1.10   USING NEW REMOTELY-SENSED DATASETS IN MOS DEVELOPMENT:
A STEP TOWARD TRUE HIGH-RESOLUTION STATISTICAL
QUANTITATIVE PRECIPITATION FORECASTS

Mark S. Antolik *
Meteorological Development Laboratory
Office of Science and Technology
National Weather Service/NOAA
Silver Spring, Maryland

1.   INTRODUCTION

Along with the recent proliferation of high-resolution Numerical Weather Prediction (NWP) model output has come increased demands upon forecasters to supply meaningful forecasts to the public at scales of a few kilometers. For example, within the National Weather Service (NWS), forecasters are now beginning to make use of the new Interactive Forecast Preparation System (IFPS), which will serve as their interface to the National Digital Forecast Database (NDFD; see Glahn and Ruth 2003). The NDFD contains human-generated forecasts at 5-km resolution. Accordingly, there is increasing demand for a new generation of statistical guidance designed to help forecasters "populate" the NDFD.

The NWS Meteorological Development Laboratory (MDL) traditionally has used the Model Output Statistics (MOS; Glahn and Lowry 1972) technique to post-process NWP model forecasts. The MOS technique employs a joint sample of NWP model output and surface weather observations to develop relationships which predict future sensible weather under a given set of model forecast conditions. A properly constructed MOS system can remove a significant portion of systematic NWP model bias as well as yield predictions of weather elements that the underlying model does not explicitly forecast (including those, such as thunderstorms, which occur on scales finer than the native resolution of the NWP model grid).

When applied in the "traditional" fashion, however, the MOS technique requires that observations of the predictand be collocated with forecast points in the developmental data sample. Currently-operational MOS forecast systems were developed by using observations from either automatic or manually-operated instruments located at standard, hourly surface observing sites. Consequently, the station-oriented MOS systems in place today typically produce forecasts valid at not more than about 1500 locations throughout the United States.

As we proceed with the development of high-resolution statistical forecast systems suitable for input to the NDFD, however, it has become necessary to explore ways of expanding the traditional application of the MOS

* *Corresponding author address:* Mark S. Antolik, 1325 East-West Highway, Room 11334, Silver Spring, MD 20910-3283 email: mark.antolik@noaa.gov

technique to produce forecasts valid everywhere on fine-scale grids. In so doing, it becomes imperative to make use of whatever "nonstandard" observational data might be available. These new data might include observations from local mesonets, remotely-sensed quantities from radar and satellites, and even information of a more geophysical nature, such as assessments of soil moisture or land use. This paper discusses overall MDL efforts to produce a new generation of "enhanced-resolution" MOS guidance in support of the NDFD, with particular focus on a new fine-scale gridded MOS Quantitative Precipitation Forecast (QPF) system. A thorough treatment of the technical issues associated with the development of previous station-oriented MOS QPF systems may be found in Antolik (2000).

2.   NEW ENHANCED-RESOLUTION MOS SYSTEMS

The newest statistical forecast systems currently under development at MDL involve applications of MOS in its more "traditional" station-oriented form as well as efforts to extend the MOS technique to produce gridded forecasts. The particular type of system under development depends upon the density and type of observations available to provide "ground truth" for the weather element (predictand) to be forecast. Where available, surface station observations still are likely to provide the most reliable developmental data for statistical forecast systems.

2.1 *Station-Oriented Systems*

If a station-oriented MOS system is to be of much use in NDFD applications, attempts must be made to increase the number of observation sites in the developmental data sample. To this end, MDL has begun to utilize station data from a number of specialized surface observing networks. The first steps down this path were undertaken to support NWS River Forecast Center (RFC) operations by improving the resolution of MOS maxmium/minimum (max/min) temperature guidance for use in snowmelt forecasting. Data from supplemental observing sites belonging to the SNOwpack TELemetry (SNOTEL) system and the US cooperative observer (co-op) network were provided to MDL by certain RFCs, enabling the generation of max/min forecasts for these locations in addition to the sites already served by the primary operational MOS system. As a result, forecast density was significantly enhanced along major river stems. Development of a new MOS snowfall amount prediction system which uses observations from the co-op network is also

well underway (Cosgrove and Sfanos 2004). The first version of this system uses snowfall observations from more than 5000 co-op observing sites in conjunction with output from the Global Forecast System (GFS) developed by the National Centers for Environmental Prediction (NCEP). A complete description of the most recent version of this model is available online (NCEP 2003).

One drawback to the use of co-op data, of course, is the fact that observations are only available once per day. A complete, centralized MOS system designed to produce high-resolution forecasts for a broad spectrum of weather elements and valid times requires high-density station data from additional sources. Consequently, MDL already has taken steps to obtain observations from a number of major regional and statewide mesonetworks. Among these are the MesoWest system (Horel et al. 2002) and the Oklahoma Mesonet (Brock et al. 1995). In many portions of the country, the combined resolution of these specialized surface observing networks at least begins to approach that of the NDFD. MDL envisions that the use of certain high-resolution geophysical datasets, in concert with these additional observations, will facilitate the development of new, regionalized MOS equations. By using these equations, it should be possible to retain fine-scale variability and skill at the resolution of the target grid.

2.2 Gridded MOS development

Certain weather elements lend themselves quite naturally to specification on grids, enabling the development of true gridded MOS systems without the need to resort to specialized techniques. Generally, these weather elements are those which may be observed with remote sensors. For instance, MDL has been producing gridded thunderstorm and severe local storm forecasts for several years. In these MOS systems, predictand observations are specified by data from radar and/or lightning detection networks in conjunction with severe storm reports compiled by the NWS Office of Climate, Water, and Weather Services (OCWWS). The latest system of this type uses data from the mesoscale version of the NCEP eta-coordinate model (Black 1994) to produce forecasts on a 48-km grid (Hughes 2002). Efforts also are underway to increase the resolution of this product so as to become more compatible with both aviation and NDFD requirements (Hughes and Trimarco 2004).

