

Radar and Multisensor Precipitation Estimation Techniques in National Weather Service Hydrologic Operations

David Kitzmiller¹; Dennis Miller²; Richard Fulton³; and Feng Ding⁴

Abstract: This paper describes techniques used operationally by the National Weather Service (NWS) to prepare gridded multisensor (gauge, radar, and satellite) quantitative precipitation estimates (QPEs) for input into hydrologic forecast models and decision-making systems for river forecasting, flood and flash flood warning, and other hydrologic monitoring purposes. Advanced hydrologic prediction techniques require a spatially continuous representation of the precipitation field, and remote sensor input is critical to achieving this continuity. Although detailed descriptions of individual remote sensor estimation algorithms have been published, this review provides a summary of how the estimates from these various sources are merged into finished products. Emphasis is placed on the Weather Surveillance Radar-1988 Doppler (WSR-88D) Precipitation Processing System (PPS) and the Advanced Weather Interactive Processing System (AWIPS) Multisensor Precipitation Estimator (MPE) algorithms that utilize a combination of in situ rain gauges and remotely sensed measurements to provide a real-time suite of gridded radar and multisensor precipitation products. These two algorithm suites work in series to combine both computer-automated and human-interactive techniques, and they are used routinely at NWS field offices [river forecast centers (RFCs) and weather forecast offices (WFOs)] to support NWS's broader hydrologic missions. The resulting precipitation products are also available to scientists and engineers outside the NWS; a summary of characteristics and sources of these products is presented. DOI: [10.1061/\(ASCE\)HE.1943-5584.0000523](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000523). © 2013 American Society of Civil Engineers.

CE Database subject headings: Precipitation; Radar; Hydrology; Predictions; Satellites.

Author keywords: Precipitation; Radar; Hydrologic prediction; Rain gauge; Satellite; Multisensor.

Introduction

Hydrologic operations of the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) are performed at 13 river forecast centers (RFCs) and 122 weather forecast offices (WFOs) situated throughout the United States, Puerto Rico, and Guam. The focus of the RFCs is primarily on producing short- to long-term forecasts of streamflow and stages at selected locations on major rivers in their multistate regions of responsibility. The focus of WFOs is on monitoring and warning for flash flood events in small basins. Staff at all these field offices must collect, ensure quality control of, and interpret real-time hydrologic point data (e.g., rain and stream gauge reports, temperature) and remote sensor precipitation

estimates derived from satellite and radar. These data are then integrated to yield gridded representations of the hourly precipitation field, which can be input directly to hydrologic models.

This paper will summarize the techniques by which the gridded precipitation products are created, with an emphasis on those derived from weather radar, rain gauge, and satellite observations. While detailed descriptions of individual estimation algorithms have been published elsewhere (e.g., [Seo et al. 2010](#)), and as listed below, this article will describe the logic by which their outputs are combined to create finished, gridded precipitation fields.

Among the succeeding sections of this paper, the second and third sections ("Use of Precipitation Estimates in Hydrologic Operations" and "Precipitation-Observing Systems") describe how gridded multisensor rainfall products are used at NWS field offices and the three major data sources and their most important advantages and limitations. The fourth, fifth, and sixth sections ("WSR-88D Radar-Only Estimation Techniques," "Multisensor Precipitation Estimator Algorithm Suite," and "MPE Products and Estimation Techniques") describe the radar Precipitation Processing System (PPS), the Multisensor Precipitation Estimator (MPE), and the suite of products produced by MPE. The remaining sections ("Validation of Radar and Multisensor Rainfall Estimates," "Recent and Future Enhancements," "Sources of Radar and Multisensor Precipitation Estimates in Digital Formats," and "Conclusions") feature a review of published studies that have evaluated NWS operational radar-only and multisensor precipitation products, a brief summary of future plans, sources of radar data and of radar and multisensor precipitation estimates, and a brief summary of this paper.

¹Office of Hydrologic Development, National Weather Service, National Oceanic and Atmospheric Administration, 1335 East West Highway, Silver Spring, MD 20910 (corresponding author). E-mail: david.kitzmiller@noaa.gov

²Office of Hydrologic Development, National Weather Service, National Oceanic and Atmospheric Administration, 1335 East West Highway, Silver Spring, MD 20910.

³Office of Systems Development, National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration, 1335 East West Highway, Silver Spring, MD 20910.

⁴ADNET Systems Inc., 164 Rollins Ave., Suite 303, Rockville, MD 20852; formerly, TCoombs & Associates LLC, 6551 Loisdale Ct., Suite 500, Springfield, VA 22150.

Note. This manuscript was submitted on April 11, 2011; approved on October 17, 2011; published online on January 15, 2013. Discussion period open until July 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Hydrologic Engineering*, Vol. 18, No. 2, February 1, 2013. © ASCE, ISSN 1084-0699/2013/2-133-142/\$25.00.

Use of Precipitation Estimates in Hydrologic Operations

As a prerequisite for describing the estimation techniques in later sections, one must understand how and why the precipitation products are used. Because the hydrologic operations of the RFCs and WFOs are complementary, yet different, they will be summarized separately.

River Forecast Centers

The RFCs have utilized the NWS River Forecast System (NWSRFS) and supporting real-time data processing systems to produce deterministic and probabilistic hydrologic forecasts at various forecast points along major rivers (McEnery et al. 2005). The NWSRFS is a framework containing several calibrated, time-continuous models for soil moisture accounting, such as the Sacramento model (Burnash 1995), which are driven by basin-averaged precipitation from radar and rain gauges, snowmelt, and evapotranspiration. The model basins generally range in size from 300 to 2,000 km² across the United States. The models typically operate with a time step of 6 h and produce forecasts that extend from several days to several months. The RFC operations also produce flash flood guidance (FFG), an estimate of the 1-h, 3-h, and 6-h rainfall totals required to cause small streams to exceed bank-full flow.

Hydrologic operations at RFCs have been transferred to a new framework, the Community Hydrologic Prediction System (CHPS; Roe et al. 2010). The framework will facilitate the use of advanced predictive techniques, including distributed hydrologic models requiring a grid-based representation of precipitation at ≤ 4 -km mesh length and 1-h update frequency.

Weather Forecast Offices

Operations at WFOs are focused on issuance of river forecasts and river flood watches and warnings based on guidance from RFCs, and on monitoring locally heavy precipitation preparatory to issuing watches and warnings for flash flooding on rapidly responding basins. Radar estimates are particularly crucial to these operations. Hydrologic applications utilized for these operations include the Site Specific Headwater Predictor model and the Flash Flood Monitoring and Prediction (FFMP) system. The headwater predictor model produces forecast hydrographs for headwater basins, on the basis of hourly gridded precipitation input (Erb 2002). FFMP, an important tool for monitoring very small basins of less than 250 km², calculates basin-average amounts from gridded radar rainfall estimates and monitors these accumulations relative to FFG values (Smith et al. 2000). Tools are being developed to use distributed hydrologic models to continuously update estimates of soil moisture, runoff, and streamflow (Reed et al. 2006, 2007).

