About the Multisensor (NEXRAD and gauge) data
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The purpose of this write-up is to provide the DMIP participants with some sense as to how precipitation estimates were produced, what the known error sources and characteristics are, and what may be expected when using xmrg data as precipitation forcing in hydrologic models.

The main ingredients to the xmrg data are the Digital Precipitation Array (DPA) products, operational hourly rain gauge data, and interactive quality control by the Hydrometeorological Analysis and Service (HAS) forecasters at the River Forecast Center (RFC). The DPA products, sometimes referred to as the Hourly Digital Precipitation (HDP) products, are generated by the Precipitation Processing Subsystem (PPS), which is one of many automatic algorithms in the WSR-88D Radar Product Generator (RPG). For a description of PPS, the reader is referred to Fulton et al. (1998). Even though it has "precipitation" as its first name, PPS is designed to estimate rainfall and rainfall only. As such, its products are of highly suspect quality in times and areas of snowfall, sleet or hail.

The DPA products are radar-only estimates of hourly accumulation of rainfall on an approximately 4x4 km2 rectilinear grid. This grid, referred to as HRAP (Hydrologic Rainfall Analysis Project), is based on the polar stereographic projection. It is a subset of the Limited Fine Mesh (LFM) grid used by the Nested Grid Model (NGM) at the NWS National Centers for Atmospheric Prediction (NCEP). For further details of this mapping, the reader is referred to Greene and Hudlow (1982) and Reed and Maidment (1999).

The accuracy of the DPA products are affected mostly by the following factors; 1) how well the radar can see precipitation near the surface given the sampling geometry of the radar beams and the reflectivity morphology of the precipitating cloud, 2) how accurately the microphysical parameters of the precipitation system are known (Z-R, hail cap, etc.), 3) how accurate the radar hardware calibration is, and 4) various sampling errors in the radar measurement of returned power (how many pulses per sampling volume, how many scans per hour, beam width, etc.)

The first, known as the vertical profile of reflectivity (VPR) effect, can introduce a factor of two (or lower) overestimation (where the radar beam intercepts the bright band layer) and a factor or ten (or higher) underestimation at far ranges of the radar (where the radar beam samples ice particles rather than liquid precipitation) in well-developed stratiform precipitation in the cool season. The following rule of thumb may be useful in assessing the presence and spatial extent of the VPR effect in WSR-88D precipitation estimation. The axis of the lowest radar beam (approximately 0.5 elevation angle) reaches the altitudes of 1, 2, 3, 4, 5 km at ranges of approximately of 60, 120, 160, 200, 230 km, respectively. Hence, if the freezing level is at 2 km above the ground, one may expect bright band enhancement at and around the range of 120 km (resulting in overestimation of rainfall if the Z-R parameters are applicable to the surface rainfall, which very often is not the case) and radar sampling of ice particles beyond that range (resulting in severe underestimation of rainfall if the Z-R parameters are applicable to the surface rainfall). Note that, at Oklahoma City, the climatological freezing level is at or below 2 km in the months of February and March, and at or below 3 km through May (Smith et al. 1997).

One of the more important changes in the production of DPA, related to the sampling geometry of the radar beams, occurred in the spring of 1996 when bi-scan maximization (see Fulton et al. 1998 for details) in PPS was essentially disabled. What that means is that DPAs afer the spring of 1996 suffer less from bright band contamination and are less range-dependent. The net effect of this change to the overall quality of xmrg data over the DMIP basins, however, is less clear because bi-scan maximization tended to compensate, to an extent, for radar underestimation of rainfall due to nonuniform vertical profile of reflectivity (Seo et al. 2000) and inaccurate Z-R parameters. It is difficult to pinpoint the exact timing of this change in the xmrg product (which is based on DPAs from many sites: see below) because each radar is operated independently and hence the timing of the change varies from site to site. For a summary of radar-only and radar-gage evaluation of DPA products prior to the disabling of bi-scan maximization, the reader is referred to Smith et al. (1996). For similar analyses based on the DPA products since the disabling of bi-scan maximization, the reader is referred to Smith et al. (1997).