Accumulated precipitation amount is another weather element that is now estimated remotely by post-processing reflectivity data from the WSR-88D radar network. These estimates are then used in operational streamflow and flash flood forecasting. Accordingly, MDL is developing a new high-resolution gridded MOS QPF system compatible with both NDFD requirements and the needs of the hydrologic community. Most of our work thus far has centered around the selection of appropriate predictand data and the adaptation of such data for use in a statistical forecast system.

3. THE HIGH-RESOLUTION QPE DATASET

3.1 RFC-generated Precipitation Estimates

3.1.1 Radar-based Techniques

WSR-88D precipitation estimates are utilized by the NWS in a number of ways, including the generation of areal QPE products used as input to hydrologic models run routinely at the RFCs. In order to arrive at regional QPE suitable for hydrologic applications, the Hydrometeorological Analysis and Support (HAS) units within each RFC must first mosaic hourly precipitation estimates from individual radars into a product which covers their entire Hydrologic Service Area (HSA). These data are mapped to subsectors of the 4-km grid developed for the Hydrologic Rainfall Analysis Project (HRAP) which is now the standard for gridded data used in hydrologic applications.

As part of this process, available gauge data are used to debias the field of radar precipitation estimates. This step is made necessary by various physical limitations associated with using radar to detect precipitation remotely and because radar-based precipitation amounts are calculated from empirical relationships between radar reflectivity and rainfall rates. In addition to a general bias correction, HAS forecasters also apply certain manual quality control procedures to both the gauge and radar data in real time to help remove gross errors and assure spatial continuity in the precipitation fields. HAS forecasters may also make adjustments to the radar/gauge "blend" used to prepare the final precipitation estimates, depending upon weather conditions and the apparent accuracy of the radar-based data at a given hour. Where radar-derived amounts are deemed to be of poor quality or are missing entirely, the gauge observations may receive substantial weight in the final QPE analysis. The radii of influence of individual gauge observations may also be adjusted at the HAS forecaster's discretion. The HSA-wide mosaics of QPE values which result from this process are commonly referred to as "Stage III" precipitation products (Breidenbach et al. 1998).

In recent months, the RFCs have implemented an improved version of the HSA-wide precipitation estimation process which features improved (locally-varying) bias estimation procedures (Seo and Breidenbach 2002) and a radar height-of-coverage analysis designed to ensure that precipitation estimates in areas of overlapping radar coverage are made by using data from the radar having the lowest unobstructed beam. The improved process is also designed to allow for the incorporation of precipitation data from other sensors such as satellites into the RFC QPE mosaics. This new technique is called the Multisensor Precipitation Estimator (MPE; NWS Hydrologic Laboratory 2003), although the term "Stage III" is still often used to refer to any HSA-wide precipitation product generated by the RFCs, regardless of the algorithm used in its construction.

3.1.2 *Mountain Mapper*

Because radar coverage is severely compromised by beam blockage over mountainous terrain, the three westernmost RFCs rely on a different methodology for the construction of their HSA-wide precipitation estimates. At these offices, hourly gauge data are generally regarded as the most suitable input for constructing the regional precipitation estimates used in operational streamflow forecasting. Radar data are still used in some local applications and a Stage III/MPE product is still produced, but these radar-based products are generally deemed inadequate for area-wide hydrologic forecasting.

To assist with the mapping of gauge observations to the HRAP grid, the western RFCs rely on a software package called "Mountain Mapper", which utilizes the high-resolution PRISM (Precipitation-elevation Regressions on Independent Slopes Model) climatology developed by the University of Oregon (Daly et al. 1994). The Mountain Mapper (hereafter denoted by "MM") program is calibrated against the PRISM climatology by using certain user-selected gauge observations in areas where data coverage is deemed adequate. When precipitation occurs at the calibration sites, MM compares the hourly observed amounts with the collocated monthly PRISM value. The high-resolution PRISM field for the given month is then used to "project", via an inverse-distance weighting procedure, amounts at HRAP gridpoints in a manner which strives to preserve the relationships between the observed hourly precipitation amounts and the monthly PRISM normals at nearby gauge locations. Before carrying out the interpolation, the MM software also allows the HAS forecaster to perform manual quality control of the input gauge observations.

3.2 *Centralized Processing*

At the end of each hydrologic day (defined as the 24-h period ending at 1200 UTC), the RFCs reanalyze the hourly QPE to take advantage of any additional data that may not have been received in time for the initial mosaicking process. At some RFCs, daily totals from the hourly estimates are further checked against any available co-op precipitation reports. Once the final quality control steps are complete, HSA-wide mosaics of 6-h accumulated amounts are created by summing the gridded hourly estimates covering each of the four 6-h synoptic reporting periods of the hydrologic day (i.e. 12-18 UTC,18-00 UTC, 00-06 UTC, and 06-12 UTC). After final quality control and data reanalysis are complete, the 6-h, gridded QPE produced by each RFC are then transmitted to the National Precipitation Verification Unit (NPVU) at NCEP.

Accordingly, NPVU assembles the 6-h QPE received from each RFC into a nationwide composite. Since the RFC HRAP subgrids generally extend beyond their individual HSAs, the NPVU mosaicking procedure assigns QPE values to the composite grid by means of a bitmap which essentially truncates the individual RFC subgrids at their HSA boundaries. The results are assembled on the full 1121 by 881-point, HRAP grid covering the contiguous U.S. at 4-km resolution, and these final, nationwide "supermosaics" of 6-h QPE are then output in the World Meteorological Organization standard format for GRIdded Binary data (GRIB). Complete nationwide mosaics of 6-h QPE are available beginning in late October 2000, or shortly after the Western RFCs first began transmitting MM-gridded estimates to NPVU, though Stage III QPE from a number of the eastern RFCs are available several months prior to this date. The datasets are available through the NPVU website (NPVU 2003).

4. THE PROPOSED GRIDDED MOS QPF SYSTEM

4.1 *Structure and Challenges*

A centralized system of gridded MOS guidance for the entire 5-km NDFD grid will require the routine production of forecasts at roughly 1.5 million points. Developing a viable forecast system of this density will require changes to the procedures used for both development and operational production of MOS guidance. For the first time, the number of computations required to produce MOS forecasts will begin to rival those involved in running the underlying NWP model itself. Hence, computational speed and dynamic storage capacity may become significant considerations.