Precipitation-Observing Systems

There are three primary measurement platforms used by the NWS in estimating precipitation in real time: automated telemetering rain gauges, Weather Surveillance Radar–1988 Doppler (WSR-88D), and Geostationary Operational Environmental Satellite (GOES). Each has its own unique strengths, weaknesses, and error characteristics, but when intelligently combined, they can provide precipitation estimates that are better than any single source. This section summarizes the observational advantages and drawbacks of each, as pertains to their importance to NWS hydrologic operations.

Rain Gauges

Rain gauges are in situ measurement devices that have been used operationally for many decades as the only source of precipitation observations for hydrologic forecasting. The RFCs and WFOs run automated gauge preprocessing software procedures that collect the raw gauge data into relational databases and convert the data as necessary into hourly incremental values ending at the top of the hour, as required by radar-gauge merging algorithms. Daily and 6-h rain gauge reports are also used in river forecast operations; nationwide, there are considerably more daily reporting than hourly reporting sites. These reports are disaggregated to hourly, on the basis of radar or nearby hourly gauge reports.

At NWS offices, gauge data are ingested from multiple sources, including the Hydrometeorological Automated Data System (HADS; NWS 2011) and the Meteorological Assimilation Data Ingest System (MADIS; NOAA Earth Systems Research Laboratory 2010). Individual offices often obtain regional observing network data through agreements with local government and utility agencies.

Mechanical problems, telemetry errors, siting deficiencies, and wind-associated undercatch can render individual gauge reports incorrect (Groisman and Legates 1994; Steiner et al. 1999). Considerable staff effort is devoted to quality control of gauge input, and MPE and other Advanced Weather Interactive Processing System (AWIPS) algorithms contain intercomparison and editing features for identifying, and as necessary removing, suspect gauge reports (Glaudemans et al. 2009).

Despite various quality, reliability, and data coverage issues, rain gauge observations are unquestionably critical to hydrologic operations and radar bias correction, and they are commonly treated as local ground truth after suitable quality control measures have been applied. The operational precipitation estimates are still based only on gauge reports in areas or meteorological situations in which radar coverage is incomplete or unrepresentative, such as in areas far from any radar (Maddox et al. 2002) or in snow events.

Radar

The WSR-88D network of more than 160 radars, jointly maintained by the Departments of Commerce, Defense, and Transportation, was deployed beginning in the early 1990s. It has provided the first opportunity to measure rainfall remotely over large areas at high resolution in time and space, and it has contributed greatly to improved flash flood monitoring and warning operations (Polger et al. 1994). Multiple offices within NOAA have collaborated to implement and maintain various techniques to estimate precipitation from these radars.

However, radar estimates contain various well-known errors that can degrade their effectiveness for certain kinds of hydrologic applications, when used alone or without appropriate adjustments. The NWS and its partners have pursued numerous studies to reduce systematic WSR-88D rainfall errors. These studies include ones aimed at understanding the long-term spatial distribution of radar estimate errors (Smith et al. 1996; Baeck and Smith 1998; Klazura et al. 1999; Young et al. 1999), optimally tuning the adaptable parameters within the radar algorithms (Anagnostou and Krajewski 1998; Fulton 1999), and developing new precipitation analysis techniques (Seo et al. 2000; Vignal and Krajewski 2001; Kessinger et al. 2003; Zhang et al. 2011a).

A significant radar error source is vertically varying hydro-meteor distributions within the radar beam, which gets progressively more problematic with increasing range as the beam becomes broader and higher. In particular, radar generally overestimates rainfall in the range zone where the beam detects

water-coated snowflakes in the melting layer (bright band), it and generally underestimates precipitation at long ranges where only dry snow might be detected. To date, no operational techniques have been implemented in the WSR-88D processing system to mitigate these major radar error sources, though MPE functions can partially correct them through merging with rain gauge reports, as explained subsequently in the section on MPE products (“MPE Products and Estimation Techniques”).

Geostationary Satellites

The NWS utilizes operational satellite-based rainfall estimates produced by NOAA’s National Environmental Satellite Data and Information Service (NESDIS). The Hydroestimator technique (Scofield and Kuligowski 2003) utilizes the GOES infrared channels to relate brightness temperature from space to surface rainfall rate and then to hourly rainfall accumulation, after several correction procedures using ancillary atmospheric model data. The advantages of this platform include its extensive spatial coverage at high resolution (~4-km footprint) that is not compromised by terrain blockages and range effects that affect ground-based radar estimates, and the availability of estimates after only a minimal time delay. A disadvantage, however, is the sometimes poor correspondence between measured cloud-top brightness temperature and surface rainfall rate, resulting in systematic rainfall errors that are a function of season and storm type (McCollum et al. 2002).

To date, precipitation estimates from polar-orbiting satellites have not been incorporated directly in MPE, because of the multihour time delay generally necessitated by satellite-to-ground communication limitations. However, algorithm development is underway to statistically correct geostationary infrared estimates with recent collocated polar-orbiter microwave estimates (Kuligowski 2002).

WSR-88D Radar-Only Estimation Techniques

Radar estimates from the WSR-88D are by far the most commonly applied remote sensor input in NWS hydrologic operations. The Radar Product Generator (RPG) subsystem contains the PPS (Fulton et al. 1998), which generates real-time estimates of liquid precipitation at the ground, and the Snow Accumulation Algorithm (SAA) that produces snow depth and snow water equivalent estimates (Super and Holroyd 1997). The SAA has been used infrequently in river forecasting operations because of a more general reliance on snow accumulation models using gauge observations, surface temperature measurements, and snow depth reports. Because the PPS radar-only products are used in NWS operations and are disseminated to the general public, a description of their characteristics is presented in this paper.

PPS Logic

The PPS is a fully automated algorithm that generates graphical and digital, gridded precipitation products out to a maximum range of 230 km from the radar unit. The products are updated every 4–10 min depending on the radar volume coverage pattern. The various coverage patterns sample different sets of antenna elevations depending on the presence, range, and nature of the most significant weather in the immediate area. The PPS converts radar reflectivity measurements that have been spatially averaged to every 1 degree in azimuth by 1 km in range, to rain rate estimates, and then integrates these in time to produce gridded precipitation products. This occurs after a number of initial automated quality control steps to filter out some reflectivity data not associated with

rainfall, for example, that caused by ground clutter, point targets, and anomalous propagation along the radar beam.

After reflectivity preprocessing is completed, a conversion from reflectivity Z (mm^6/m^3) to rain rate R (mm/h) is carried out. All these relationships assume that the precipitation is liquid; algorithms are available (Super and Holroyd 1997; Zhang et al. 2011a) for estimating the liquid equivalent of reflectivity from snow. Fulton et al. (1998) describes two existing Z - R relations that are typically used operationally ($Z = 300R^{1.4}$ for convection; $Z = 250R^{1.2}$ for tropical cyclones). There have been additions to this list to permit greater flexibility (Marshall-Palmer’s $Z = 200R^{1.6}$ for summer stratiform rain, $Z = 130R^{2.0}$ for winter stratiform rainfall east of the Continental Divide, and $Z = 75R^{2.0}$ for the western United States in the cool season). These parameter sets are selected by the radar operator, based on an assessment of the meteorological situation, and are applied at all locations within the radar umbrella.

