Quantitative Precipitation Forecast Process Assessment

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Executive Summary

The Assistant Administrator for Weather Services, John J. Kelly, Jr., commissioned nine individuals from diverse components of the National Weather Service (NWS) to review the Quantitative Precipitation Forecast (QPF) process. The charge to the committee was to determine if the current process to generate QPF in support of NWS hydrologic services constitutes an effective and beneficial use of agency resources. Director Kelly acknowledged the importance of QPF to the hydrologic forecast system. He also noted that human resources involved in the QPF process, including meteorologists from the Hydrometeorological Prediction Center (HPC) of the National Centers for Environmental Prediction (NCEP), forecasters at the various Weather Forecast Offices (WFOs), and personnel who comprise the Hydrometeorological Analysis and Support (HAS) function at River Forecast Centers (RFCs), must be utilized in an efficient manner.

As part of its mission, the NWS generates hydrologic forecasts and warnings via interaction of RFCs and WFOs. Nationwide, 13 RFCs were established by hydrologic basin subdivisions which vary in size, topography, and prevailing climate. Diverse hydrologic regimes have led to unique operating procedures and forecasting techniques among the RFCs over the years.

The current QPF process involves objective guidance from Numerical Weather Prediction (NWP) models and Model Output Statistics (MOS), together with manual forecasts produced by HPC, WFOs, and RFCs. The simulation of streamflow is based on parameterization of hydrologic processes, with precipitation, temperature, and evapotranspiration data inputs. In the case of precipitation (one of the most critical input variables), mean areal precipitation (MAP) amounts are derived from observed and forecast data. In mountainous areas, the analysis of MAP is more complex due to highly variable and poorly sampled precipitation. Various techniques have been developed to analyze and forecast MAP for these regions. For most RFCs, NWS river forecasts use QPF input for the 0-24 h period.

The NWS recently completed a national objective whereby WFOs routinely produce QPFs for inclusion in the NWS River Forecast System (NWSRFS). WFOs utilize NWP, MOS, and HPC guidance to produce QPFs which are "mosaicked" (either interactively or non-interactively) by RFC HAS forecasters and then input to the NWSRFS. Interactive mosaicking involves HAS function coordinating and editing of WFO-prepared QPFs to reconcile discrepancies between neighboring WFOs.

Since river flooding results in catastrophic property damage and numerous fatalities, the NWS has invested substantial resources toward the production of high-quality QPF for use by the NWSRFS. Unfortunately, there are deficiencies in the current QPF process. In particular, HPC guidance products are not produced in a format and content required by the NWSRFS; the QPF expertise of WFO and HAS forecasters varies considerably; software tools and training need to be enhanced and standardized; the RFC-WFO coordination process is extensive and cumbersome; and, the overall involvement of HAS forecasters in the QPF process is not consistent among RFCs.

In response to Director Kelly's charge, four scenarios that could improve the QPF process were considered. One involves enhancements to the current process (modified status quo), and the three others each involve substantial refocusing of activities at either the HPC, WFOs, or RFCs. Each scenario embodies improvements specified in the NWS Quantitative Precipitation Information (QPI) Plan (Office of Meteorology 1999), although the forecast process outlined in the QPI Plan most closely resembles the modified status quo. Since HPC does not provide QPF for Alaska, and the current effort there involves modest resources (three WFOs and one RFC), the review team decided to defer the study of activities for this area. Finally, the Pacific Region was outside the scope of this assessment since WFOs there do not issue main-stem river forecasts.

To investigate the viability of the various QPF process scenarios, several information gathering efforts were undertaken. An objective comparative verification study that included QPF products from NWP, MOS, HPC, WFOs, and HAS operations was conducted for a 6-month cool-season period for three RFC areas in geographically and climatically diverse regions--Ohio RFC (OHRFC), Arkansas-Red Basin RFC (ABRFC), and California-Nevada (CNRFC). As a by-product of this effort, development of the national QPF verification system outlined in the QPI Plan was accelerated. A second effort involved the subjective examination of the QPF products, validation data, and objective comparative verification results for selected moderate-to-heavy precipitation events. A third effort involved the analysis of responses to questionnaires sent to all WFOs and RFCs.

The information gathering efforts uncovered substantial inefficiency and complexity in the current QPF process. *Hence, the committee recommends simplifying the QPF process. Because the production of the WFO QPF consumes the greatest amount of resources with little if any improvement in skill of the WFO QPF mosaic, all WFOs, except those in the Western Region (initially), should be relieved of producing QPF.* Although the assessment recommends removal of the WFO component to the current QPF process, there may be WFOs who provide the most skillful product for their Hydrologic Service Area (HSA) (the team did not evaluate the skill of *individual* WFO QPFs). With this change, WFO forecasters can focus on watch/warning programs and provide new forecast products.

To fully satisfy RFC QPF requirements, existing resources at HPC must be mobilized to enhance and reformat QPF guidance products for direct use by HAS forecasters. This change in QPF activities should be phased in over a one-year transition period. During this transition period, a cool-season verification study should be conducted for the Western Region. The ultimate decision regarding the QPF involvement of WFOs in this region will depend upon the outcome of this study.

A clear signal related to the effectiveness of the QPF process emerged from the results of the objective comparative verification for the ABRFC and OHRFC. The mosaicked WFO QPF was found to be less skillful than HPC and model guidance and at or below the skill level of the HAS QPF product. This is not surprising, since the WFOs indicated QPF is one of their most difficult forecast problems. Furthermore, training to date has met only minimum forecaster needs, and WFO experience with QPF is considerably less than HPC. In fact, the average number of years WFOs have been producing QPF is nearly five nationwide compared to 39 years at HPC. Additional factors which likely contribute to a less coherent and less skillful WFO QPF product include: 1) the structure of the current QPF process enables forecasters at each WFO to independently assess and apply a variety of guidance products available from the NWP system, MOS, and HPC; 2) the lack of an effective means to display neighboring WFO QPFs hinders coordination and results in inevitable discontinuities across HSA boundaries; and, 3) the lack of access to timely objective verification data makes it difficult for WFO forecasters to calibrate their skill.

For the CNRFC, the WFOs were more skillful than HPC and model guidance. However, two factors may have contributed to the WFO skill. First, identical post-processing of WFO QPF and observed data may have created an artificial correlation. Second, updated WFO QPFs issued during the forecast validation period were included in the verification sample.

Responses to the questionnaires from both the WFOs and RFCs indicate the WFO QPF product is perceived to be a critical part of the forecast process. This WFO activity, which in routine situations averages 25 minutes for product generation and coordination, is generally deemed by the field offices to improve the accuracy of river forecasts. Overall, considerable WFO resources related to forecaster training, shift scheduling, and coordination with other offices and the RFCs have been utilized to generate a QPF for input to NWSRFS. In fact, a per forecast comparison of the average resources (hours) expended per issuance to produce and coordinate a CONUS QPF in non-flooding situations revealed aggregate totals of approximately 8 h, 47.5 h, and 7 h for the HPC, WFOs, and RFCs, respectively, which corresponds to a HPC:WFO:RFC relative labor expenditure of 1.1:6.8:1.0. In flooding situations, the totals are approximately 8 h, 76 h, and 13 h for the HPC, WFOs, and RFCs, respectively, or a HPC:WFO:RFC relative labor expenditure of 1.0:9.5:1.6. Surprisingly, WFOs have been devoting considerable time to satisfy an RFC requirement, yet in the eastern U.S. the resulting WFO mosaic adds no additional skill. Nevertheless, we recognize that individual WFOs may be producing a skillful QPF for their area of responsibility.

Information gathered by the assessment team indicates WFO resources are not being utilized in the most effective manner. Hence, the QPF process should be restructured to provide efficient delivery of a more skillful product for the RFC domain. To accommodate this recommendation, the HPC must reprogram existing resources to produce a national QPF product for the NWSRFS to replace the current products produced by multiple WFOs. Based on the verification results, this product will be as good as, *if not better than*, the WFO-generated products the RFCs are currently receiving. Through use of QPF provided by the HPC and modified by the HAS, the WFOs will continue to coordinate with and support the needs of local users and customers. The servicing RFC will provide QPF to WFOs in a format consistent with QPF products distributed to external users in the past, based on established requirements.