We anticipate that most other structural characteristics of the new gridded MOS QPF will be very similar to those of the currently-operational MOS QPF systems. Mosaics of NPVU QPE are available in 6-h increments, so we will continue to develop gridded MOS probability of precipitation (PoP) forecasts and QPF for the current 6-, 12-, and 24-h time periods through at least the 72-h forecast projection. The gridded MOS PoP/QPF also will be produced for the traditional warm (April-September) and cool (October-March) seasons. As we will see, seasonal differences in the character of radar-based QPE tend to make it even more essential that the dependent data be seasonally stratified.

The new gridded MOS QPF system will utilize a set of binary predictands similar to those described in Antolik (2000), enabling forecasts of the entire probability density function for precipitation amount. However, given the high density of predictand "observations" in the NPVU QPE dataset and the fact that a 3-year sample of predictand data is now available, it may be possible to develop equations to predict the probabilities of accumulated amounts greater than 2 inches for at least the longest forecast valid periods. This will provide improved capability in specifying the tails of the forecast probability distributions.

Summary measures of the MOS probability distribution will be provided at each forecast gridpoint. Expected values (Antolik 1996), perhaps in combination with information about the second moment of the distribution, would seem to be ideal for use in hydrologic applications which require forecasts of mean areal precipitation (MAP) over river basins. MOS categorical forecasts may also be produced, but likely for selected locations only.

4.2 Using NPVU QPE in MOS Development

4.2.1 Suitability and Characteristics of the Dataset

In short, the NPVU dataset represents a gridded composite of the best-available QPE for hydrologic use in terms of accuracy, resolution, and areal extent. As such, we feel that it is presently the best choice for use in developing a nationwide, centralized, gridded statistical QPF system. Other nationwide compilations of "Stage IV" or similar radar-based QPE are available, but these generally are lacking in either period of record, manual quality control, or data coverage in areas poorly sampled by radar. The same characteristics which make the NPVU dataset most appropriate for hydrologic purposes, however, also make it necessary to use caution when utilizing these data. In broadest terms, these issues generally center around the limitations of radar as a precipitation sensor and the efforts of the HAS units to compensate for these limitations while striving to produce a QPE product having the best possible areal coverage. Over areas of relatively flat terrain and during episodes of widespread, light-to-moderate, liquid precipitation, the NPVU QPE are likely to be of excellent quality, since these are the conditions under which precipitation is well-sampled by existing radar and gauge networks. In the mountainous West, the MM estimates also should be of greatest utility when precipitation satisfies these conditions, but with the additional requirement that the synoptic pattern does not deviate appreciably from the "usual" climatic conditions.

Under these circumstances, the NPVU dataset should be quite adequate for specification of MOS predictand and "ground truth", such as appears to be the case for the hydrologic day ending at 1200 UTC on 30 October 2000. During that period, widespread, relatively moderate precipitation occurred over much of the western U.S., the eastern Missouri Valley, and the Ozark-Ouachita ranges of Arkansas and Oklahoma, along with surrounding areas of eastern Texas. Note in Fig. 1 how the continuity of the radar-based rainfall estimates in the NPVU dataset appears to be quite good in the bands that span RFC HSA boundaries. This is even true of precipitation maxima which cross the boundaries of the Arkansas-Red River Basin RFC (ABRFC) HSA, and extend into adjacent areas of Texas and northern Arkansas. Further west, the same sort of continuity can be seen in the MM estimates across the RFC service area boundaries. There even is reasonable agreement between the light precipitation depicted by the MM analysis over the Northwest RFC (NWRFC) area of responsibility and the radar-based estimates over adjacent portions of the Missouri Basin RFC (MBRFC).

As the ability of radar to accurately detect precipitation diminishes, the RFC QPE process relies more heavily upon gauge observations at gridpoints falling outside of areas well-sampled by the radar. Inadequate radar coverage can be the result of basic geometry, where earth curvature effects lead to overshooting of the precipitating areas of cloud or to intersection of the hydrometeor melting level. Even outside of the mountainous West, the

radar beam can be fully or partially blocked by trees and/or man-made structures near the radar site, or by surrounding elevated terrain. Beam attenuation and propagation characteristics may also limit radar effectiveness at longer distances from the radar site or under abnormal thermodynamic conditions. Effective radar range is also limited during episodes of frozen precipitation due to the diminished reflectivity of ice relative to an equivalent concentration of water targets.
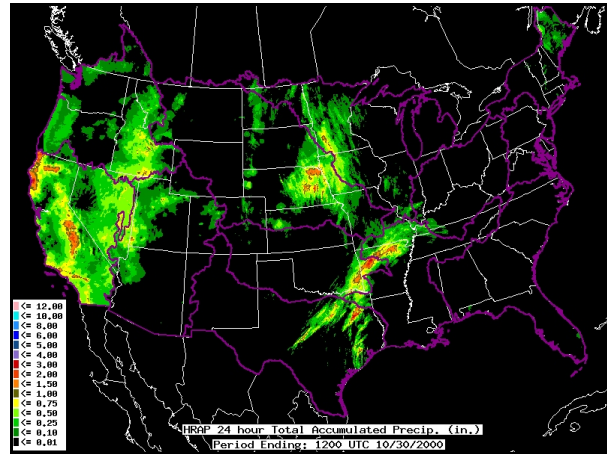

Figure 1. NPVU 24-h QPE as depicted on the 4-km HRAP grid for the hydrologic day ending at 1200 UTC, 30 October 2000. Purple boundaries outline the RFC HSAs.