Radar-Only Precipitation Products

Precipitation products are generated from the original instantaneous rates at multiple timescales, space scales, and precision levels. Polar-gridded products, centered on the radar, include the instantaneous Digital Hybrid Scan (DHR) reflectivity and the Digital Storm Total Precipitation (DSP). The Digital Precipitation Array (DPA) is generated on a Cartesian grid of 4-km mesh length. The map projection is designated the Hydrologic Research Analysis Project (HRAP) grid (Reed and Maidment 1999). These products all feature 8-bit (256-level) quantization and are used for downstream applications requiring further computations, such as the Flash Flood Monitoring and Prediction System (Smith et al. 2000). The DPA is the primary radar input to the Multisensor Precipitation Estimator. Other hourly and multihour products with 4-bit quantization, suitable for graphic display, are also available (Office of the Federal Coordinator for Meteorology 2006).

Pending Major Improvements in Radar Precipitation Processing

Operationally significant improvements to radar precipitation processing are about to be realized through two major development efforts. First, algorithms for vertical reflectivity profile correction and hydrometeor identification have been implemented within the National Mosaic and Multisensor Quantitative Precipitation Estimation (NMQ) system, which is under continuing development by the National Severe Storms Laboratory (Zhang et al. 2011a). The NMQ suite executes enhanced quality control to filter nonprecipitation echoes, and it derives precipitation rate estimates only after compositing data from multiple radars. It features an automated selection of Z - R relationships that can vary continuously in space and time, based on local reflectivity profiles and temperature and humidity conditions. At present, NMQ output is available to RFCs from a real-time prototype platform; its output is sometimes integrated into final products. Planning is underway to make it fully operational.

A major upgrade to the WSR-88D itself is underway with the deployment of dual-polarization capability at the existing field sites, scheduled to take place between 2011 and 2013. Algorithms for time- and space-varying hydrometeor identification, and precipitation rate estimation based on those identifications, will be deployed along with the necessary hardware and software upgrades. These algorithms (Ryzhkov et al. 2005a, b) are expected to yield operationally useful improvements in the quality and consistency of the radar quantitative precipitation estimates (QPEs). Software upgrades to integrate dual-polarization products into MPE are now underway.

Multisensor Precipitation Estimator Algorithm Suite

Operational QPE techniques within the NWS utilize multiple independent inputs to overcome the limitations of any one of the available sensing systems. Use of rain gauge reports integrated with radar rainfall estimates has been a common practice since the WSR-88D radars were first deployed in the early 1990s. Use of satellite input followed in the early 2000s. The MPE has been the most widely used package in NWS operations for ingest, quality control, and merging of precipitation inputs. Both automated and interactive procedures are applied in these processes. A schematic of observing systems and data flows is shown in Fig. 1.

Because radar-only and multisensor QPEs from various stages of the operational processes have been made available to end-users, and the products and their names have evolved over time, a brief history of MPE and its predecessors is presented next. Subsequent subsections describe the current state of MPE.

History of NWS Multisensor Precipitation Products

The NWS originally developed and deployed radar-gauge multisensor estimation techniques in the early 1990s for the RFCs and termed them Stage II and Stage III precipitation processing (Fulton et al. 1998). These techniques have been executed within the NWS's AWIPS computer system, which was deployed to field offices in the mid-1990s. The PPS radar rainfall algorithm, which was called Stage I and executed within each of the WSR-88D RPGs, served as the first of these three major sequential processing steps for quantitative use in downstream hydrologic operations. Stage II referred to the follow-on algorithm that performed quantitative merging of radar and rain gauge data to remove radar biases and produce multisensor rainfall products for each individual radar. Stage III referred to regional mosaicking of these Stage II radar-gauge products and the interactive quality-controlling procedures used by the forecasters to remove suspect radar and gauge data.

Starting in 2002, the legacy AWIPS Stage II and III processing algorithms were both replaced at the RFCs by the Multisensor Precipitation Estimator. Although incremental improvements to Stage II and III had been implemented during the previous decade, the MPE incorporated more fundamental and significant improvements, based on experience gained previously (Breidenbach et al. 1999; Breidenbach and Bradberry 2001). Several years later, MPE was delivered to the WFOs for their use, permitting the use of real-time rain gauge data to adjust PPS radar estimates, a capability previously available only to the RFCs. Initial overviews of MPE are included in Breidenbach and Bradberry (2001) and Lawrence et al. (2003). Story (2000) describes how RFC forecasters create and use WSR-88D multisensor rainfall products. Although some RFCs have developed other gauge-radar merging techniques (e.g., McCormick 1995), these are conceptually similar to the single optimal interpolation approach used in MPE, described briefly subsequently (Seo 1998a; Seo et al. 1999).

Stage IV is a term used to describe the final stage of rainfall processing, the nationwide mosaicking of manually edited, regional Stage III or MPE products produced by each of the RFCs on an hourly basis. This mosaicking has been performed by the NWS Office of Climate, Weather and Water Services and National Centers for Environmental Prediction (NCEP) since 2002. A completely automated, Conterminous United States (CONUS) scale version of Stage III/MPE has been operated by NCEP since 1996 (Lin and Mitchell 2005).

Overview of MPE Functions

MPE uses as input the HRAP-gridded DPA 1-h rainfall product from PPS for each radar ending at the top of the hour. As a result, any scientific enhancements to the PPS will necessarily be reflected in improved downstream MPE products. The MPE also uses any recent gauge reports that are available within AWIPS at the time that it executes, typically at approximately 25 min past each hour.

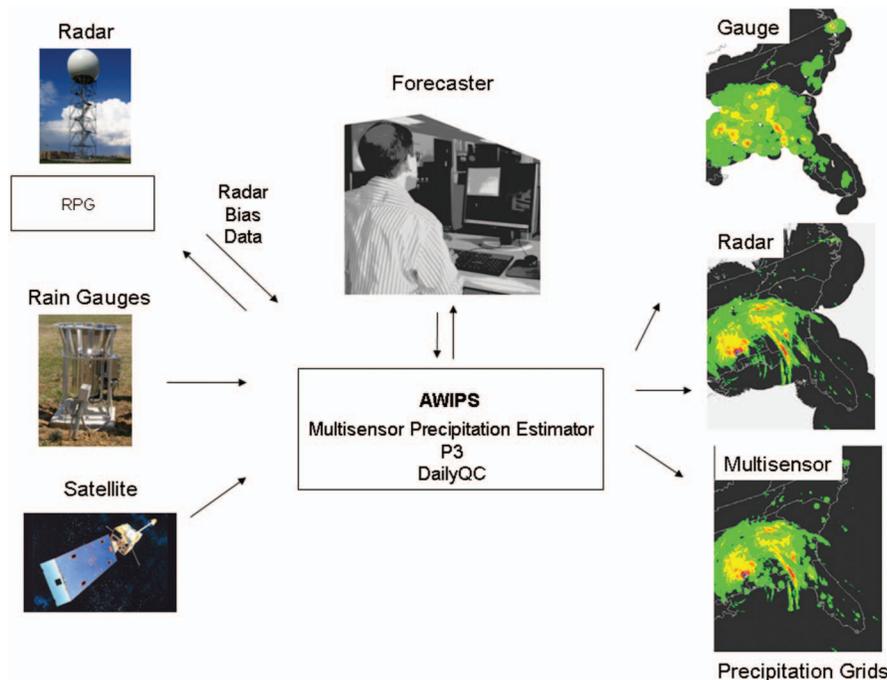


Fig. 1. (Color) Schematic of relationship among observing and processing systems, human input, and final gridded precipitation products; radar precipitation products are created in the RPG; MPE, P3, and DailyQC applications run within the AWIPS (images of satellite and radar are courtesy of NOAA)

As explained subsequently, MPE produces a suite of rainfall products each hour that result from various single or multisensor merging techniques. In addition to running the most recent MPE analyses each hour, analyses are also typically regenerated and updated for each of the two or three previous hourly periods.

