar precipitation events is relatively good for data obtained after November 2003 (Fig. 4C). Storm activity during these events, however, could still benefit from postprocessing bias adjustment with gauge readings as the Boise radar overestimated gauge catch for this time period.

Data processing procedures that could improve the accuracy of NEXRAD precipitation estimates must be implemented at the Stage I, Level II processing stage. Anagnostou and Krajewski (1999a) describe a detailed methodology to optimize Stage I, Level II radar data for spatial precipitation estimation. These processing steps have been shown to reduce the discrepancy between radar and gauge rainfall estimates over a given radar measurement domain (Anagnostou and Krajewski 1999b). Direct access to Level II radar data is available for research applications but is impractical for many, if not most, potential users of this technology (Crum and Kelleher 1997; Crum et al. 1998; Kruger et al. 1999; Del Greco 2003). Current systems for direct access to Stage I, Level II data require an extremely large data storage capacity for even a single day of data (Crum and Kelleher 1997; Huggins and Kingsmill 1999; James et al. 2000; Del Greco 2003). Real-time access for watershed and land management applications in the $< 10\,000$ km^2 spatial range could be facilitated by development of programming code to reduce data storage requirements for users who can directly access Level II data (Kruger and Krajewski 1997). Real-time Level II data storage requirements could be reduced by immediate processing to eliminate data that do not pertain to precipitation, or are outside the specific spatial domain of interest. These reduced data sets could retain individual scan estimates of reflectivity, at all elevation angles, for the higher-resolution, Level II grid array. Individual users could then apply optimization procedures of the type described by Anagnostou and Krajewski (1999a) to produce high resolution precipitation estimates specific to their watershed or field site of interest.

MANAGEMENT IMPLICATIONS

As they currently exist, Stage I, Level III precipitation data for the Boise (CBX) radar are unsuitable for rangeland management and natural resource modeling applications, which require calculation of total annual precipitation. These data could be useful for extreme event modeling applications but are relatively difficult to access and process. Accuracy of estimation for total annual precipitation might be higher for radar locations in other climatic regimes. We suggest that programming modifications to the current precipitation processing system would facilitate bias evaluation and enhance the utility of these radar data for a large number of potential users of radar detection technology.

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