The questionnaires revealed more than 60% of the personnel performing the HAS function throughout the NWS are meteorologist qualified, and other data from the Office of Hydrology indicated all current HAS forecasters are meteorologist qualified. For the HAS function to assume an augmented role in QPF analysis and generation, these individuals must be provided with the QPF guidance and other support to accomplish their task. The current role of "WFO QPF mediator" should give way to a more active mode whereby the HAS function forecaster reviews and analyzes model output, HPC guidance, and surrounding WFO forecast products to tailor a QPF for the RFC domain. As mentioned previously, this will require an enhanced HPC product suite in digital form. RFC requests for QPF updates and requirements for longer range QPF products must be supported by the HPC. Routine coordination between the HAS function and HPC will provide the HAS with an important resource for the interpretation of NWP models and guidance products. All HAS forecasters will provide updates to the QPF in the first six hours based on the latest observational data. During periods of flooding, the HAS will continue to coordinate hydrologic information with the affected WFOs, because the WFOs are responsible for issuing main-stem river flood watch/warning products. QPF generated for input to the NWSRFS will be available to the WFO (and other users) in graphical and text formats.

Benefits associated with simplifying the QPF process include: 1) the more efficient use of human resources; 2) improved QPF input for the NWSRFS; 3) potentially improved NWS watch/warning programs; 4) simplified coordination; and, 5) more rapid infusion of science and technology in operations. This simplified and more efficient QPF process should improve hydrologic and other services.

Quantitative Precipitation Forecast Process Assessment

I. Objectives

On February 11, 1999, John J. Kelly, Jr. selected nine individuals from various field offices, the regional and national headquarters, and national centers to comprise the QPF Process Assessment Team. The primary objective of this assessment was to determine if the current system to produce QPF in support of the NWS hydrologic forecast system constituted an efficient and beneficial use of agency resources. When Mr. Kelly subsequently met with the team on February 25, he urged the group to be cognizant of the following themes:

- the role of HPC, WFO, and RFC HAS function forecasters in the production of QPF appears to be highly variable, somewhat confused, and devoid of consistent policies and comprehensive verification data;
- NWS resources are limited, so all recommendations must be efficient and cost effective;
- sound business practices and common sense should guide the way;
- the analysis must be quantitative, objective, and unbiased with a primary focus on the next 3 years;
- the review must account for impacts on the hydrologic and meteorologic user communities;
- past or current practices, and organizational allegiances among the team members, must not be allowed to influence either the assessment or the recommendations;
- and, while the team should consult with other personnel to gather information and data, the report and final recommendations shall be prepared directly for consideration by the NWS Director.

While Director Kelly acknowledged the importance of QPF to the hydrologic forecast system, he indicated that the duties of personnel at HPC, the WFOs, or the RFC HAS function might be refocused on other more fruitful activities in support of the NWS mission if the assessment revealed that their particular contributions to the QPF process were not cost effective or essential.

II. Background Information

a. The QPF Process

The current NWS forecast process for QPF involves NWP and statistical guidance, HPC, WFOs, and RFCs. The fundamental steps are:

- the real-time collection of observations, which include all in situ and remotely sensed data;
- the assimilation of data into operational NWP models in real time via the National Centers for Environmental Prediction model-based data assimilation systems;
- the application of NCEP global, regional, mesoscale atmospheric models and ensemble prediction systems;
- the automated generation, dissemination, and use of national statistical guidance products;
- the manual generation and dissemination of national QPF guidance products from the HPC of NCEP;
- the manual production of local QPF products at WFOs and their dissemination to servicing RFCs and other users;
- the assimilation of WFO-prepared QPFs by RFCs for input to the hydrologic forecast system;

- the production of hydrologic and flood guidance at RFCs and its provision to the WFOs within the RFC forecast domain;
- the preparation of all public hydrologic forecast, watch, and warning products at WFOs, and the coordination of this information with emergency managers, the media, and other end users.

TDL

The Techniques Development Laboratory has produced statistical quantitative precipitation forecasts based on operational synoptic-scale NWP models for more than two decades. Although much of this statistical guidance is disseminated routinely to the field in categorical form, probabilistic forecasts (PQPF) have long been an integral part of this system.

Current operational synoptic-scale MOS QPF guidance for 6- and 12-h periods for projections up to 60 hours after 0000 and 1200 UTC is based on output from the Nested Grid Model (NGM), and is available for almost 700 stations throughout the contiguous United States and 60 stations in Alaska. Categorical forecasts are available in alphanumeric form, while corresponding probabilistic and expected-value forecasts in graphical form are made available to the NCEP Hydrometeorological Prediction Center.

The synoptic-scale package of TDL QPF guidance will soon be supplemented by short-range guidance from the Local AWIPS MOS Program (LAMP) QPF model. The LAMP system produces probabilistic, categorical, and expected-value forecasts on a 20-km grid for 1-, 3-, and 6-h periods in the 1-22 hour range. As input, the LAMP model uses the NGM-based MOS QPF probabilities together with a few direct model output fields from the NGM. Sub-synoptic-scale predictor input consists of objectively-analyzed conventional surface observations and output from simple numerical models. Mesoscale predictor input includes fine-scale high-resolution precipitation climatology, hourly and three-hourly antecedent precipitation analyses, and topography.

HPC

Manual QPFs, representing spatially-averaged precipitation and covering the continental United States, have been routinely prepared and issued since 1960 by forecasters in the National Precipitation Prediction Unit (NPPU) of the Forecast Operations Branch (FOB) of the HPC. Twenty-four hour Day 1 QPFs are issued by FOB forecasters early each morning. These forecasts are valid from 1200 to 1200 UTC the following day, and are based on the 12-36 hour forecast from the 0000 UTC NWP model run. In addition, a Day 2 QPF and a Day 2 Update are issued, each valid for the 24-hour forecast period beginning 1200 UTC the following day. The Day 2 QPF and Day 2 Update products are issued in the early morning and early afternoon, respectively.

Forecast guidance to support flash and river flood operations throughout the contiguous United States include the Excessive Rainfall Outlooks and short-range 6-h QPF product. The Excessive Rainfall Outlooks consist of a graphical Rainfall Potential Exceeding RFC Flash Flood Guidance Product and an accompanying Excessive Rainfall Discussion. Six-hour forecasts are issued every 12 hours covering the 24-hour period from 1200-1200 UTC or 0000-0000 UTC. The forecasts for the first 18 hours of each of these two periods are updated once daily. The Excessive Rainfall Outlooks are produced three times per day with special issuances as needed. HPC guidance is not issued for Alaska, Hawaii, Guam, and Puerto Rico.

FOB forecasters reconcile differences between the observational data, operational NCEP NWP models, and statistical guidance during the preparation of the aforementioned manual, spatially-averaged QPFs and associated guidance products. Verification of these manual products over the past 35 years, has shown a steady improvement in forecast skill, with consistent improvements over the best NWP models. The HPC provides QPF products and services to a wide variety of partners and customers. A recent survey by the University Corporation of Atmospheric Research, as part of their review of the HPC, provided useful information as to which of the various HPC products are of most utility, and it also indicated the general level of user satisfaction with the products. The survey revealed that HPC QPF products are widely used, and that the quality of these products appears to be acceptable. The private sector meteorological community, in particular, uses both the graphic products and the text version of the isohyet locations to provide rainfall estimates to their customers in a repackaged format. The national media requires QPF to define areas of moderate to heavy rainfall across the contiguous United States. Other government agencies including the Corps of Engineers, the Bureau of Reclamation, and various state and local water managers, use the HPC products for water resources management and flood management.

WFOs and RFCs

WFOs utilize NWP, MOS, and HPC guidance to produce QPFs, which are mosaicked either interactively or non-interactively (depending upon the RFC) by forecasters in the HAS forecast function at the RFC. The mosaicked QPF forecasts are used as input to the NWSRFS. Interactive mosaicking requires that the HAS forecaster coordinate and edit WFO-prepared QPFs to reconcile any substantial differences between QPFs provided by neighboring WFOs whose forecast domain intersects an RFC's area of hydrologic responsibility.

During the past year, the NWS has completed a national effort to have WFOs routinely produce QPFs for inclusion in NWSRFS. While HPC has routinely generated QPFs since 1960, and a select number of WFOs have produced QPFs for more than two decades, the NWS national QPF effort only began in earnest in the mid 1990's. Exceptions to the list of WFOs routinely generating QPFs for NWSRFS include the WFOs in Key West, FL and Caribou, ME, which have not yet assumed full forecast and warning responsibility, and the WFOs in Honolulu, Guam, and Puerto Rico, which do not issue main-stem river forecasts. However, the Honolulu and San Juan WFOs produce QPFs in support of local flash flood operations.