Mosaicking of Overlapping Radars

MPE can generate regional rainfall estimates by mosaicking individual DPA radar products from multiple radars. The density of the WSR-88D network over the United States is such that there is often overlap of adjacent radar umbrellas at the nominal 230-km range limit for precipitation estimation. One advantage of mosaicking in these overlap regions is that it helps to alleviate range degradation of the individual radar estimates. For the estimate at points covered by multiple radars, users have the option to select the value from the radar with the lowest beam height over the point, the maximum value from all radars, or an average of all overlapping values.

Radar Climatologies for Effective Coverage Delineation

Several studies and operational experience have shown that effective radar coverage rarely extends to the assumed range of 230 km from the radar, particularly in the cool season when rainfall systems tend to be shallower and more likely to be overshoot by even the lowest elevation beam or in zones of terrain blockage (e.g., [Smith et al. 1996](#)). The developers have dealt with this coverage issue by developing radar precipitation climatology for each site, from multiple years of DPA products. The resulting precipitation maps clearly show the effects of local blockage and the ranges at which precipitation detection efficiency becomes unacceptably low, as a function of azimuth ([Breidenbach et al. 1999](#)).

Quality Control of Rain Gauge Reports

Users of MPE have several capabilities for rain gauge quality control, including both manual and automated procedures. Users can manually edit or delete bad gauge reports for a given hour using a map-based graphical interface or after examining a rain gauge table display that can be ranked by gauge amount. A gauge-radar visual overlay capability is available to aid in identifying suspect gauge reports. In addition to gauge removal, the user may insert pseudogauges in data-sparse locations to incorporate nonstandard reports or to nudge the multisensor analysis toward a value that is considered more realistic. This feature makes use of the multisensor algorithm's assumption that gauge reports represent the best estimates in the immediate area (see subsection "Merged Multisensor Mosaic Based On Bias-Adjusted Radar and Gauges").

The MPE also includes two automated quality control procedures, the Spatial Consistency Check and the Multisensor Check, which aid users by visually flagging potentially bad reports and reducing the time they must spend examining the data. These are documented in [Kondragunta and Shrestha \(2006\)](#). Capabilities for automated storage of manual QC results have been developed ([Kim et al. 2009](#)).

Quality Control of Radar

Despite the application of automated quality control procedures in PPS, some DPA products are contaminated by erroneous accumulations from ground clutter, anomalous propagation, or other non-meteorological targets such as migrating birds ([Gauthreaux and Belser 1998](#)) or fixed ground targets. The MPE user is provided the capability to delete the entire product from further use for that given hour. Manual editing of local suspect regions of precipitation

within the radar's umbrella can be carried out through polygon edits, by either setting precipitation to zero, pasting in data from an alternative source, or applying a local bias factor to the initial estimates within a user-defined region.

MPE Products and Estimation Techniques

This section summarizes the suite of MPE hourly rainfall products and the techniques used to generate them. Related products, such as radar-only, gauge-only, and gauge-radar precipitation, are constructed through alternative combinations of inputs from the various data sensors, with different options for bias correction also available. Each product can be generated automatically by MPE once per hour, valid at the top of the hour, and is viewable and editable using the MPE graphical user interface. The RFC and WFO forecasters routinely choose whichever one they believe is best for application of manual quality control procedures (if necessary) and for eventual use in their hydrologic operations.

Radar Only

The simplest rainfall product is the mosaic of raw DPA radar products from PPS without any gauge-based bias adjustment having been applied. Because it can contain varying rainfall biases of occasionally large magnitude depending on the radar, season, and type of rainfall, this product by itself is rarely used quantitatively as input to the hydrologic forecast models.

Gauge Only

As discussed previously, in some areas across the United States, poor radar coverage indicates that rain gauges may be the only reliable source of real-time precipitation information. The algorithm described by [Seo \(1998b\)](#) is used in MPE to create a 1-h gridded gauge-only analysis field that is influenced by radar or satellite rainfall estimates. This algorithm is based on optimal interpolation of available hourly gauge reports and incorporates scaling corrections for local climatic differences in the gaps between the gauges, based on the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) rainfall climatology ([Daly et al. 1994](#)). Gauges are assumed to have an azimuthally uniform radius of influence. As a consequence, however, gridded analyses from sparse networks sometimes feature unrealistic circular isohyetal patterns.

An alternative gauge-only analysis technique, commonly referred to as DailyQC ([Schaake et al. 2004](#)), was implemented in MPE in 2008. DailyQC has been used as a stand-alone application by RFCs in the western United States, where radar suffers from significant beam blockages. It utilizes daily and subdaily gauge reports to produce 6-h and daily totals, and it also employs PRISM adjustments in performing spatial interpolation of the gauge reports.

Mean Field Bias-Adjusted Radar

Each radar rainfall product can have systematic biases relative to rain gauges and to adjacent radars (i.e., errors that are spatially correlated and approximately uniform over the radar's 230-km scan domain). This is not uncommon and can be caused by several factors, primarily the use of inappropriate *Z-R* parameters in the PPS and/or significant reflectivity calibration differences between radars ([Brandes et al. 1999](#)). It is possible to quantify these radar-wide mean field biases by computing, for each hour, the sample bias correction factor that is a multiplicative ratio of all available hourly

gauge observations divided by the coincident hourly radar-gridded estimates overlaying those gauges. A computed factor of 1.0 would indicate that the radar is perfectly estimating the areal rainfall relative to the gauges on average, whereas factors >1 indicate radar underestimation, and values <1 indicate overestimation. This time- and radar-dependent bias correction factor is then applied as a multiplier to all pixels in each constituent DPA radar product, before mosaicking of the products.

The actual procedure used in NWS operations is based on a Kalman-filtering procedure with optimal estimation and is described in detail in Seo et al. (1999). Only nonzero hourly gauge and radar rainfall pairs are used to compute the mean field bias, and these pairs must lie within the effective coverage area of the radar umbrella. There is also a user-specified minimum threshold number of nonzero-valued pairs (currently a default value of 10) needed to ensure a representative sample of precipitation points for application of the bias correction factor. For the case of widely scattered rainfall or for radars with sparse gauge networks where 10 raining pairs cannot be identified for the most recent 1-h period, the algorithm will go back in time hour by hour from the current hour until it is able to accumulate a total of at least 10 raining pairs, in which case the computed bias factor will necessarily be from multiple hours of observations.