As for the microphysical parameters, the Z-R is the most important. Initially, only the "convective" Z-R parameters were used; Z=300R1.4. Though they work well for deep convective precipitation systems, the convective parameters underestimate, often severely, for other types of storms. In 1997, the "tropical" Z-R parameters, Z=250R1.2, were added to be used for hurricanes, tropical storms, small scale deep-saturated storms fed by tropical oceanic moisture, etc. In December of 1999, the "stratiform" Z-R parameters were also added to be used for general stratiform events (Z=2001.6) and for winter stratiform events at sites east (Z=130R2.0) and west (Z=75R2.0) of the continental divide. Loosely speaking, the tropical Z-R produces about a factor of two more rainfall than the convective.

Whereas the errors describe above affect many bins over a relatively large area in more or less the same ways, the effects of sampling errors are much more random and can vary from one HRAP bin to the next. The operational experience of xmrg data is limited to the lumped models, for which the effect of the sampling errors tends to average out. The effect of the sampling errors in distributed modeling is still largely unknown.

Another important source of error in earlier DPA products, was strictly computational. Due to the CPU and RAM limitations in the "legacy" Radar Product Generator (RPG), PPS uses I*2 arithmetic (rather than I*4). Inconsistencies were found in the arithmetic that resulted in truncation, as opposed to rounding-off, of rainfall amounts. The net effect of this bug (which has mostly been fixed in 2001) is minimal for most rainfall events. For long-lasting stratiform events, however, the total loss of rainfall (due to not counting very small amounts) can be rather significant (see http://hsp.nws.noaa.gov/oh/hrl/papers/2001mou/Mou01_PDF.html). Also, it is estimated that this error is a large contributing factor to the conditional bias seen in the DPA products, i.e., the smaller the rainfall estimate in the DPA product is, the larger the bias (on the low side) relative to the gauge rainfall (Seo et al. 1996).

Whereas the ABRFC relied on the Stage III algorithm for xmrg production prior to 1996, they adapted the use of a locally grown Process1 (P1} for the vast majority of the xmrg creation starting in late 1996. P1 calculates HRAP bin-specific ratios of gauge-to-radar rainfall at gauge locations, and performs spatial interpolation of the ratios based on triangulation of gauge locations (Young et al. 2000, Seo and Breidenbach 2002). The net result is a local bias adjustment that tended to compare very favorably to the radarwide bias used in Stage III. For a comparative analysis of Stage III and P1 products, the reader is referred to Young et al. 2000). The ABRFC found that the P1 algorithm provided a much more accurate estimate of rainfall with much less effort than the Stage III software.

Another algorithm, “preP1” is run locally at the RFC to mosaic the DPAs. This process creates a mosaic of all the radars that cover the RFC basin, with simple averaging of grid bins where more than one radar has an estimate for a given grid bin. Operational experienced has shown that a simple averaging of the grids has yielded better results than choosing a maximum value. The preP1 process also prepares a set of hourly gage values that will be used by the P1 algorithm to adjust the raw mosaiced gridded estimates of rainfall. Only those gages deemed acceptable by flags in the database are presented for each hour. Forecasters have the ability to “turn on” and “turn off” the use of gauges, and the “bad gauge” list is reviewed after every large storm to determine if any gauges need to be removed.

Because of the variety of the sources of error in radar-based/-aided precipitation estimation, the Hydrometeorological Analysis and Service (HAS) forecasters play a critical role in improving the quality and accuracy of xmrg data. The primary tool used for this man-machine interaction is the P1 Graphical User Interface (GUI). P1 has many features that the forecaster can use to manipulate the precipitation grids. One of the largest weaknesses of the current PPS algorithm deals with estimates of precipitation during snowfall. P1 has procedures which allow the forecaster to draw in snow using polygons. The forecaster can use reflectivity echos, along with surface observations to suggest areal coverage and hourly estimates of the water equivalents. Other polygons can be drawn in to multiply areas of precipitation up and down. In other cases, the forecaster may want to swap a polygon area to use the maximum grid value instead of an average value that is the default value.

The role of the HAS forecasters is particularly important in quality-controlling rain gauge data. Real-time hourly rain gauge data are subject to all kinds of errors (see, e.g., Steiner et al. 1999), and it is well known that an alarmingly large fraction of all observations that come in to the RFC is unusable. In fact, the ABRFC normally has at least 40% of all available gauge data set as non-usable due to various reasons, including a gauge stuck at zero, underreporting, or reporting obviously excessive amounts. Also, because almost all of the gauges are not heated in the winter, the “make snow” algorithm in P1 will set to missing any gauge located within the constructed polygon.