WFO-produced QPFs are provided to the servicing RFCs on a scheduled basis where they are utilized along with other input parameters such as soil moisture, antecedent precipitation, snow depth, and temperature to generate site-specific river forecasts. The majority of NWS field offices routinely generate deterministic 6-h QPFs through a range of 24 hours, twice per day and year round, utilizing the PC-based WinQPF software application developed by the Ohio River Forecast Center (OHRFC). The predictand is a Hydrologic Rainfall Analysis Project (HRAP)-gridded representation of spatially-averaged precipitation. HAS function forecasters at the RFCs which support these WFOs utilize the UNIX-based HASQPF software application, also developed and supported by the OHRFC, to interactively mosaic QPF for input to NWSRFS. Notable exceptions to this rule are the Western and Pacific Regions, where point rather than gridded QPFs have been the standard for many years. Alaska Region field offices also issue QPFs in a point format, and have been doing so on a routine basis since the Fall of 1996. Point QPFs are issued in these Regions primarily due to a lack of high resolution forecast guidance and observations which accurately account for the significant spatial variability of the precipitation in complex terrain. Western Region offices are further distinguished by the fact that they issue longer-range QPFs (typically through 72 hours) only during the “wet season,” which typically extends from October through April. During the remainder of the year, there is considerably less precipitation which is largely convective and localized in nature. Additionally, Western Region WFO and HAS function forecasters use a different QPF software application entitled Mountain Mapper, recently developed by the Colorado Basin RFC, to prepare and mosaic QPFs. Mountain Mapper is a UNIX-based application which utilizes high-resolution gridded climatic precipitation data to interpolate point observations and forecasts of precipitation to the HRAP grid and compute MAP and forecast MAP values for input to NWSRFS. Alaska Region plans to use Mountain Mapper operationally, once a similar high resolution gridded climatic precipitation database becomes available for their region.

b. NWS River Forecast System

As part of its mission, the NWS generates hydrologic forecasts and warnings via the interaction of the River Forecast Centers and Weather Forecast Offices. The 13 RFCs throughout the nation were established according to hydrologic basin subdivisions that vary considerably in size, geographic diversity, and prevailing climate. Historically, diverse hydrologic regimes have led to unique operating procedures and forecasting techniques, which evolved over the years at the various RFCs. However, in the late 1960's, work began within the Hydrologic Research Laboratory of the Office of Hydrology to develop a nationally supported software system with state-of-the-art forecasting tools for the RFCs.

The NWSRFS Operational Forecast System is a suite of software that provides hydrologic and hydraulic model support for the NWS River Forecast Centers and serves as the basis for hydrologic forecasts and other guidance products for Weather Forecast Offices. The NWSRFS is comprised of more than two dozen models and procedures, five preprocessor functions, and has been in use at RFCs since 1985. By relying on a modular approach, the NWSRFS is an extensible system, and has provided the framework for introducing scientific advances into hydrologic and hydraulic forecasting. It has most recently been extended and enhanced to include interactive capabilities, and to utilize precipitation estimates from the WSR-88D precipitation processing system.

Since precipitation is one of the most important input variables for river forecasting, and QPF is the primary focus of this report, a brief discussion of its use in NWSRFS is warranted. The simulation of streamflow involves the parameterization of the hydrologic characteristics of a basin, with input data for precipitation, temperature, and evapotranspiration. These data are typically specified as a time-series of mean areal values over a basin. In the case of precipitation (one of the most critical input variables), mean areal precipitation (MAP) amounts are derived from observed and forecast data. In mountainous areas, the analysis of MAP is more complex due to highly variable and poorly sampled precipitation. Various techniques have been developed to analyze and forecast MAP for these regions. QPF has been utilized in water resource management and reservoir operations by the Corps of Engineers since the early 1940s, although widespread use within the NWS did not occur until the middle 1990s. For most RFCs, NWS river forecasts use QPF input for the 0-24 h period.

Precipitation, whether observed or forecast, is converted to runoff through a rainfall-runoff model within the NWSRFS. The model produces a space-time distribution of runoff as only one component of a multidimensional process. Other components include evapotranspiration losses, subsurface flow, and deep percolation. The impact of a given QPF on any hydrologic forecast is dependent on a number of factors, including: intensity, duration, location (within a basin) of the precipitation, and current conditions of soil, vegetation, and streamflow. Adjustments are made to the river modeling system to balance the simulation for actual observed streamflow responses in producing an operational forecast simulation. The QPF input to the NWSRFS may still require adjustment by RFC hydrologists to ensure the most accurate streamflow predictions.

c. Near-Term Evolution (within 5 years)

Several issues have recently been identified to improve and modernize the NWS QPF process. These issues were identified by the Hydrometeorological Information Working Group (HIWG) and documented in their January 1999 document entitled "The Modernized End-to-End Forecast Process for Quantitative Precipitation Information: Hydrometeorological Requirements, Scientific Issues, and Service Concepts." This document (Office of Meteorology 1999) was approved by the directors of the six NWS Regions, the Office of Meteorology, the Office of Hydrology, NCEP, and the Office of Systems Development, and includes the following issues which are currently being or planned to be addressed:

- Implementing improved data assimilation techniques, advanced and higher resolution regional mesoscale NWP models, regional and stormscale NWP models, and a regional ensemble prediction system at the Environmental Modeling Center of NCEP.
- Providing improved and expanded centrally-produced Model Output Statistics QPF/PQPF guidance products based on operational NWP models, including global and regional ensembles. This includes a transition from point forecast to gridded MOS guidance. Currently, MOS QPF guidance is only available in point format from the NGM model.
- Providing improved and expanded HPC guidance products that include gridded forecasts for both the 0000 and 1200 UTC forecast cycles through Day 3. These enhancements will ensure the valid times and formats of HPC products are more consistent with those required by WFOs and RFCs.
- Providing WFO, RFC, and HPC forecasters the AWIPS software tools together with the necessary training to prepare (display, integrate, and edit), coordinate (mosaic), and verify QPFs.
- Initiating a transition from deterministic to probabilistic QPFs for use in the Advanced Hydrologic Prediction System (AHPS), in order to satisfy the user requirement for hydrologic products which quantify uncertainty and convey risk.
- Implementing a national verification program to quantify and improve, through timely feedback, the performance of QPF/PQPF products and assess the value added at each step of the NWS QPF Process.

Through the migration to AWIPS, and via the implementation of more standardized components, the NWS River Forecast System forecast preparation and dissemination process is undergoing dramatic changes. Nonetheless, the current system is comprised primarily of quasi-distributed models wherein the processes, input variables, and watershed characteristics are lumped. In contrast, other processes more directly related to the output streamflow predictions, such as the rainfall-runoff process, are fully distributed. Advances from the use of antecedent precipitation indices and more sophisticated soil moisture accounting models and improved dynamic routing techniques should provide for the more optimum use of QPF in the production of river forecasts.

Increasingly, users such as emergency managers and other state and local officials are recognizing and articulating a need for hydrometeorological guidance products which quantify forecast uncertainty and convey risk. Probabilistic hydrometeorological forecast and warning products are beneficial for determining how and when personnel and equipment should be deployed, since they enable local officials to weigh forecast probability and lead time vs. potential flood severity to utilize resources most effectively to preserve life and property. Recommendations and findings published in the several recent Natural Disaster Survey Reports and Service Assessments highlight the need to provide and/or explore the utility of probabilistic hydrometeorological forecast products. The need for river forecast products, which quantify the forecast uncertainty and include future precipitation, stems from a recognition that probabilistic guidance would enable NWS personnel, emergency managers, water facility operators, and other state and local officials to make more informed decisions based on a risk assessment, thereby reducing human suffering and economic loss through improved warnings and mitigation actions. The provision of probabilistic hydrologic products is contingent upon the implementation of AHPS and the routine generation of PQPF input.

With the participation of numerous individuals in the production of QPF, substantial resources are required to support training programs, coordination activities, and applications software maintenance and enhancement for product preparation. Even further resources will be required to provide forecasters with the additional training and software applications to support a probabilistic QPF system.