The bias values themselves are calculated within AWIPS, with the results being returned to the RPG for later dissemination (Fig. 1). The RPG has an option to apply the uniform bias factor to outgoing radar QPE products, other than the DPA.

Local Bias-Adjusted Radar

Although mean field bias adjustment is effective in improving radar estimates in many instances, spatially nonuniform biases often exist within individual DPA radar products. For example, in the cool season, radar often overestimates at close ranges because of bright band effects and underestimates at longer ranges because of beam overshooting. In such instances, mean field bias adjustment may make rainfall estimates worse (Borga et al. 2000; Chumchean et al. 2006). Seo and Breidenbach (2002) described a procedure for adjusting radar estimates for local biases, subsequently implemented in MPE. Fundamentally, it is similar to the procedure for mean field bias correction, except that at any one place, only hourly radar-only mosaic and rain gauge reports within a fixed radius of influence of each grid box (currently, the default is 40 km) are used to estimate the bias. Thus, a grid of spatially varying biases is computed and applied to the original radar estimates.

Merged Multisensor Mosaic Based On Bias-Adjusted Radar and Gauges

This product represents a local merging of individual, point rain gauges and the gridded radar rainfall mosaic that has been corrected for mean field bias (Seo 1998a). It is often called simply the multisensor mosaic and is the MPE product chosen most often for use in the NWS hydrologic forecast models. The gauge-radar merging is done using the mean field bias-adjusted mosaic described previously because the single optimal estimation procedure that is used requires that the radar estimates be unbiased before merging. The final estimate at any place is a weighted average of nearby gauge reports and the radar value for that point; thus the procedure also corrects local gauge/radar biases. The difference between the bias-corrected and multisensor mosaics is that in the former, the gauge estimates only change the local magnitude of the radar-indicated precipitation amounts, not the size and shape of the area; in the latter, the gauge observations locally override

the radar estimates and thus can change the shape of the precipitation area.

In gauge-sparse regions, the multisensor mosaic is nearly identical to the bias-adjusted radar mosaic; in regions with a dense gauge network, the final mosaic is very similar to the gauge only. In regions where the rainfall estimates from multiple radars are totally blocked by terrain, the multisensor mosaic automatically fills in by interpolating across the missing areas using the nearest available gridded radar data along the gap's perimeter and any available gauge data lying within the missing region itself.

A conceptually similar algorithm known as P3, first developed by the U.S. Army Corps of Engineers (McCormick 1995) and later refined at the Arkansas-Red River Basin RFC, is used at some offices and is available within MPE. It also generates a QPE field constrained to agree with gauge reports near gauge sites.

Satellite and Satellite-Multisensor Products

Space-based estimates of rainfall from NESDIS have been used operationally by the NWS as stand-alone precipitation products for flash flood monitoring and nowcasting (Scofield and Kuligowski 2003). The NESDIS Hydroestimator algorithm produces nationwide satellite-only rainfall rates and 1-h accumulations on a 4-km grid mesh, based on an empirical, fixed power law relation between GOES infrared brightness temperature and ground-level rainfall rate (Vicente et al. 1998; Scofield and Kuligowski 2003).

Satellite rainfall estimates can feature temporally and spatially varying biases. The NWS has developed real-time techniques to locally adjust hourly satellite estimates with real-time rain gauge data to remove biases, in a manner analogous to that described in the previous subsection on local bias-adjusted radar QPE ("Local Bias-Adjusted Radar") (Fortune et al. 2002; Kondragunta and Seo 2004). The satellite multisensor MPE product merges gauge, radar, and satellite data (Kondragunta et al. 2005) in a three-step process involving bias correction of radar and satellite fields individually, followed by direct insertion of the satellite QPE field in areas not covered by rain gauges or radar.

Enhanced Resolution Precipitation Rate Analyses

An enhanced MPE, referred to as the High-Resolution Precipitation Estimator (HPE), was deployed in AWIPS in 2008. This version generates multiradar mosaics with a 1-km grid mesh, updated at 5-min intervals. Both accumulations and instantaneous rate grids are produced. The output of HPE can be input to FFMP, and it serves as input to a 0- to 1-h short-range forecast algorithm (Fulton and Seo 2000; Guan et al. 2005; Kitzmiller et al. 2008). The HPE products are not publicly disseminated.

Forecaster Adjustment and Merging of Multiple Products

Although the multisensor products described previously can be supplied directly to river models, there is often extensive human input to the final QPE field beyond quality control of the input, which includes identification and removal of suspect gauge reports and anomalous radar indications of precipitation. The QPEs themselves can be locally adjusted with forecaster-supplied bias factors. Forecasters sometimes insert different products from the suite described previously in different portions of the area of responsibility. For example, the final estimate might feature DPA- and NMQ-based radar QPE and satellite QPE in different regions. These choices are guided by forecasters' knowledge

and assessment of how well the different radar products agree with available gauge estimates in the current situation, considerations attributable to local climatic factors, and indications provided by other remote-sensing products such as lightning and satellite infrared imagery.

Examples of Multisensor Products

The effects of merging gauge, radar, and satellite data on estimated precipitation coverage and spatial pattern details are illustrated in Fig. 2, for the area of Texas, New Mexico, and northern Mexico. Estimates of 1-h precipitation are shown for gauge-only, radar-only, mean field bias—corrected radar, and Hydroestimator satellite algorithms [Figs. 2(a–d), respectively]. Areas of white background indicate regions of no effective radar or gauge precipitation coverage, with zero precipitation appearing dark gray. The effect of bias correction on the radar estimates is apparent in the reduction of peak values over New Mexico and north-central Texas [Figs. 2(b and c)]. It is apparent that there is likely to be precipitation in areas just beyond the southwestern margin of the radar coverage. Merging of satellite estimates [Fig. 2(d)] enables complete coverage over the western portion of the West Gulf RFC area, which encompasses much of the Rio Grande basin. The final operational estimate as produced by the West Gulf River Forecast Center [Fig. 2(e)] illustrates the merging of all data sources. The estimates include some nonzero gauge values over northern Oklahoma, which is outside the zone of radars ingested by the RFC. Some small areas of radar echoes were removed over southeastern Texas.

Validation of Radar and Multisensor Rainfall Estimates

Many users have studied and reported on the properties of WSR-88D and multisensor precipitation estimates, for both meteorological accuracy (comparison with independent rain gauge reports) and utility in hydrology (hydrologic modeling studies). Although a

review of these studies is beyond the scope of this paper, the overall quality of MPE-gridded precipitation products created by RFCs has improved substantially, in terms of local biases and random errors, since they were first made available to users in the 1990s. This improving trend in the archived products was observed and discussed in Johnson et al. (1999) for the Oklahoma region; Dyer and Garza (2004) for Florida; Jayakrishnan et al. (2004) for the Texas region; and Yilmaz et al. (2005) for Arkansas, Mississippi, and Georgia.