Thus, the NPVU dataset exhibits the properties of pure gauge data to a varying degree across the entire domain, and these properties are not temporally consistent at any given location. At certain times and in some areas of the country, gauge data (or gauge data in conjunction with available climatology, as in the case of MM estimates) may even be the sole component of the NPVU estimates. Any statistical inhomogeneities in the predictand data due to spatial and temporal differences in the multisensor "blend" can be exacerbated by the human element in RFC data quality control. What is deemed an acceptable radar observation by one HAS forecaster may be edited or replaced in the analysis by another forecaster. Also, the radius of influence of gauge observations may vary, depending upon an individual HAS forecaster's assessment of precipitation type and radar performance over the RFC HSA. Varying amounts of attention may be given to the manual portion of the estimation process, depending upon the significance of the precipitation event and the criticality of the hydrologic situation.

Even the automated QC and radar post-processing procedures are not uniform from RFC to RFC, and these procedures have been in almost constant evolution since NPVU began collecting data. The introduction of the MPE post-processing algorithm generally occurred at most RFCs in late 2001 or early 2002. However, many RFCs did not begin using MPE to generate QPE products until several months afterward. Even at the present time, all

RFCs are not yet using MPE products for routine hydrologic forecast applications. The three western RFCs generate MPE products locally but have chosen to use MM estimates in the hydrologic models. Other offices (most notably ABRFC) have local, in-house procedures which can be used to replace or augment the MPE-generated QPE, especially during episodes of frozen precipitation. Certain RFCs also may choose to use satellite data in the MPE analysis to fill in areas otherwise devoid of data.

Finally, and most troublesome from the standpoint of statistical development, is the treatment of HRAP gridpoints at which no reliable precipitation estimates can be made from any combination of available sensors or post-processing methods. At the present time, RFC HAS units set the values at these gridpoints equal to "0", since current versions of hydrologic models are not equipped to handle missing values as input. Since MOS systems tend to at least partially reflect the climatology of the dependent data, any "false zeroes" in the dependent sample would tend to contribute to an artificial dry bias in the statistical forecasts. This characteristic makes it imperative that the NPVU QPE be subject to additional pre-processing or quality control prior to their use as MOS predictand data.

Evidence of the characteristics outlined above can be seen in Fig. 2, which depicts the 24-h NPVU QPE for the hydrologic day ending at 1200 UTC on 31 December 2000. On this date, a fast-moving upper-level shortwave system exited the southern Plains and moved up the Ohio Valley, depositing a trail of generally light snowfall along its path. As the disturbance approached the Atlantic, secondary surface cyclogenesis occurred off the New Jersey coast. As a result, significant snowfall occurred across much of New England late in the period.

Figure 2a shows the nationwide NPVU mosaic of 24-h estimates. Along the track of the upper-level vortex, measurable precipitation was analyzed over the domains of the ABRFC and the Ohio RFC (OHRFC), but there are suspicious gaps in precipitation coverage elsewhere.
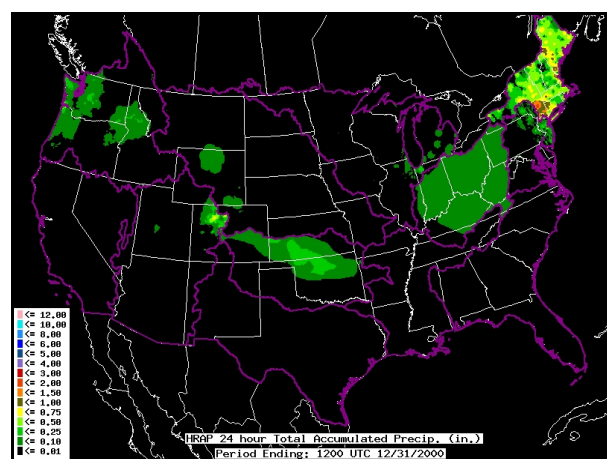
Within these two RFC HSAs, analyzed precipitation areas are broad, regularly-shaped, and cover nearly the entire east-west extent of the domain. This pattern is suggestive of manual augmentation of the radar data by the HAS units of these RFCs. Presumably, light precipitation also fell in adjacent areas, but this precipitation may not have been well detected by the radar network and may not have been deemed significant by the other RFCs.

Over the Northeast, Fig. 2b shows additional data artifacts that can result from the RFC QPE process. In this region, frozen precipitation was more intense and widespread than across the rest of the country, but radar estimates still are of limited use in these situations, especially at long ranges. Accordingly, while radar estimates seem to have been used to define the general extent of precipitation coverage, the gauge data appear to be primary in the final, multisensor QPE analysis. Note the regular, circular patterns in the estimates. "Bulls-eyes" at the center of these circles are probably the result of the interpolation of gauge observations to the HRAP grid, for which a rather large radius of influence appears to have been used.

The analysis of Fig 2b also shows some of the effects of variability in radar coverage. Snowfall amounts likely were enhanced by orographic lifting as saturated air traveled up the Hudson Valley. Nevertheless, the analyzed amounts in the NPVU QPE data tend to increase in the vicinity of the Albany, New York, WSR-88D site, where detection efficiency is greatest. These amounts appear to reach a maximum coincident with the station location. By contrast, notice the spottiness in the analyzed precipitation amounts along the peaks of the White Mountains in northern New Hampshire. This area is precisely where orographic effects are likely to be maximized (especially given the heavy amounts analyzed in the upslope flow in western Maine), but where coverage from WSR-88D radar sites at Burlington, Vermont, and Portland, Maine, is blocked by the elevated terrain. Here, amounts appearing in the NPVU QPE analysis are likely to have been under-estimated, and a number of "false zeroes" are likely to have been generated at HRAP gridpoints.
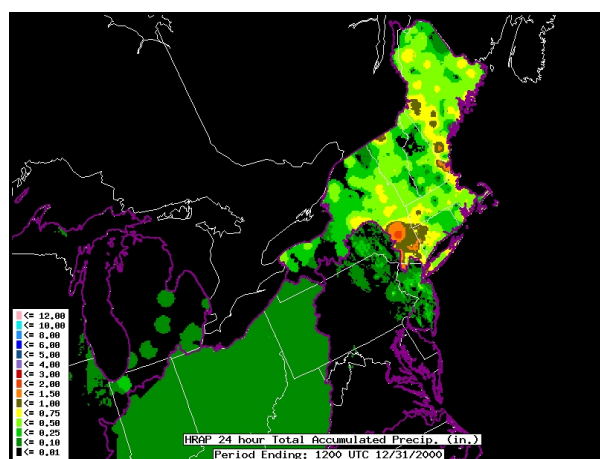

Figure 2a. NPVU 24-h QPE mosaic for hydrologic day ending at 1200 UTC 31 December 2000.