III. Decision Process Options

Since river flooding results in catastrophic property damage and fatalities, the NWS has invested substantial resources toward the production of high-quality QPF for use by the hydrologic forecast system. As noted in the prior section, numerous personnel working at HPC, the WFOs, and the RFC HAS function, are currently involved in the QPF process. Currently, the HPC QPF guidance products generally are not produced in the appropriate format for optimum use by the hydrologic forecast system. Also, the experience, training, and support tools of the WFO forecasters vary considerably throughout the nation, as does the involvement of the HAS forecasters from one RFC to another. In the attempt to determine if NWS resources are being properly utilized, the assessment team considered a variety of scenarios for the production of QPF to support the hydrologic forecast system. After close scrutiny, four scenarios emerged as alternatives for further consideration. Since HPC does not provide QPF for Alaska, and the current process involves the relatively modest expenditure of resources at three WFOs and one RFC, the Assessment Team decided to postpone a detailed review of activities for this area.

a. The Modified Status Quo

The high degree of contrast in the operational policy, products, training, and procedures associated with the current approach to the production of QPF has resulted in confusion, ambiguity, and the perception of inefficiency. The assessment team eliminated the status quo as a viable option for consideration. However, a "modified status quo" approach with clearly demonstrated value-added increments of QPF by the HPC, WFO, and RFC forecasters was considered. This could be accomplished if agency policies were to be clarified and standardized, supplemental training programs were initiated, enhancements to product preparation and coordination software were accomplished, and formats of the QPF guidance products were modified for direct use by the hydrologic forecast system.

b. Refocusing Activities at HPC

For the past four decades, forecasters at HPC have provided enhancements to the QPF guidance produced by the numerical weather prediction system. Currently, personnel at the WFOs review the NWP and HPC guidance products to generate QPF in support of the hydrologic forecast system. The WFO forecasters produce a QPF product for the local region which conforms to the unique spatial and temporal requirements of each RFC. However, the HPC products cannot be used directly by the RFCs. And as the accuracy of the dynamical weather prediction system continues to improve via the use of enhanced computer technology and scientific advances in numerical weather prediction, the magnitude of the HPC improvement over the model guidance could be diminished. Hence, the assessment team considered the possibility of using the NWP and statistical guidance directly and refocusing HPC efforts on other products and services.

c. Refocusing Activities at the WFOs

Each WFO is responsible for all local products and services, so the production of value-added QPF for use in the hydrologic forecast system would appear to be an important and necessary activity. However, HPC devotes considerable resources and expertise toward the generation of QPF guidance, RFC HAS function personnel assimilate QPF for each RFC's area, and neither comprehensive nor standardized verification procedures have been implemented to quantify the accuracy of the QPF and the ensuing river forecasts. Hence, it is unclear if the resources to produce QPF at the WFOs are being utilized in the most effective and beneficial manner. If the HPC QPF products were to be modified to better meet the needs of the NWSRFS, and the HAS function forecasters were provided with considerable assistance from HPC, it might be possible to reduce the QPF responsibilities of the WFOs. The assessment team considered and documented the ramifications of this option.

d. Refocusing Activities at the RFCs

As noted previously, both the manner and degree to which the HAS function personnel at the RFCs modify or enhance the QPF provided by the WFOs varies considerably throughout the agency. The HAS function personnel possess the background and expertise to properly adjust the WFO QPF to complement the hydrologic processes that influence the river forecasts for the RFC area of responsibility. However, if the WFO QPF were produced in a manner that ensured a higher level of spatial and temporal consistency from office to office, and more effective automated procedures were implemented to facilitate the production of the mosaics of QPF for each RFC area, it might be possible to standardize the role of the HAS function in a manner that would require considerably less time for coordination and modification of the QPF produced by the WFOs. Hence, the assessment team examined this option.

IV. Data Gathering and Analysis

In order to thoroughly review and investigate the potential impacts associated with each of the four QPF process options under consideration by the assessment team, several data gathering activities were initiated. As mentioned previously, the QPF process involves the coordinated efforts of personnel at HPC, the WFOs, and the RFCs. Regional diversity and highly variable operational procedures between the WFOs and RFC, and the absence of consistent and comprehensive verification data for all forecast process components, made it quite challenging to evaluate the overall effectiveness of this activity. Nonetheless, a comprehensive verification study, which included QPF produced by dynamical models and statistical techniques, HPC, the WFOs, and the HAS function personnel, was conducted for a 6-month period for three RFC areas in geographically and climatically diverse regions. In addition, past heavy precipitation events were examined to: 1) illustrate the role of each forecast component; 2) evaluate the impact of the QPF produced by HPC and the WFOs, and assimilated by the HAS function personnel; and, 3) examine the unique characteristics of each QPF product. Finally, detailed questionnaires were distributed to each WFO MIC and RFC HIC to determine the current amount of effort expended to produce and coordinate QPF both on a routine basis and during flood events, and to obtain their impressions of how much value is added in the various steps of the QPF process.

a. Objective Comparative Verification

Overview

The purpose of the objective verification is to produce quantitative, comparable measures of skill of the various operational QPF products in order to assess the relative value added to the QPF process by HPC, WFO, and RFC forecasters. The results are used together with those obtained from the MIC/HIC questionnaires and selected case studies to formulate recommendations to improve the effectiveness and efficiency of the NWS QPF process.

A comprehensive comparative verification of operational QPF products in the NWS poses a number of challenging problems. Although there have been previous verification efforts within parts of the QPF process (i.e., at the HPC, TDL, RFCs, etc.), a systematic investigation of the complete process has not been accomplished. OM has recently commenced a national QPF verification program (Office of Meteorology 1999), but it is only at its formative stages. Thus, this QPF verification study is essentially a pioneering effort.

Methodology

The verification study is comprehensive in some respects and limited in others. It is comprehensive in the number and types of QPF products considered, ranging from those produced by NCEP NWP models to localized QPFs produced at WFOs. It is more limited in regard to the valid period of the forecasts (the 1200 to 1200 UTC period valid 12-36 h after 0000 UTC), period of historical data record (01 October 1998 to 31 March 1999), types of validation data utilized (Stage III Analyses and Mountain Mapper renditions of 6-h gage data), and the areal coverage over the U.S. (the OHRFC, ABRFC, and CNRFC domains). The various QPF products included in the study together with their issue times and valid periods are shown in Fig.1, and the RFC domains are shown in Fig. 2. The limitations of the study are due to the short time allocated to the study and to the lack of conveniently available and complete archived data. Nevertheless, we believe the scope is adequate to base conclusions regarding the relative skill of the various QPF products in an NWS-wide sense.

Much of the challenge posed by the comparative verification problem results from the diversity in spatial resolution, rendering (i.e., grid or point), and form of the various QPF products and validation data (not to mention the burden posed by the multiplicity of formats of the various product archives). For instance, one problem stemmed from the fact that the HPC graphical QPF product is in semi-continuous form. That is, both the 6- and 24-h graphical QPF products have a beginning contour of 0.25 inch (not 0.01 inch as the fully continuous QPF products have) and additional contours at fixed intervals (Fig. 3). In the verification preprocessor for this product, a grid is generated from the contoured map with a graph-to-grid interpolation scheme. The proper operation of the scheme requires that a zero precipitation contour first be inserted at the boundaries of the HPC product domain. (The contour is placed just outside the CONUS borders.) The interpolation scheme, thus, generates bogus precipitation values everywhere outside the 0.25 inch isohyet; the bogus values decrease from 0.25 inch (at the 0.25 inch contour) to 0.00

inch at the borders of the CONUS (Fig. 3)[1]. Because of the bogus values, a proper application of the continuous scoring method to this gridded product presents a challenge. This issue is discussed in the next section.

Another problem faced in the verification study stems from the diverse operations among the three RFCs. That is, the WFO and RFC (HAS) QPF product generation procedures (and the ensuing product forms) between the CNRFC and the two eastern RFCs are quite different. For the CNRFC, the QPFs are issued for specific points (averaging 4 to 6 per WFO) within the WFO's HSA. The Mountain Mapper (MM) scheme renders the point QPFs to the HRAP grid through application of fine-scale monthly climatic precipitation data. The HAS forecasters do not modify the WFO point QPFs, except possibly for the first 6-h period. Thus, an RFC-generated QPF does not exist for CNRFC. For the ABRFC and OHRFC, the generation of the required HRAP gridded QPF is based on a process (WINQPF at the WFOs and HASQPF at the RFCs) that is quite similar to the graph-to-grid interpolation system used at NCEP to obtain the gridded QPF. There is one important difference, however. The complication noted earlier with the HPC product does not exist for the WFO QPF, because the latter product includes the measurable precipitation isohyet.