This evolution of product quality presents particular problems in hydrologic applications. For example, local biases in radar or gauge-radar fields have changed over time, rendering calibration of hydrologic models from longer periods of record inaccurate relative to current MPE characteristics. This has been demonstrated for the period 2001–2005, during which a numerical truncation error in the PPS was corrected (Fulton et al. 2003). There are ongoing efforts to correct this truncation error in archived precipitation estimates, by either reprocessing the input data with greater attention to adding more gauge data (Marzen and Fuelberg 2005; Nelson et al. 2010) or adjusting the archived MPE multisensor grids toward better agreement with gauge-only references (Zhang et al. 2011b).

Recent and Future Enhancements

Work is ongoing to improve inputs to MPE and its interactive functionality. As discussed previously, dual-polarization radar QPE will soon be available as an input. Radar and multisensor products from the NMQ system can be ingested and used within MPE, and NMQ itself is evolving to improve single-polarization QPE and to integrate dual-polarization data. Interactive features for using 6-h and daily 24-h rain gauge reports in multisensor products have recently been refined (Paul Tilles, personal communication).

The extension of MPE capabilities to monitor rapidly evolving events, particularly flash flooding, continue. Higher-resolution precipitation estimates and short-range forecasts based on radar data have been introduced into operations, and initial investigations

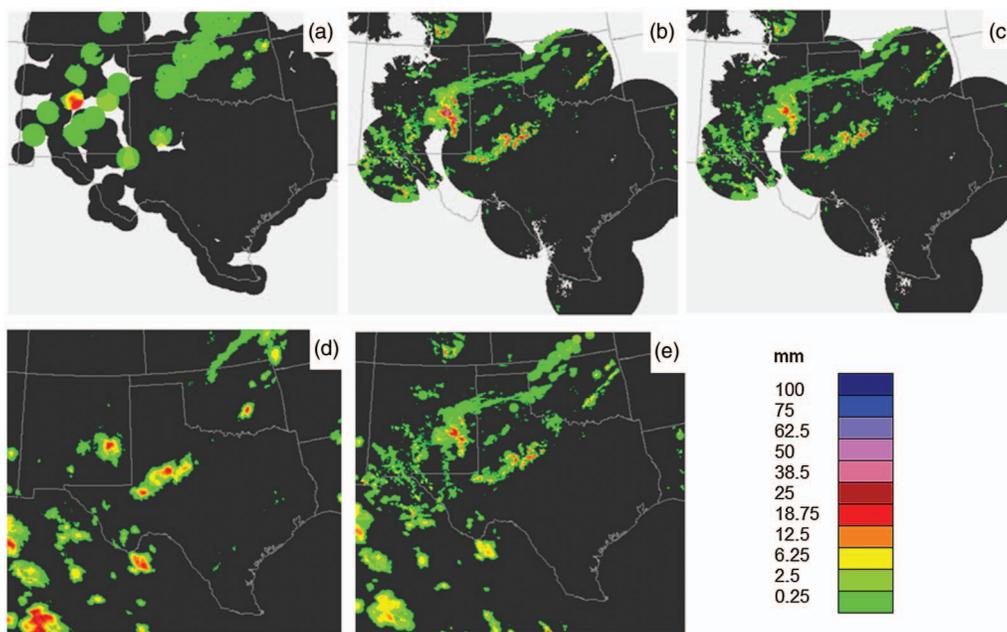


Fig. 2. (Color) Illustration of MPE blending of gauge-only (a), radar-only (b), radar with gauge bias adjustment (c), and satellite infrared (IR) rainfall (d) estimates into a combined final analysis (e); estimates are 1-h precipitation ending 0000 Coordinated Universal Time (UTC), July 27, 2005, prepared at West Gulf River Forecast Center; precipitation color scale shown at lower right

are underway to make subhourly rain gauge reports available for flash flood monitoring applications such as FFMP.

Sources of Radar and Multisensor Precipitation Estimates in Digital Formats

Single-radar precipitation products as described previously, including the DPA, are available in the original digital format from the National Climatic Data Center (<http://www.ncdc.noaa.gov/nexradinv/>).

An archive of multisensor Stage IV and NCEP Stage II precipitation estimates, for 1-, 6-, and 24-h periods, is available from the University Corporation for Atmospheric Research (<http://data.eol.ucar.edu/codiac/>). The most recent Stage IV products are available in digital and graphical form through a NOAA Web interface (<http://water.weather.gov/precip/>). An archive of Stage III and MPE products from individual RFCs, from 1993 to 2005, is maintained by the NWS Office of Hydrologic Development (<http://www.nws.noaa.gov/oh/currenthist.htm>).

Conclusions

This paper briefly describes current operational techniques used routinely in National Weather Service field offices to generate precipitation products for use in their hydrologic operations. These techniques combine WSR-88D radar, rain gauge, and satellite data to create a suite of precipitation products of high temporal and spatial resolution. The performance of radar and multisensor rainfall estimation algorithms like the PPS and MPE described in this paper depends on their ability to systematically and intelligently isolate and remove error sources at each stage of the processing. Because there are many error sources in radar rainfall estimation (not to mention rain gauge reports and satellite estimates), this is a challenge that will continue to be a subject of research and development.

Because of their ability to detect and quantify precipitation, radar and satellite are crucial to advances in hydrologic modeling, particularly distributed modeling (e.g., Smith et al. 2004). The National Oceanic and Atmospheric Administration remains committed to further development of radar hardware and precipitation science to meet current and expanding needs for precipitation information.

Acknowledgments

There are many people who have significantly contributed to the success of operational WSR/88D and multisensor rainfall estimation capabilities in the National Weather Service, especially the many field forecasters whose suggestions and experience led to innovations in operational practice and software. The vision and leadership of Dr. Michael Hudlow, former director of the Office of Hydrology, through the 1980s and early 1990s, is most noteworthy. The late Timothy O'Bannon of the WSR-88D Radar Operations Center is also recognized as a very important source of technical leadership in improving the radar precipitation processing system. Dong-Jun Seo, Jay Breidenbach, Chandra Kondragunta, Bryon Lawrence, Mark Glaudemans, James A. Smith, and Paul Tilles were instrumental in creating, deploying, and maintaining MPE. The authors are indebted to many others who have contributed to the development of the PPS and MPE, within the NWS, National Severe Storms Laboratory, and the university community.