Normally, the RFC produces hourly estimates of rainfall by 45 minutes past the top of the hour. Because of the time delay of up to four hours that occurs with the receipt of GOES satellite data (one of the main sources of gauge data), the forecaster at the RFC will often go back and re-run the precipitation processing for the previous five hours when precipitation is occurring. This allows all available hourly gauges to be used in the calibration of the radar estimates of rainfall.

Each morning, shortly after 12z GMT, the RFC receives 24 hour co-op values of precipitation from the extensive co-op network located around the country. Using graphical display software at the RFC, the forecaster is able to compare the co-op values with the 24 hour accumulation of xmrg data. When the two value do not match, or a bias is observed, the forecaster will first verify that the co-op gauge value is correct, and then go back to the appropriate hours when rainfall was occurring and adjust the rainfall using a variety of methods. It is estimated that 7 times out of 10, the forecaster is increasing the rainfall amounts of the xmrg data. The RFC puts a lot of effort into this QC process, and hopes to achieve the best estimate of rainfall (or water equivalent) possible.

It is possible, to gain some sense of event-specific volumetric bias that may be present in the xmrg data based on the streamflow observations. For example, one may run the hydrologic model of choice many times using different adjustment factors to the xmrg data until the resulting simulated hydrograph is reasonably close, at least in the volumetric sense, to the observed. Obviously, the resulting bias estimate, representing the bias in the xmrg data aggregated at the space and time scales of the basin and the basin response, respectively, is subject to model errors and uncertainties in the initial conditions, and hence must be interpreted due caution (much more so in the model warm-up period). Nevertheless, in the absence of any direct evidence (in the form of high-quality rain gauge data), such inference may be the only way to glimpse at the magnitude of the first-order errors in the xmrg data at the event scale of temporal aggregation.

Such an exercise, based on the Sacramento model-unit hydrograph combination in the lumped mode, was carried out for TIFM7, WTTO2 and BLUO2 in the context of variational assimilation, which produces bias estimates in precipitation forcing as a by-product (see Seo et

al. 2002 for details). The event-specific bias estimates ranged from 0.86 to 2.14 for TIFM7, 0.83 to 1.39 for WTTO2, and 0.85 to 1.68 for BLUO2. It is also seen that, for TIFM7, the Stage III data in the first year or so is of highly suspect quality and may not be taken seriously, and that, for BLUO2, consistent and significant low bias exists in the Stage III data well into 1996.
Because many of the error sources are tied to the sampling geometry of radar (and to that of gauges to some extent), very often, visualizing Stage III data (say, at the temporal scale of aggregation of a day) over the entire domain offers very good clues as to the kinds of errors that the Stage III data may be subject to. As such, the DMIP participants are encouraged to visually examine the Stage III data (e.g., at http://www.abrfc.noaa.gov/archive) associated with significant flood events for signs of artifacts and anomalies.

Obviously, the event-specific bias estimates described above (even if they are in the ball park) shed little light on the magnitude of error at a finer scale (say, at the HRAP and hourly scales). The hope is that, given that unbiasedness at a larger scale is a necessary condition for that at a smaller scale, such estimates may offer some guidance as to how much stock one may put in the model calibration and/or intercomparison results at a smaller scale.
In summary, due to a variety of error sources (sampling-geometrical, reflectivity-morphological, microphysical, sampling by sparse rain gauges, algorithm changes, etc.), the xmrg data are subject to systematic errors that may vary over various time scales (a storm scale, an intra-storm scale, seasonal, etc.). As such, care must be exercised in accepting and interpreting the model simulation results. The participants are also strongly encouraged to visually examine the xmrg data and to perform, e.g., sensitivity analysis to help gauge the magnitude of error that may be present in the xmrg data.

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Office of Hydrologic Development
National Oceanic and Atmospheric Administration
National Weather Service
1325 East West Highway
Silver Spring, MD 20910
Page Author: ohd.webmaster@noaa.gov 