The validation data used in the verification study required different methodologies for ABRFC/OHRFC and the CNRFC. For the eastern RFCs, Stage III Analyses, which some consider to be the best ground truth data, were used in the verification. For the CNRFC, where Stage III data are not used in the NWSRFS, the verification data are based on 400-500 automated gages over California and Nevada that report hourly or three-hourly. As with the WFO point QPFs, the point observations are interpolated to the HRAP grid with the MM system. A consequence of the identical post-processing procedures for the WFO QPF and the ground truth gage data is that an artificial correlation (resulting from the common climatological input) could ensue. Reference is made to this possible problem for the comparative verification in the discussion of the CNRFC verification results.

A final issue in the comparative verification for CNRFC is the incorporation of updated WFO QPFs. For this RFC, updated WFO QPFs (QPF updates are issued for all RFCs on hydrologically-significant days) replaced the original product issuances in the archive. Thus, the updated QPFs were included in the verification study. For CNRFC, WFO QPF updates, which could be issued as late as 18 hours into the 24-h verification period (as illustrated in Fig. 1), may result in an advantage for the WFO product in the comparative scoring. This issue is also revisited in the discussion of the CNRFC results.

A central issue faced in the verification study is that the Stage III and MM validation data have a much finer spatial scale than any of the forecast products. A consequence of this scale discrepancy is that a meaningful comparison of skill of the diverse products is not possible unless appropriate procedures are applied to introduce a measure of consistency into the spatial resolution and rendering of the QPF products and validation data.

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[1]The HPC gridded 24-h QPF product during the period 01 October 1998 to 27 January 1999 is fully discrete. That is, the product contains only the discrete values of 0.00, 0.25, 0.50, 1.00, etc. during this period. For the remainder of the 6-mo verification period, the gridded product is semi-continuous, as described in the above text. The change in the gridded 24-h product from discrete to semi-continuous form results from a change in the graph-to-grid interpolation scheme applied at HPC.

The diversity in spatial resolution and rendering of the QPF products and validation data was reduced by remapping both to a common rectangular grid. The grid chosen (sometimes referred to as "1/6th LFM") has a mesh length of about 30 km over the three RFC HSAs (e.g., Fig. 4 for ABRFC), which essentially preserves the finest spatial scale in the QPF fields for all products considered. The WFO and RFC QPFs, which are presumed to contain the finest spatial resolution among all products (they are rendered on the 4-km HRAP grid), were translated to the 30-km grid by averaging the HRAP grid values within 30x30 km boxes centered on the corresponding 30-km gridpoints. For the AVN, NGM, and Eta model QPF products, which are rendered on grids of equal or coarser resolution than the verification grid, the translation to the verification grid was done using an "area-preservation" interpolation technique. The HPC QPF products, available in the original graphical form in which they were issued, were represented on the 30-km grid using the graph-to-grid interpolation scheme noted previously. Finally, the raw validation data, which are specified on the HRAP grid, were specified on the 30-km grid via spatial averaging identical to that done for the WFO/RFC QPF products. Examples of the raw gridded data and the corresponding mappings on the 30-km verification grid for the Stage III and WFO products are shown in Figs. 5 and 6, respectively. These images illustrate that the translation to the 30-km grid does not degrade, in a significant way, the spatial resolution of the finest scale QPF product included in the verification study. The figure also shows that the spatial averaging (smoothing) applied to the raw validation data makes the resolution of the smoothed data much more consistent with the WFO QPF product.

Because of the unique predictand definitions inherent to the MOS and LAMP statistical QPF products, their verification on the 30-km grid was limited. In particular, precipitation amount products from both systems are in the form of the best category[2] and expected value[3]. Also, the MOS products are unique in that they are issued for randomly-spaced points (stations). Thus, each station-oriented MOS QPF was (properly) verified on the basis of a single HRAP box that coincides with the station. The consequence of this unique verification procedure is that the verification sample as well as the predictand definition does not match that for the other products. Thus, the verification for MOS was not truly comparative and thus it had limited value in this study. The LAMP best category and expected value products are issued on a 20-km grid. The expected value was remapped to the 30-km verification grid and verified with the same 30-km precipitation mean used for other products. The LAMP best category, which could not be interpolated to the 30-km grid (because of its spatial discreteness), was verified on the 20-km grid on the basis of an average of the HRAP grid values within 20-km grid boxes centered on the corresponding gridpoints. Thus, the verification sample for the LAMP best category was also different than other

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[2]The best category is computed from probabilities for cumulative precipitation categories. The best category is obtained by first applying predetermined threshold probabilities to the forecast probability for each category. The best category is then specified as the highest category for which the threshold is equaled or exceeded, when all lower categories also meet this condition. The predetermined threshold values are derived to yield a particular bias (for the best category product) over a significant statistical sample.

[3]The expected value is computed from forecasts issued in the form of probabilities for discrete, exhaustive precipitation categories. The expected value is equal to the sum (over all categories) of the probability of a category multiplied by the conditional (climatic) mean precipitation amount for the category. Thus, the expected precipitation forecast is computed from quantitative estimates of the certainty of occurrence of each of the possible precipitation categories together with predetermined conditional means within the categories.

products verified on the 30-km grid, and the LAMP best category verification also had limited utility in this study.

Verification Measures

Consistent with the national QPF verification plan described in the QPI Plan (Office of Meteorology 1999), the verification scores applied for the QPF products fall in either of two classes, which are referred to as "continuous" and "categorical" scoring. The continuous scoring rules/measures include the bias (volumetric), mean error, mean absolute error, standard error, reduction of variance, and correlation coefficient. These scores were computed for the NWP model, MOS/LAMP expected value, and WFO/RFC continuous precipitation forecasts, and the HPC semi-continuous products as well. Special care was taken in applying the continuous scoring system to the semi-continuous HPC QPFs because of the bogus precipitation values inserted for this product below 0.25 inches (noted earlier). For the categorical scoring system, the scores are computed from multiple-category forecast-versus-observed precipitation contingency tables. The scoring rules include bias (categorical), probability of detection, false alarm ratio, threat score, equitable threat score, and Heidke skill score. These measures were computed for the MOS/LAMP best category QPFs, as well as from "categorized" manual and model QPFs originally specified in continuous (semi-continuous for HPC) forms. Also, the continuous 6-h manual and NWP model QPFs were summed over the four 6-h periods and "categorized" so that ensuing categorical precipitation scores could be compared with those from corresponding 24-h forecasts produced by HPC.

The comparative scores were computed separately for the full 6-mo samples as well as for monthly or 3-monthly sub-samples of the selected 6-mo verification period. Verification over the sub-samples was conducted, in part, to mitigate sample reductions that result when one or more of the QPF products were not available for a substantial portion of the full 6-mo period. Initially, the scores were computed separately for the three RFC areas because it was believed differences in precipitation climatology between the areas would complicate assessments of skill differences among the products. However, upon analysis of the individual RFC results it was noted the ABRFC and OHRFC samples could be combined (as discussed in the next subsection) and scored together, so as to increase the sample size.

An objective means of determining statistical significance was not developed for this study. However, a comprehensive review of all scoring measures from both the continuous and categorical systems provided rankings of relative skill among the products. Results based on this approach are described in the next section.

Results

Results from the comparative verification study focus on the assessment of the relative contributions of the three human components (HPC, WFO, and RFC/HAS) of the NWS QPF process. While the comparative verification study also included QPF guidance products from the AVN, NGM, and Eta NWP models, and the NGM MOS and LAMP statistical models, for brevity most results presented are for the AVN, Eta, and LAMP model guidance together with the three human-generated products. (Inclusion of LAMP statistical guidance over MOS was chosen because of the sample mismatch for MOS noted earlier). Also, in the assessment of the scores, careful consideration is given to the fact that the QPF products are being evaluated for their applicability to hydrologic forecasting. Thus, while the verification scores for the higher precipitation amounts are weighted more heavily than those for light amounts, the product assessment accounted for individual scores over the full range of precipitation amount.