Figure 2b. Same as Fig. 2a, but magnified to show detail over northeast U.S.

Across the boundary between the Northeast RFC (NERFC) and the Middle Atlantic RFC (MARFC) HSAs in northeast Pennsylvania, the QPE analysis more resembles the character of pure radar data. Analyzed amounts are scattered and considerably lighter than those in the adjacent section of the NERFC HSA. Although the heaviest snowfall probably occurred along the western slopes of the Hudson Valley, precipitation amounts probably were orographically enhanced in the high terrain of the Pocono Mountains and adjacent areas of southern New York as well. Yet, in these areas, only spotty precipitation has been analyzed in the NPVU QPE and values of "0" are evident at many HRAP gridpoints. In any event, it is hard to imagine that such an abrupt decline in precipitation amounts actually occurred precisely across the NERFC/MARFC HSA boundary.

4.2.2 *Quality Control of Predictand Data*

To avoid compromising the skill of the new MOS QPF system, our quality control efforts center around identifying areas of the HRAP grid which are habitually devoid of data, or within which the NPVU QPE are regularly of inferior quality. Over the eastern U.S., the overall quality of the NPVU estimates generally declines as the ability of the radar network to detect precipitation diminishes. The MM estimates also suffer in data-poor areas. Whether the primary estimates are radar- or gauge-based, there are likely to be seasonal variations in the suspect areas of the HRAP grid.

4.2.2.1 *Radar-based Estimates*

Not coincidentally, the MPE process relies on information about the effective coverage of the WSR-88D network when determining the appropriate radar observations to use at each point within the RFC domain (Breidenbach et al. 1999). Effective radar coverage is defined for each individual radar site by applying a threshold to fields of selected statistics observed in climatologies of the radar-derived precipitation estimates collected at surrounding HRAP gridpoints. The primary statistics used are the radar-derived total rainfall, mean rainfall, and the observed relative frequencies of various accumulated amounts, with the frequency of measurable precipitation generally being the most useful parameter for defining the effective coverage limits at most radar sites (Breidenbach, personal communication). Generally, the threshold is set at a level where observed values of the chosen parameter begin to drop off dramatically.

Climatologically-defined radar coverage patterns for each radar site are then used to assemble an HSA-wide effective coverage mosaic, or radar "index field". The index fields are used as part of the radar height-of-coverage analysis for each HRAP gridpoint, as well as in the specification of areas lying outside the effective coverage of the radar network where gauge observations must be given primary weight in the MPE process. MPE index fields are "dynamic," meaning that the specific sites for which climatologies are used during assembly of the coverage mosaics may change hourly, according to the availability of data from individual radars. MPE effective

radar coverage patterns have been determined at most radar sites for 6-month seasons which correspond exactly to the periods over which dependent data for the gridded MOS QPF system will be stratified. Operationally, though, a number of RFCs have elected to replace the seasonal radar climatologies with coverage fields derived from yearly data or with fields which have been manually edited by the local HAS units.

In the process of examining these radar coverage patterns, we deduced that they largely have been defined by using a "best-case" approach. That is, HRAP gridpoints may be considered to be adequately "covered" in the MPE analysis if precipitation can be detected by radar at these locations even a small fraction of the time. Presumably, any estimate, even one which needs frequent "correction" by the MPE procedure or the HAS units, is better than no estimate at all. While this approach might be appropriate for hydrologic applications, these criteria are not suitable when screening areas of the HRAP grid for data which might degrade the MOS development. Thus, we are unable to use many of the operational MPE radar coverage patterns in an objective quality control process for the NPVU QPE data.

We have now revisited the analysis of Breidenbach et al. (1999) to determine seasonal radar coverage patterns which are more appropriate for use in screening the NPVU data for statistical development. Generally, the thresholds we have applied to the radar-observed precipitation frequencies result in coverage patterns of more limited areal extent than those in use operationally. In the course of this analysis, we often have observed two areas of gradient in the climatic precipitation frequencies, probably a consequence of the 6-month seasons. Since this behavior seems to be more prevalent in the wintertime and at the northernmost radar sites, these dual gradients are likely associated with the respective contributions of liquid and frozen precipitation cases to the sample. In these cases, we generally have tried to set thresholds at about 75-80% of the average frequency of measurable precipitation at gridpoints close to the radar site, since this level of detectability is probably similar to the nominal performance of current gauge-based networks under normal operating conditions. Using relative frequency data to define radar coverage is a subjective process, however. Accordingly, we allowed our final effective coverage patterns to vary somewhat according to local conditions affecting the propagation of the radar beam, the hybrid scan strategy used at a given radar site, and the presence of real, mesoscale variability in the occurrence of precipitation.