References

- Anagnostou, E., and Krajewski, W. (1998). "Calibration of the WSR-88D precipitation processing subsystem." *Weather Forecasting*, 13(2), 396–406.
- Baech, M., and Smith, J. (1998). "Rainfall estimation by the WSR-88D for heavy rainfall events." *Weather Forecasting*, 13(2), 416–436.
- Borga, M., Anagnostou, E., and Frank, E. (2000). "On the use of real-time radar rainfall estimates for flood prediction in mountainous basins." *J. Geophys. Res.*, 105(D2), 2269–2280.
- Brandes, E., Vivekanandan, J., and Wilson, J. (1999). "A comparison of radar reflectivity estimates of rainfall from collocated radars." *J. Atmos. Oceanic Technol.*, 16(9), 1264–1272.
- Breidenbach, J., and Bradberry, J. (2001). "Multisensor precipitation estimates produced by National Weather Service forecast centers for hydrologic applications." *Proc., 2001 Georgia Water Resources Conf.*, Univ. of Georgia, Athens, GA, 179–182.
- Breidenbach, J., Seo, D.-J., Tilles, P., and Roy, K. (1999). "Accounting for radar beam blockage patterns in radar-derived precipitation mosaics for River Forecast Centers." *Proc., 15th Conf. on Interactive Information Processing Systems*, American Meteorological Society, Boston, 179–182.
- Burnash, R. (1995). "The NWS river forecast system—Catchment model." *Computer models of watershed hydrology*, V. P. Singh, ed., Water Resources Publications, Littleton, CO, 311–365.
- Chumchean, S., Sharma, A., and Seed, A. (2006). "An integrated approach to error correction for real-time radar-rainfall estimation." *J. Atmos. Oceanic Technol.*, 23(1), 67–79.
- Daly, C., Neilson, R., and Phillips, D. (1994). "A statistical-topographic model for mapping climatological precipitation over mountainous terrain." *J. Appl. Meteorol.*, 33(2), 140–158.
- Dyer, J., and Garza, R. (2004). "A comparison of precipitation estimation techniques over Lake Okeechobee, Florida." *Weather Forecasting*, 19(6), 1029–1043.
- Erb, R. (2002). "Development of a headwater model application for National Weather Service forecast offices." *Proc., 18th Conf. on Interactive Information Processing Systems*, American Meteorological Society, Boston, J188–J191.
- Fortune, M., Breidenbach, J., and Seo, D.-J. (2002). "Integration of bias corrected satellite-based estimates of precipitation into AWIPS at River Forecast Centers." *Proc., 18th Conf. on Interactive Information Processing Systems*, American Meteorological Society, Boston.
- Fulton, R. (1999). "Sensitivity of WSR-88D rainfall estimates to the rain-rate threshold and rain gauge adjustment: A flash flood case study." *Weather Forecasting*, 14(5), 604–624.
- Fulton, R., Breidenbach, J., Seo, D.-J., Miller, D., and O'Bannon, T. (1998). "The WSR-88D rainfall algorithm." *Weather Forecasting*, 13(2), 377–395.
- Fulton, R., Ding, F., and Miller, D. (2003). "Truncation errors in historical WSR-88D rainfall products." *Proc., 31st Conf. on Radar Meteorology*, American Meteorological Society, Boston, 270–273.
- Fulton, R., and Seo, D.-J. (2000). "A prototype operational 0–1 hour radar-based flash flood potential algorithm." *Proc., 15th Hydrology Conf.*, American Meteorological Society, Boston, 226–228.
- Gauthreaux, S., and Belser, C. (1998). "Displays of bird movements on the WSR-88D: Patterns and quantification." *Weather Forecasting*, 13(2), 453–464.
- Glaudemans, M., Tilles, P., and Lawrence, B. (2009). "Interactive quality control and operational product generation of hourly multi-sensor precipitation estimates in the NWS." *Proc., 25th Conf. on Int. Interactive Information and Processing Systems (IIPS) for Meteorology*, Oceanography, and Hydrology, American Meteorological Society, Boston, 5B3.
- Groisman, P., and Legates, D. (1994). "The accuracy of United States precipitation data." *Bull. Am. Meteorol. Soc.*, 75(2), 215–227.
- Guan, S., Ding, F., Fulton, R., and Kitzmiller, D. (2005). "Preliminary results for the 0–1 hour multisensor precipitation nowcaster." *Proc., 32nd Conf. on Radar Meteorology*, American Meteorological Society, Boston, 6R.4.