Before proceeding into the details of the scoring approaches and results, sampling issues involving the QPF products should be noted. First, QPFs for 6-h valid periods only are used in the NWSRFS streamflow models. Therefore, the 6-h QPFs receive focus in the assessment. However, the available sample for all 6-h products was limited to only the last three months of the pre-selected 6-mo period of study, as the archive of HPC 6-h products was limited to this sub-period. Thus, the "full" QPF process assessment involving all 6-h products was based on a relatively short sample. The sample for 6-h products was extended to 6 months (except only 5 months of data were available for the CNRFC), but the assessment was "partial" as the HPC QPF could not be included. The QPF assessment involving 24-h products was therefore used to, in effect, strengthen the assessment based on the 6-h data--all 24-h products were available for the full 6-mo period (5 months for CNRFC).

Another prefatory issue involves the geographical partitioning of the verification statistics. Initially, the scoring of the QPF products was conducted separately for the three RFC areas. It was found, however, that the comparative performance of all products was quite similar for the ABRFC and OHRFC areas. Thus, for brevity, the statistical results for these two areas are combined into a single set. For the CNRFC, the comparative scores were quite different from the eastern RFCs, so they are presented separately.

As noted earlier in this subsection, all QPF products included in this study were verified with the categorical and continuous scoring methods. The categorical scoring system measures the degree of spatial matching between forecast and observed precipitation, where precipitation is specified for areas (or points) in categories of amounts. The categories are specified as occurrence or non-occurrence, where occurrence denotes precipitation amount falling in a category (either discrete or cumulative), and non-occurrence otherwise. The continuous scoring system extends the categorical system by quantifying the error in the specific amount of forecasted precipitation for amounts in any range (discrete or cumulative precipitation intervals or even the full range). Because the continuous scoring system yields a more precise measure of forecast error, this method is preferred where either (or both) can be applied.

While the continuous scoring system is preferred, it is not obvious how best to proceed, as previous QPF verification with this method has been very limited. Some questions that needed to be addressed were: (1) should the scores be computed only as a function of the full range of precipitation amount; (2) if the scores are stratified by precipitation interval, should the intervals be cumulative or discrete; (3) should the scores be stratified as a function of observed precipitation amount, forecast amount, or as a combination of both the observed and forecast precipitation amount stratifications, and (4) what scores are sufficient upon which to base the assessment? Another issue concerns the degree to which the bogus precipitation values in the HPC QPFs are evident in the verification results for these products. To help answer these questions, comparative verification experiments were conducted in which the various alternatives and issues were examined. These experiments are discussed in Appendix A.

The findings from the continuous scoring experiments (as shown in Appendix A) are that the use of discrete precipitation intervals is appropriate for assessing the performance of the various QPF products. A weighted combination of the observed and forecast precipitation stratifications of the scores in the discrete intervals is most useful. Also, it was found that the mean absolute error (MAE) is sufficient for judging the accuracy of the QPF products and the bias (volumetric) reveals information regarding the degree of overforecasting and underforecasting. Finally, as for the issue of contamination of the HPC scores, the results showed little evidence of contamination beyond 0.25 inch.

Still, the potential issue of contamination of the HPC continuous scoring results for precipitation ≥0.25 inch warranted additional experiments, wherein results from the categorical method were compared with the continuous method. These experiments revealed that results from the categorical method applied for ≥0.25 inch were generally consistent with corresponding results from the continuous method for all products, including the "contaminated" HPC continuous scores. The results also showed that the continuous method yielded more precise performance measures, especially in the case of the bias.

Thus, from the findings associated with the experiments, it was concluded that the assessment of the various QPF products could be conducted primarily on the basis of the continuous scores. Also, in the case of the HPC products, the continuous scores must be restricted to observed precipitation ≥0.25 inch. Thus, the comparative verification with all products included begins with this observed precipitation threshold. It was also concluded that the assessment could be conducted primarily on the basis of the MAE, with the bias used as an "informational" score. Thus, the following verification results are only on the basis of these scores.

Fig. 7 shows the MAE and bias for the combined ABRFC and OHRFC areas for the 6-h QPF products over the period 01 January - 31 March 1999. The number of days comprising the sample (when all products were available) was only 75, but the combined sample size was nevertheless substantial (388649 cases). In these figures (as in all figures involving 6-h products), the maximum precipitation interval is ≥1.00 inch, as this was the heaviest interval for which a statistically meaningful number of cases[4] emerged from the overall sample. The MAE chart shows that among the three human-generated products (HPC, WFO, and HAS), HPC had the smallest precipitation error in most intervals. Between the WFO and RFC/HAS products, the HAS had an equal or smaller MAE for all intervals except ≥1.00 inch, where the WFO MAE was smaller. Among the three model products (AVN, Eta, and LAMP), LAMP had an equal or smaller MAE up to 0.50 inch, the AVN showed a clearly lower MAE for ≥1.00 inch, and the overall performance of the Eta appears to lie somewhere between these two products (when emphasis is placed on the heavier precipitation intervals). The bias chart shows that among the three human-generated products, all overforecast precipitation in the 0.25-0.50 inch, all showed a sharply decreasing bias with increasing precipitation amount, the bias decrease was somewhat greater for HPC than the WFO and HAS products, and all showed severe underforecasting for ≥1.00 inch. Among the models, the AVN strongly overforecast precipitation below 0.10 inch , but it was the only product with a good bias for the ≥1.00 inch interval. The Eta and LAMP models had a better bias than the AVN for many of the lighter precipitation intervals, but they extremely underforecast the heaviest amounts. Strong underforecasting of heavy precipitation was anticipated with the LAMP expected value product, as the high uncertainty generally associated with heavy precipitation is reflected as correspondingly reduced values of expected amounts. The LAMP expected value's extreme underforecasting of the heavy amounts is also reflected as the largest MAE among all products for the peak precipitation interval.

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[4]The maximum precipitation interval is specified as ≥1.00 for the 6-h QPF verification and ≥2.00 inch for the 24-h data. The number of forecast and observed precipitation cases that fall in the maximum interval is in the range 440-2176 for the 6-h data and 495-1448 for 24-h data; the specific number for individual verification runs depends on the particular QPF product and RFC area involved.

A reasonable subjective ranking of the performance of the six products over the full range of precipitation (but with greater weight given to heavier amounts) is: HPC and AVN performed best and at about equal levels, and the WFO and HAS products ranked next and they too performed at about equal levels. Between the remaining Eta and LAMP products, the performances were mixed depending on the interval, but the Eta was clearly better at the heaviest interval. In relevance to the QPF assessment, the most significant results were that HPC did not make a substantial improvement on the AVN guidance, and the WFO and HAS did not improve on the HPC guidance.

The corresponding MAE and bias scores for the 6-mo sample shown in Fig. 8 (where the HPC product is excluded for reasons noted previously) are similar to those just examined for the 3-mo sample. For this longer sample, the MAE chart again shows the WFO and HAS performed at roughly the same levels, but here the HAS product appears to have a small edge in overall performance (The WFO product no longer shows the clear improvement on the HAS product for ≥1.00 inch seen in Fig. 7). Also, while both of these human-generated products improved slightly on the AVN for 6-h precipitation of 0.50 inch and less, the AVN had clearly smaller error for the ≥1.00 inch interval. The corresponding bias chart shows that the AVN product had the best bias for most precipitation intervals and the Eta bias was also relatively good everywhere except for the heaviest interval. Also, the bias properties of the WFO and HAS products are similar to one another, and the LAMP product continues to show the strong bias drop seen previously, from overforecasting of the light amounts to severe underforecasting of the heavy amounts.

The MAE and bias charts for the 24-h QPFs (Fig. 9) for the full 6-mo verification period were found to effectively confirm the results for the 6-h QPFs from the 3-mo sample. In particular, the overall slight degradation in the MAE of the WFO and HAS products relative to the AVN and especially the HPC product remains evident in Fig. 9. Regarding the performances of the WFO and HAS products relative to one another, a slight shift from the results for the 6-h products emerges. In contrast to the MAE results in Figs. 7 and 8, where the overall performance of these two products was about equal, Fig. 9 for the 24-h period shows the HAS product maintained a small margin of improvement in the MAE over the WFO for the entire precipitation range. Finally, the relative performances of the model guidance products for the 24-h QPFs were also consistent with those for the 6-h products. Note that the MAEs for the Eta were larger than those for the AVN for precipitation amounts of 0.50 inch and higher, and LAMP had the largest MAE for ≥2.00 inch (Fig. 9). It is significant, however, that the LAMP MAEs were smaller or equal to those for the AVN and Eta for precipitation amounts up to 1.00 inch, which is also true for amounts up to 0.50 inch in the case of the 6-h QPFs (Figs. 7 and 8).