The effect of using seasonal climatologies to define effective radar coverage patterns can be seen in Fig. 3, which depicts the MDL-analyzed index fields for the OHRFC. Warm season radar coverage is depicted in Fig. 3a, while the cool season coverage is shown in Fig. 3b. Note how the increased proportion of frozen precipitation events leads to a reduction in coverage at individual radar sites during the cool season. As a result, several gaps appear in the coverage mosaic, revealing
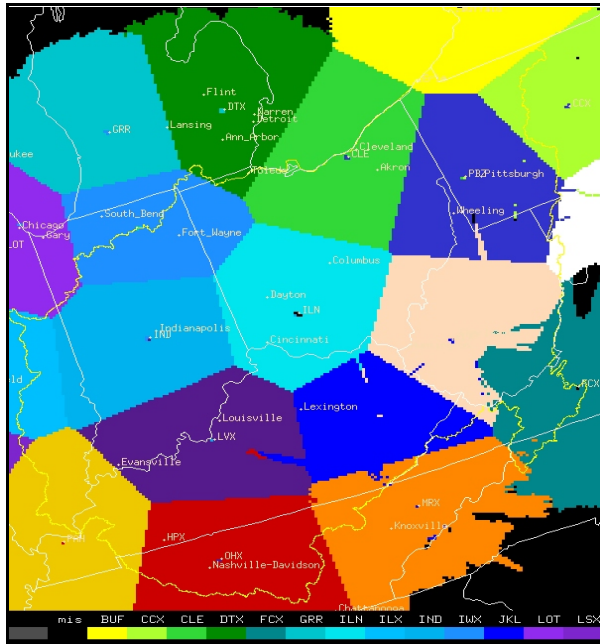
Figure 3a. Warm-season WSR-88D effective coverage mosaic (index field) for the OHRFC HSA as determined by radar-observed precipitation climatologies.
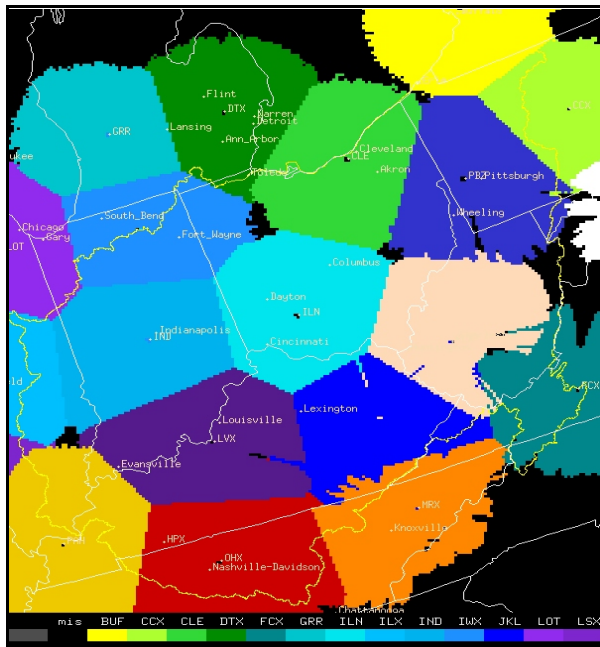

Figure 3b. Same as Fig. 3a, except for the cool season.

HRAP gridpoints at which the NPVU QPE data are not likely to be acceptable for use in MOS development. Fortunately, the density of the WSR-88D network is such that even the cool season coverage is fairly complete over the eastern U.S. This is not always the case over the Plains and western U.S., however, where significant gaps can occur in wintertime radar coverage.

Once we have determined acceptable index fields for each of the RFCs, we will generate a pair of seasonal "supermosaics" of effective radar coverage. This will be done by applying the NPVU mosaicking routines in the same fashion that the 6-h QPE are assembled on the HRAP grid from the HSA-wide HRAP subgrids. These nationwide radar coverage mosaics can then be used as a data mask for the NPVU QPE as part of an automated quality control process.

Such a process would likely be very effective in eliminating data problems of the sort seen in Fig. 4. On 24 October 2000, a strong upper-level system and associated lee-side surface cyclone was responsible for heavy precipitation extending from the Four Corners to the plains of central Kansas, Oklahoma, and Texas. The radar-based estimates have captured a wide area of precipitation amounts in excess of 1.5 inches in this area, with a maximum of over 6 inches. The heaviest precipitation appears to have been convective in nature; note now the NPVU QPE analysis can capture fine-scale "tracks" in the precipitation field resulting from the paths of individual storm cells.
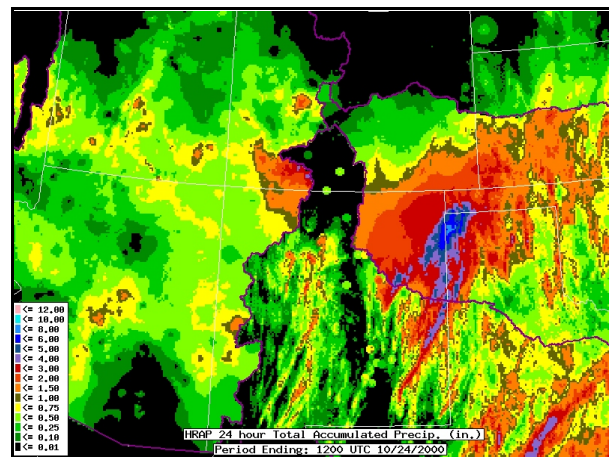

Figure 4. NPVU 24-h QPE over the southwestern U.S. for the hydrologic day ending at 1200 UTC, 24 October 2000.

Close inspection clearly shows a suspicious gap in the axis of heavy precipitation where detection by radar was effectively blocked between the Sangre de Christo and San Juan ranges in southern Colorado. Although precipitation amounts in this region may have been somewhat suppressed by downslope flow, it is not likely that the effects were as dramatic as the NPVU QPE field indicates. The fact that the shape of the area of 1.5-inch amounts in the ABRFC HSA appears to match up well with the axis of MM-derived values to the west of the San Juan range further supports this conclusion. This region falls well outside of the effective radar coverage umbrella, even under conditions of "best possible" radar coverage as depicted by the warm-season index field for the West Gulf RFC (WGRFC) (Fig. 5). The fact that the data-sparse region extends into central New Mexico suggests
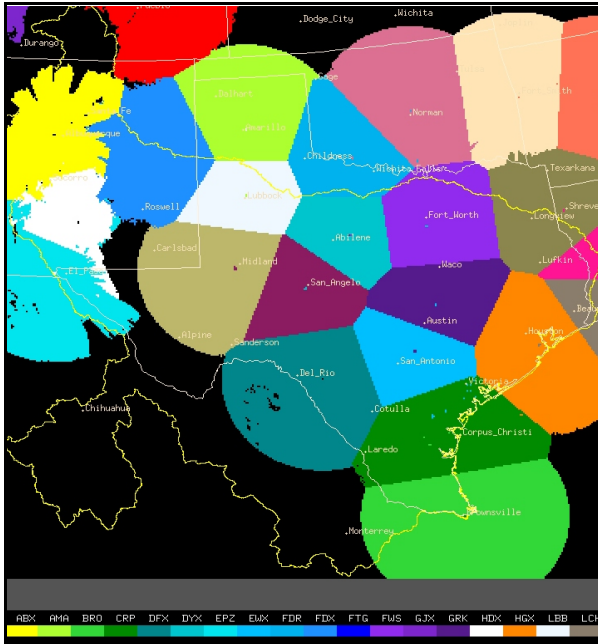
Figure 5. Warm-season WSR-88D effective coverage mosaic (index field) for the WGRFC HSA.

that data from the Albuquerque, New Mexico, WSR-88D may have been unavailable to the NPVU QPE analysis.