- Jayakrishnan, R., Srinivasan, R., and Arnold, J. (2004). "Comparison of raingauge and WSR-88D Stage III precipitation data over the Texas-Gulf basin." *J. Hydrol.*, 292(1–4), 135–152.
- Johnson, D., Smith, M., Koren, V., and Finnerty, B. (1999). "Comparing mean areal precipitation estimates from NEXRAD and rain gauge networks." *J. Hydrol. Eng.*, 4(2), 117–124.
- Kessinger, C., Ellis, S., and Van Andel, J. (2003). "The radar echo classifier: A fuzzy logic algorithm for the WSR-88D." *Proc., 3rd Conf. on Artificial Applications to the Environmental Sciences*, American Meteorological Society, Boston, P1.6.
- Kim, D., Tollerud, E., Vasiloff, S., and Caldwell, J. (2009). "Comparison of manual and automated quality control of operational hourly precipitation data of the National Weather Service." *Proc., 23rd Hydrol. Conf.*, American Meteorological Society, Boston, J6.3.
- Kitzmilller, D., et al. (2008). "Multisensor precipitation estimation in the NOAA National Weather Service: Recent advances." *Proc., World Environmental and Water Resources Congress 2008*, ASCE/Environmental and Water Resources Institute (EWRI), Reston, VA.
- Klazura, G., Thomale, J., Kelly, D., and Jendrowski, P. (1999). "A comparison of NEXRAD WSR-88D radar estimates of rain accumulation with gauge measurements for high- and low-reflectivity horizontal gradient precipitation events." *J. Atmos. Oceanic Technol.*, 16(11), 1842–1850.
- Kondragunta, C., Kitzmilller, D., Seo, D.-J., and Shrestha, K. (2005). "Objective integration of satellite, rain gauge, and radar precipitation estimates in the multisensor precipitation estimator algorithm." *Proc., 19th Hydrology Conf.*, American Meteorological Society, Boston, 2.8.
- Kondragunta, C., and Seo, D.-J. (2004). "Toward integration of satellite precipitation estimates into the multi-sensor precipitation estimator algorithm." *Proc., 18th Hydrology Conf.*, American Meteorological Society, Boston, 5.
- Kondragunta, C., and Shrestha, K. (2006). "Automated real-time operational rain gauge quality-control tools in NWS hydrologic operations." *Proc., 20th Hydrology Conf.*, American Meteorological Society, Boston, P2.4.
- Kuligowski, R. J. (2002). "A self-calibrating real-time GOES rain fall algorithm for short-term rainfall estimates." *J. Hydrometeorol.*, 3(2), 112–130.
- Lawrence, B., Shebsovich, M., Glaudemans, M., and Tilles, P. (2003). "Enhancing precipitation estimation capabilities at National Weather Service field offices using multisensor precipitation data mosaics." *Proc., 19th Conf. on Interactive Information Processing Systems*, American Meteorological Society, Boston, 15.1.
- Lin, Y., and Mitchell, K. (2005). "The NCEP stage II/IV hourly precipitation analyses: Development and applications." *Proc., 19th Hydrology Conf.*, American Meteorological Society, Boston, 1.2.
- Maddox, R., Zhang, J., Gourley, J., and Howard, K. (2002). "Weather radar coverage over the contiguous United States." *Weather Forecasting*, 17(4), 927–934.
- Marzen, J., and Fuelberg, H. (2005). "Developing a high resolution precipitation dataset for Florida hydrologic studies." *Proc., 19th Hydrology Conf.*, American Meteorological Society, Boston, J9.2.
- McCollum, J., Krajewski, W., Ferraro, R., and Ba, M. (2002). "Evaluation of biases in satellite rainfall estimation algorithms over the continental United States." *J. Appl. Meteorol.*, 41(11), 1065–1080.
- McCormick, B. (1995). *RainView (cal_rad subsection)*, U.S. Geological Survey, Tulsa District Office, Tulsa, OK. [Copy available from NWS Office of Hydrologic Development].
- McEnery, J., Ingram, J., Duan, Q., Adams, T., and Anderson, L. (2005). "NOAA's advanced hydrologic prediction service—Building pathways for better science in water forecasting." *Bull. Am. Meteorol. Soc.*, 86(3), 375–385.
- National Oceanic and Atmospheric Administration (NOAA) Earth Systems Research Laboratory. (2010). "Meteorological assimilation data ingest system." (<http://madis.noaa.gov/>) (Oct., 2011).
- National Weather Service (NWS). (2011). "Hydrometeorological automated data system (HADS)." (<http://www.weather.gov/oh/hads/>) (Oct., 2011).
- Nelson, B., Seo, D.-J., and Kim, D. (2010). "Multisensor precipitation reanalysis." *J. Hydrometeorol.*, 11(3), 666–682.
- Office of the Federal Coordinator for Meteorology. (2006). *Federal meteorological handbook 11, doppler radar meteorological observations, Part C: WSR-88D products and algorithms*, Silver Spring, MD.
- Polger, P., Goldsmith, B., Przywarty, R., and Bocchieri, J. (1994). "National Weather Service warning performance based on the WSR-88D." *Bull. Am. Meteorol. Soc.*, 75(2), 203–214.
- Reed, S., Fulton, R., Zhang, Z., and Guan, S. (2006). "Use of 4 km, 1 hr, precipitation forecasts to drive a distributed hydrologic model for flash flood prediction." *Proc., 20th Hydrology Conf.*, American Meteorological Society, Boston, J8.4.
- Reed, S., and Maidment, D. (1999). "Coordinate transformations for using NEXRAD data in GIS-based hydrologic modeling." *J. Hydrol. Eng.*, 4(2), 174–182.
- Reed, S., Schaake, J., and Zhang, Z. (2007). "A distributed hydrologic model and threshold frequency-based method for flash flood forecasting at ungauged locations." *J. Hydrol.*, 337(3–4), 402–420.
- Roe, J., et al. (2010). "NOAA's community hydrologic prediction system." *Proc., 4th Federal Interagency Hydrologic Modeling Conf.*, Advisory Committee on Water Information, Las Vegas.
- Ryzhkov, A., Giangrande, S., and Schuur, T. (2005a). "Rainfall estimation with a polarimetric prototype of the WSR-88D." *J. Appl. Meteorol.*, 44(4), 502–515.
- Ryzhkov, A., Schuur, T., Burgess, D., Heinselman, P., Giangrande, S., and Zrnich, D. (2005b). "The joint polarization experiment: Polarimetric rainfall measurements and hydrometeor classification." *Bull. Am. Meteorol. Soc.*, 86(6), 809–824.
- Schaake, J., Henkel, A., and Cong, S. (2004). "Application of PRISM climatologies for hydrologic modeling and forecasting in the western U.S." *Proc., 18th Conf. on Hydrology*, American Meteorological Society, Boston, 5.3.
- Scofield, R., and Kuligowski, R. (2003). "Status and outlook of operational satellite precipitation algorithms for extreme-precipitation events." *Weather Forecasting*, 18(6), 1035–2051.
- Seo, D.-J. (1998a). "Real-time estimation of rainfall fields using radar rainfall and rain gauge data." *J. Hydrol.*, 208(1–2), 37–52.
- Seo, D.-J. (1998b). "Real-time estimation of rainfall fields using rain gauge data under fractional coverage conditions." *J. Hydrol.*, 208(1–2), 25–36.
- Seo, D.-J., and Breidenbach, J. (2002). "Real-time correction of spatially nonuniform bias in radar rainfall data using rain gauge measurements." *J. Hydrometeorol.*, 3(2), 93–111.
- Seo, D.-J., Breidenbach, J., Fulton, R., and Miller, D. (2000). "Real-time adjustment of range-dependent biases in WSR-88D rainfall estimates due to nonuniform vertical profile of reflectivity." *J. Hydrometeorol.*, 1(3), 222–240.
- Seo, D.-J., Breidenbach, J., and Johnson, E. (1999). "Real-time estimation of mean field bias in radar rainfall data." *J. Hydrol.*, 223(3–4), 131–147.
- Seo, D.-J., Seed, A., and Delrieu, G. (2010). "Radar and multisensor rainfall estimation for hydrologic applications." *Rainfall: State of the Science, Geophysical Monograph Series*, F. Y. Testik, and M. Gebremichael, eds., Vol. 191, AGU, Washington, DC, 79–104.
- Smith, J., Seo, D.-J., Baeck, M., and Hudlow, M. (1996). "An intercomparison study of NEXRAD precipitation estimates." *Water Resour. Res.*, 32(7), 2035–2045.
- Smith, M., et al. (2004). "The distributed model intercomparison project (DMIP): Motivation and experiment design." *J. Hydrol.*, 298(1–4), 4–26.
- Smith, S., et al. (2000). "Flash flood monitoring and prediction in AWIPS Build 5 and beyond." *Proc., 15th Hydrology Conf.*, American Meteorological Society, Boston, 3.7.
- Steiner, M., Smith, J., Burges, S., Alonso, C., and Darden, R. (1999). "Effect of bias adjustment and rain gauge data quality control on radar rainfall estimation." *Water Resour. Res.*, 35(8), 2487–2503.
- Story, G. J. (2000). "Determining WSR-88D precipitation algorithm performance using the stage III precipitation processing system." *Electron. J. Oper. Meteorol.*, 1(4), 1–13.

- Super, A., and Holroyd, E. (1997). "Snow accumulation algorithm for the WSR-88D radar." *Proc., 28th Conf. on Radar Meteorology*, American Meteorological Society, Boston, 324–325.
- Vicente, G., Scofield, R., and Menzel, W. (1998). "The operational GOES infrared rainfall estimation technique." *Bull. Am. Meteorol. Soc.*, 79(9), 1883–1898.
- Vignal, B., and Krajewski, W. (2001). "Large sample evaluation of two methods to correct range-dependent error for WSR-88D rainfall estimates." *J. Hydrometeorol.*, 2(5), 490–504.
- Yilmaz, K., Hogue, T., Hsu, K.-L., Sorooshian, S., Gupta, H., and Wagener, T. (2005). "Intercomparison of rain gauge, radar, and satellite-based precipitation estimates with emphasis on hydrologic forecasting." *J. Hydrometeorol.*, 6(4), 497–517.
- Young, C., et al. (1999). "An evaluation of NEXRAD precipitation estimates in complex terrain." *J. Geophys. Res.*, 104(D16), 19691–19703.
- Zhang, J., et al. (2011a). "National mosaic and multi-sensor QPE (NMQ) system: Description, results, and future plans." *Bull. Am. Meteorol. Soc.*, 92(10), 1321–1338.
- Zhang, Y., Reed, S., and Kitzenmiller, D. (2011b). "Effects of retrospective gauge-based readjustment of multi-sensor precipitation estimates on hydrologic simulations." *J. Hydrometeorol.*, 12(3), 429–443.