It is apparent from a simple comparison of the 6- and 24-h results (Figs. 8 and 9) that a decrease in accuracy from the 24-h QPFs to the 6-h QPFs is present, especially for precipitation amounts of ≥1.00 inch. For instance, the MAEs for the 6-h products in Fig. 8 are only slightly lower than the MAEs for the 24-h products in Fig. 9, despite the higher observed peak amounts for the 24-h period. The difficulty of forecasting heavy precipitation amounts in 6-h periods is further underscored by the bias charts for the 6- and 24-h periods. Fig. 9 reveals that all 24-h products except LAMP and Eta exhibited bias values that did not deviate greatly from perfect (1.0) for precipitation in the 0.50-2.00 inch range. For the 6-h products, Fig. 8 (6-mo period) shows a significant dry bias for precipitation beyond 0.50 for all products except for the AVN in the 0.50-1.00 inch interval. This result reflects the great difficulty of forecasting heavy precipitation within relatively short periods.

As noted previously, the performance evaluation of the QPF products was conducted separately for the CNRFC, as the product rankings there were significantly different than those just discussed for the eastern RFCs. Also, results are not shown for the HAS product, as HAS forecasters for this RFC do not modify the WFO forecasts (as noted earlier).

The CNRFC MAE and bias for 6-h QPFs over the 3-mo period is shown in Fig. 10. The MAE chart exhibits a marked departure from the results discussed to this point for the eastern RFCs, as the WFO product is the clear performance winner, especially for precipitation amounts of 0.50 inch and more. For precipitation of ≥0.25 inch, the HPC product ranked behind the WFO product, but ahead of all three model products. Among the model products, the LAMP product scored better than the AVN up to 0.50 inch, but the AVN was clearly better for ≥1.00 inch. The Eta performed worse overall than the AVN and about equal to LAMP, and its relative standing (at least for the ≥1.00 inch interval) is better than it was for the eastern RFCs (see Fig. 7). The superior performance of the WFO product is also evident in the corresponding bias chart (Fig. 10), as this product exhibited the best bias values over the full range of precipitation values. The bias patterns for all other products show a steeper drop-off from overforecasting of light amounts to underforecasting of heavy amounts. The corresponding 6-h QPF results for the 5-mo period that exclude the HPC product (not shown) were virtually identical to those just discussed.

The CNRFC MAE and bias results for the 24-h products over the 5-mo verification period (1 November 1998 - 31 March 1999) shown in Fig. 11 indicate only minor changes from corresponding results for the 6-h products. Fig. 11 shows that the WFO product maintains its superior MAE values, at least for precipitation in the two heaviest precipitation intervals. The HPC product ranked next in performance, but it showed a clear improvement on the LAMP model product (the next overall best product) only for the heaviest precipitation interval. The AVN followed LAMP in overall performance, as it had higher MAEs everywhere except for the heaviest interval, and the Eta closely followed the AVN in regard to MAE. The bias values for the 24-h products (Fig. 11) were quite good for most products, except at the lightest and heaviest precipitation intervals, the HPC product shows near perfect bias values over the full precipitation range for which it is valid.

It is worth noting that the scores for the CNRFC were substantially better than those for the eastern RFCs. For instance, a close comparison of the MAE charts for the 6-h (Figs. 7 and 8) and 24-h (Figs. 9 and 11) periods shows that the forecast error for the highest interval about one-third from the eastern RFCs to the CNRFC. A clear improvement is also seen in the corresponding bias scores from the eastern to the western U.S. This result indicates that the orographically-forced precipitation that predominates during the cool season near the West Coast is a more tractable forecast problem. Orographic forcing is fixed spatially, whereas regions lacking mountainous terrain are subject to more diverse forcing both spatially and temporally.

Clearly, one of the more striking findings in this comparative verification study is the superior performance of the WFO QPF for the CNRFC. Several factors, already alluded to in the comparative verification methodology subsection, can explain this result. One is that WFO forecasters are intimately familiar with the unique precipitation climatologies of the small number of points (in mountainous terrain) for which the QPF product is originally issued. Of course, this factor gives the WFO an advantage over HPC (and other QPF products as well) because the QPFs from HPC are not tailored climatologically for the WFO forecast points. A second advantage for the WFO results from the likely artificial correlation between the QPF and the validation data that stems from the identical post-processing of both data types. And yet a third advantage afforded the WFO is the inclusion of updated QPFs (whose issuances could be well into the 24-h verification period) in the computation of the verification statistics. Obviously, if the last two WFO advantages resulted in a significant improvement of their verification scores, the findings from the comparative verification for the CNRFC would be open to question. Because of these problems with the comparative verification for the CNRFC, the results must be regarded as preliminary, and a further assessment study is needed.

b. Case Studies

Overview

Reviewing selected cases provides an opportunity to examine the QPF process during a variety of "real-world" hydrometeorological events. A twofold approach was adopted to collect and evaluate case studies. First, an extensive search of historical QPF cases was conducted. Next, recent events were reviewed as potential case studies. Both groups were then examined in terms of appropriateness for evaluating the current QPF process. Cases were chosen based on the amount of data that were available, the severity of the resultant flooding, if any, and the geographic location of the event.

The selection of prior case studies to demonstrate the entire QPF process proved to be challenging. Few cases provided QPF verification data, and those that did focused on only one phase of the QPF process. Each of the cases utilized a different approach to evaluate the accuracy of QPF, making comparisons between these studies virtually impossible. In addition, expanding the data sets for the cases to incorporate the entire QPF process was hindered by the lack of archived data. As a result, new cases of more recent events were developed to evaluate the entire QPF process.

The search for more recent events focused on those with data covering all steps of the QPF process. This precluded events older than one year since many RFCs archive data for that period only, or over the previous "wet" season. The RFC archives are the main source of WFO QPF, HAS QPF, and Stage III precipitation data. Events were identified throughout the United States and included a variety of weather conditions that produced moderate/heavy precipitation.

From the available data, six events, two from each of the RFCs used in the verification study (OHRFC, ABRFC, and CNRFC), were selected as case studies. These events comprised a variety of hydrologic conditions and provided snapshots of the operational QPF process. After reviewing the results from these six case studies, the number of case studies included in this report was reduced to three, one from each of the RFCs, in order to illustrate only the most salient points of the analyses.

The cases were critiqued to assess the effect of each step of the QPF process. Individual components of the QPF process were evaluated by subjective and objective means to determine their impact on the final QPF input to the NWSRFS. The objective analysis used for each case was the same approach as was used for the 6-month verification study included in this report. By generating objective comparative verification measures for each case, the magnitude of the contributions associated with the various steps of the QPF process could be evaluated and compared. The use of the same verification approach provided a basis for comparison between the individual case studies, and between the case studies and the overall verification results.

<u>Case Study Results</u>

ABRFC Case Study
02 January 1999

Case Overview

This case study graphically depicts, as was suggested by the overall verification analyses, the inefficiencies in the current QPF process. The event demonstrates that model guidance as improved by the HPC can provide a useful starting point for the QPF. It further reveals that input from 12 WFOs can promote incoherency in the final mosaic, which the HAS forecaster must resolve to produce a QPF product for input to the NWSRFS.

A strong shortwave trough moving in from the "Four Corners" area behind a weakening system combined with moisture from the Gulf of Mexico to bring heavy rain to the eastern portion of the ABRFC forecast area. Fig. 12 shows the observed precipitation for the period of 1200 UTC 1 January to 1200 UTC 2 January 1999. The heaviest rain occurred just to the east of the ABRFC forecast area, which made the placement of the QPF very important. The extreme eastern portion of the ABRFC area received heavy precipitation from this event. The heaviest rainfall occurred in Arkansas where more than 3 inches was reported at several locations. There were a large number of reports of rainfall in excess of 1.5 inches in Arkansas and a few in Oklahoma.

This rainfall was preceded by several months of extremely dry weather across the ABRFC area, so soil conditions were dry. These soil conditions dictated the hydrologic response. Runoff was minimal and resulted in only minor rises on rivers and streams in the eastern quarter of the ABRFC area where the heaviest rainfall occurred. Rises were well within bank, with no flooding problems reported. Elsewhere in the ABRFC area, very little or no hydrologic response was observed.