In the data void region, only a few gauge reports have been included in the final QPE analysis, and note how the radius of influence used for these gauges appears to be much smaller than that used by the NERFC during the wintertime case of Fig. 2. The WGRFC HAS unit may have made this particular choice due to the convective nature of the precipitation event. Surrounding the gauge reports is another wide area of gridpoints containing what appears to be false values of "0". In cases such as these, where gridpoint values have been affected by deficiencies in sensor coverage, flagging HRAP gridpoints to indicate missing data would be more appropriate.

In regions where the proposed data mask excludes HRAP gridpoints from MOS development, a new data pooling strategy may be necessary to generate MOS forecasts. Historically, we have used regionalized operator equations in MOS QPF systems (Antolik 2000). Development is done under the assumption that signals in the model predictor variables and the atmospheric response to these signals essentially are uniform everywhere a regionalized equation is applied. Consequently, MOS regions are usually contiguous geographically. In regions where radar coverage is blocked by high terrain, however, the physical mechanisms responsible for precipitation production may be quite different from those in surrounding flat terrain. Therefore, a different regionalization procedure may be required in which data are pooled with other geographically distant areas of the HRAP grid having similar terrain characteristics or climatologies.

4.2.2.2 *Mountain Mapper QPE*

Quality control of NPVU QPE for the western RFCs presents its own unique set of challenges. Clearly, MM estimates are highly influenced by the available high-resolution gauge climatologies (i.e., PRISM), and radar is generally useless for providing independent verification in high terrain. Therefore, some other quality control method must be found.

MDL experience with the NPVU QPE dataset already has pointed out potential problems with the MM estimates, especially when significant precipitation occurs in valley locations. In discussions with the HAS units at the western RFCs, we have learned that most of these problems are likely to arise in areas where few gauges are available to calibrate the MM software and the elevation of the gauges used in calibration is substantially different from the height of nearby ridges. Due to the design of the MM interpolation procedure and the PRISM climatology, inaccuracies in the MM estimates are exacerbated if the available calibration gauges also are situated far from ridge tops. If these conditions exist and a significant precipitation event happens to occur at the calibration gauge location, the MM procedure tends to paint wide swaths of extreme precipitation centered along the adjacent ridge axes.

This behavior can be seen in Fig. 6, which depicts MM estimates over the western U.S. for the 24-h period ending at 1200 UTC, December 14, 2001. Amounts in excess of 2 inches were observed at gauge locations in the interior valleys of Northern California and in Washington. However, MM has depicted wide swaths of heavy precipitation along the entire coastal range, as well as along the primary inland mountain ranges of the Cascades and Sierra Nevada. MM amounts in these swaths generally exceed 3 inches, with several embedded areas having estimates in excess of 5 inches.
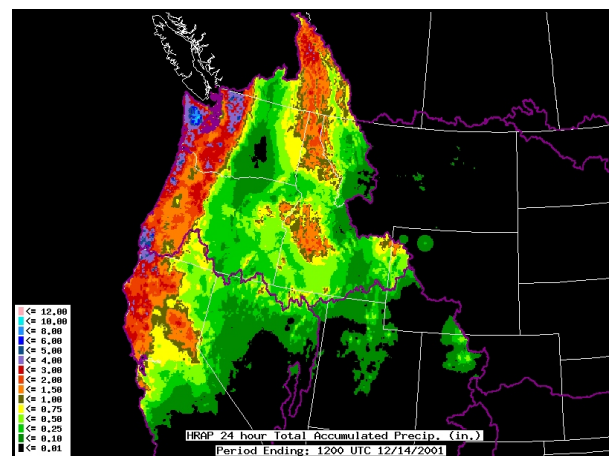

Figure 6. NPVU 24-h QPE over the western U.S. for the hydrologic day ending at 1200 UTC, 14 December 2001.

The same behavior can be seen farther east along the Bitterroot and Salmon River Ranges in Idaho, and along the Columbia Range north of the Canadian border. Here, this behavior occurred despite nearby gauge amounts which were considerably less than those observed nearer to the coast. Note, too, that MM estimates in this area are not well correlated with the lack of reported precipitation in adjacent sections of the MBRFC HSA where radar-based estimates are the primary source of the NPVU QPE. Although considerable suppression of precipitation should occur in the lee side downslope flow, the gradient in the precipitation estimates seems far too severe if the high-terrain MM estimates were completely accurate.

While orographic enhancement is one of the primary mechanisms responsible for heavy precipitation in mountainous areas (especially in the cool season), it is questionable whether such extreme precipitation amounts actually occur over broad, continuous areas of elevated terrain with the regularity observed in the NPVU QPE. Clearly, some pre-processing of the MM data will be required prior to development of a MOS QPF system for the western U.S. We hope to draw heavily upon the operational experience of the HAS units within the three western RFCs in determining areas of the HRAP grid where MM estimates may be unsuitable for use in MOS development.

5. DISCUSSION AND SUMMARY

5.1 *Benefits of Proposed System*

As we have seen, by combining the strengths of the MOS approach with judicious use of the NPVU QPE dataset, we can develop a true, high-resolution, gridded statistical QPF system of nationwide scope. This system will be compatible with IFPS/NDFD requirements as well as the current NWS hydrologic forecast procedures. The MOS technique is also well suited to a probabilistic forecast paradigm. The inclusion of additional information regarding forecast uncertainty is being emphasized as NWS field operations transition to the use of IFPS/NDFD and a new ensemble streamflow prediction system. Through the use of summary statistics of the MOS QPF probability distributions at HRAP gridpoints, automated guidance for probabilistic forecasts of basin MAP will now be possible.

The character of the NPVU QPE dataset makes it difficult to predict the eventual skill of gridded MOS QPF forecasts of the heaviest precipitation amounts. Assuming that data-void areas of the QPE are treated appropriately, however, the NPVU dataset appears to do an excellent job of delineating rain/no-rain areas with great detail, even if the estimated amounts are not always accurate. Therefore, the major benefit from the proposed gridded MOS QPF system may be a highly-detailed and skillful set of gridded PoP forecasts. Such guidance is likely to be ideal for initializing the IFPS to produce high-resolution PoP for inclusion in NWS zone forecasts.

5.2 *Implications for Hydrologic Operations*

We also have seen how many of the decisions made by HAS forecasters can affect the character of the NPVU QPE dataset. By extension, these decisions also will affect the performance of the gridded MOS QPF and any future forecast system based upon RFC-generated QPE. Because of the presence of the HAS forecasters, perhaps no other dataset in the meteorological lexicon is subject to as much human quality control and analysis in near real-time. To be sure, the HAS function is an essential first line of defense against gross errors in the operational QPE products. At the same time, this function has the potential to alter the statistical "character" and homogeneity of data which may be used at a later date. Now that the NPVU archive has been established, it must be kept in mind that RFC-generated QPE may have additional future use in research, forecast product development, and forecast verification.

In order to ensure a consistent dataset which has application beyond immediate hydrologic operations, we suggest that the RFCs strive for as much standardization as possible in QPE processing procedures. There is little question that locally- or regionally-devised procedures often are necessary to arrive at the best possible QPE for hydrologic use at all locations (e.g., Mountain Mapper). However, variable QPE processing will almost certainly lead to variable performance of MOS forecasts based upon these data. While this might be a favorable situation from the HAS forecaster's standpoint (i.e., the automated QPF is somewhat "tailored" to the biases of the QPE normally used in the local hydrologic models), this may render the gridded MOS QPF somewhat less appropriate for other users. Perhaps, these concerns could be addressed by the routine production of a second RFC-generated QPE dataset, specifically for archive purposes, in which all QPE are produced to some common standard.

6. ACKNOWLEDGMENTS

7. REFERENCES

Antolik, M. S., 1996: Toward an objective NGM-based expected-value quantitative precipitation forecast system. Preprints, *13th Conf. on Probability and Statistics in the Atmospheric Sciences*, San Francisco, CA, Amer. Meteor. Soc., 57-64.

____, 2000: An overview of the National Weather Service's centralized statistical quantitative precipitation forecasts. *J. Hydrol.,* **239**, 306-337.

Black, T. L., 1994: The new NMC mesoscale Eta model: Description and forecast examples. *Wea. Forecasting*, **9**, 265-278.

Breidenbach, J. P., D. J. Seo, and R. Fulton, 1998: Stage II and III post processing of NEXRAD precipitation estimates in the modernized Weather Service. Preprints, *14ᵗʰ Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and, Hydrology (IIPS)*, Phoenix, AZ, Amer. Meteor. Soc., 263-266.

____, ____, P. Tilles, and K. Roy, 1999: Accounting for radar beam blockage patterns in radar-derived precipitation mosaics for river forecast centers. Preprints, *15ᵗʰ Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and, Hydrology (IIPS)*, Dallas, TX, Amer. Meteor. Soc., 179-182.

Brock, F. V., K. C. Crawford, R. L. Elliott, G. W. Cuperus, S. J. Stadler, H. L. Johnson, and M. D. Eilts, 1995: The Oklahoma mesonet: A technical overview *J. Atmos. and Oceanic Tech.*, **12**, 5-19.

Cosgrove, R. L., and B. Sfanos, 2004: Producing MOS snowfall amount forecasts from NCDC cooperative observer reports. Preprints, *16ᵗʰ Conf. on Wea. Analysis and Forecasting*, Seattle, WA, Amer. Meteor. Soc., CD-ROM, P6.3.

Daly, C., R. P. Neilson, and D. L. Phillips, 1994: A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteor.*, **33**, 140-158.

Glahn, H. R., and D. A. Lowry, 1972: The use of Model Output Statistics (MOS) in objective weather forecasting. *J. Appl. Meteor.*, **11**, 1203-1211.

____, and D. P. Ruth, 2003: The new digital forecast database of the National Weather Service. *Bull. Amer. Meteor. Soc.*, **84**, 195-201.

Horel, J., M. Splitt, L. Dunn, J. Pechmann, B. White, C. Ciliberti, S. Lazarus, J. Slemmer, D. Zaff, and J. Burks, 2002: MesoWest: Cooperative mesonets in the western United States. *Bull Amer. Meteor. Soc.,* **83**, 211-226.

Hughes, K. K., 2002: Automated gridded forecast guidance for thunderstorms and severe local storms based on the eta model. Preprints, *19ᵗʰ Conf. on Wea. Analysis and Forecasting,* San Antonio, TX, Amer. Meteor. Soc., J19-J22.

____, and R. A. Trimarco, 2004: Impacts of resolution on gridded probability thunderstorm forecast guidance. Preprints, *16ᵗʰ Conf. on Wea. Analysis and Forecasting*, Seattle, WA, Amer. Meteor. Soc., CD-ROM, J6.5.

NCEP, cited 2003: The GFS atmospheric model. [Available online at: http://wwwt.emc.ncep.noaa.gov/gmb/moorthi/gam.html.]

NPVU, cited 2003: NPVU data archive. [Available online at: http://www.hpc.ncep.noaa.gov/npvu/archive.]

NWS Hydrologic Laboratory, cited 2003: RFC-wide multisensor precipitation estimator (MPE) training course outline. [Available online at: http://www.nws.noaa.gov/oh/hrl/presentations/mpe_training_wkshp_0601/course_outline.htm.]

Seo, D. J., and J. P. Breidenbach, 2002: Real-time correction of spatially nonuniform bias in radar rainfall data using rain gauge measurements. *J. Hydromet.*, **3**, 93-111.