Verification Analysis

Fig. 12 indicates the model QPF and the observed 24-h precipitation for the period of 1200 UTC 1 January to 1200 UTC 2 January 1999. The AVN model provided reasonable guidance for this event, although the forecast precipitation was more widespread than observed, and the maximum value, while well forecast, covered too large an area and thus placed a large volume in the ABRFC forecast area. The NGM model positioned the heavy rainfall shield too far west, while the Eta QPF was too far east.

To evaluate the contribution of the human components of the QPF process, Fig. 13 illustrates the 24-h QPF from HPC, the supporting WFOs, and the ABRFC HAS. HPC guidance looked similar to the AVN forecast in that the location of the precipitation maximum was well defined, but a little too far north, and the areal coverage was too large. HPC maximum precipitation values were reduced over the ABRFC area from those forecast by the AVN. The observed data showed this was the proper correction. WFOs placed the heavy precipitation too far west, and the isolated maxima, which were underestimates, resembled bull's eyes over the particular WFO's HSA. The HAS QPF shows the role of the HAS in trying to resolve the incoherency in the WFO mosaic. For this case, the HAS forecaster apparently combined the three maxima into one large area. The WFO forecasters might suspect that the HAS reduced the spatial detail the WFO forecaster provided. However, the HAS was likely trying to produce a spatially consistent QPF that can be assimilated by the NWSRFS.

Objective verification scores provide a measure of skill for each of the constituents in the QPF process. Since the 6-h QPF is input to the NWSRFS, these scores will be the focus of the discussion. Fig. 14 shows the mean absolute error (MAE), and indicates that HPC provided the most skillful 6-h QPF given it had the lowest MAE in each category above 0.25 inches. The Eta provided the best model guidance as it had the lowest MAE of the NWP models. From Fig. 13, the AVN forecast too much precipitation in the highest category, which reduced its overall skill. Even though the AVN had the best position for the heaviest rainfall, its high bias reduced the skill to less than the Eta. The high bias of the AVN can easily be seen in Fig. 15, which shows the volumetric bias. The volumetric bias is the ratio of the average precipitation for the forecast and observed precipitation areas. This is computed within the intervals shown. A bias of one means the correct volume of rain was forecast within the specified interval.

The WFO and HAS forecasters showed reduced skill compared to the HPC. This is also evident in Fig. 14, since both products placed the QPF too far to the west. The perception that WFOs add valuable detail to the QPF over that available from HPC and the models is not supported in this case. The WFOs provided an incoherent QPF mosaic that reduced the overall skill of the product. The HAS forecaster attempted to produce a coherent QPF, but started with a less skillful product (WFO mosaic) and thus was able to improve the QPF only slightly. The bias statistics indicate that the WFO and HAS have overforecast the lighter amounts of precipitation while under forecasting the heavier amounts. The HPC also under forecast the heaviest amounts.

Case Summary

This case typifies the larger sample of data examined in the statistical verification. That is the NWP guidance is an excellent starting point for the QPF. In this case the HPC forecaster most likely chose the AVN as the best model, but reduced the amount of precipitation forecast. It appears that the WFO forecasters responsible for the southeast section of the ABRFC domain, each had a different idea of the "best" model or how to modify the model solutions. This resulted in a rather incoherent WFO mosaic. The HAS forecaster was left with the task of translating the WFO mosaic into a coherent product that can be input to the NWSRFS. Although the HAS added back some skill, the skill level was less than that of the HPC.

OHRFC Case Study
23 January 1999

Case Overview

This case illustrates that little if any value is added by having three separate forecasters involved in the QPF process. This is substantiated from the objective comparative verification statistics. Additionally, in a flooding situation, the time spent by the 16 WFOs preparing the QPF most likely impacted the local watch/warning program and the ensuing coordination with local emergency managers.

A persistent stationary front and strong moisture advection from the Gulf of Mexico focused widespread rain over the OHRFC forecast area. Short wave disturbances traveling through a strong jet stream contributed instability and mid-level moisture to the region. Continuous light rain, with occasionally moderate to heavy rain, was observed in southern Indiana and western and north-central Kentucky. An outflow boundary moving into western Tennessee was associated with thunderstorms and moderate rain as it moved eastward.

Rainfall in excess of one inch covered the southern third of Indiana and the western two-thirds of Tennessee and Kentucky during this event as shown in Fig. 16, which depicts the 24-h rainfall from 12 UTC 22 January to 12 UTC 23 January 1999. Rainfall amounts in the 2- to 3-inch range were common in parts of western Kentucky and Tennessee.

Runoff from the event was considerable across all of the OHRFC area. This runoff produced widespread small stream and flash flooding across the region. River flooding occurred throughout the region as well, and was most significant in Indiana where evacuations occurred in a number of places and several state highways were closed. Moderate flooding also occurred in Illinois and West Virginia where evacuations and road closures were reported. Elsewhere in the OHRFC area, minor flooding occurred. Five deaths were attributed to flooding. Most of these deaths were caused when motorists attempted to cross flooded roadways.

In the northern part of the OHRFC area the rainfall amounts were lower and the accompanying warmer temperatures produced appreciable snowmelt. The runoff from snowmelt and rainfall was sufficient in dislodging ice on rivers and streams in northern Illinois, Indiana, Ohio, and in western Pennsylvania. Ice jams were reported throughout this region of the OHRFC area and resulted in minor to moderate flooding necessitating evacuations of homes and the closure of roads in this region.

Verification Analysis

The tendency of the NWP guidance was to forecast the heavy rainfall too far to the north and west of the observed location. The Eta was the only model which did not place a relative minima in precipitation where in fact the heaviest precipitation was observed, Fig. 16. The manual forecasts apparently focused on the Eta model as all had a relative maxima in precipitation where it was observed. The HPC forecasted the heaviest precipitation near where it was observed, Fig. 17. A subjective examination of Fig. 16 shows the Eta model did not extend the higher precipitation values as far north as the other models. Also, the Eta extended the heavier precipitation farther to the east in Kentucky and Tennessee, which more closely matched the observed pattern.

Examination of the 6-h MAE and bias scores, Figs. 18 and 19, shows the Eta model was the most skillful of the NWP models evaluated. The HPC QPF was slightly better than the Eta in categories greater than 0.50 inch. Examination of the performance of the three manual forecasts, shows no clear winner. This supports the recommendation that the HPC forecast could have been the starting point for the HAS without degrading the QPF.

Case Summary

The 6-month comparative verification statistics showed the AVN to be the “best” NWP model for QPF. However, in this case the Eta was the clear winner. This case demonstrates the ability of an experienced forecaster to select the appropriate NWP guidance in a given situation. Thus even though the numerical guidance shows significant skill, maintaining human involvement in the QPF process provides for the selection of the appropriate numerical guidance. Since the difference in skill for the QPF issued by each of the manual forecasts was minimal, three separate manual forecasts do not appear to promote the most efficient use of human resources nor the most effective QPF forecast process.

CNRFC Case Study
7 February 1999

Case Overview

Strong zonal flow across California and Oregon brought moist, Pacific air onshore. Heavy precipitation was focused along the northern Coast Range and northern Sierra Nevada mountains as revealed in the plot of 24-h precipitation from 1200 UTC 6 February to 1200 UTC 7 February 1999, Fig. 20. This event is typical of moderate/heavy precipitation events which occur along the western U.S. coast during the winter months.

Rainfall totals in excess of 4 inches were reported in extreme southwestern Oregon and in the northern Sierra Nevada Mountains north of Lake Shasta. Rainfall totals in excess of 3 inches were reported over most of the Coast Range from San Francisco Bay northward to Oregon. Precipitation over the Sierra Nevada Mountains north of I-80 was in the 2-inch plus range. Except for the central coast range, precipitation was light across the southern half of California for this event.

Substantial rises occurred on rivers and streams in northern California during this event. River flooding was confined to the Napa and upper Sacramento Rivers. However, rises on many other rivers in the region were above established warning stages, requiring action related to flood control structures and monitoring of levees. Minor river flooding was reported, and a trailer park, agricultural lands, and a few roads were affected. Urban and small stream flood advisories were issued for a number of locations throughout the region due to minor flooding of roadways and underpasses.

Verification Analysis

All of the numerical models exhibited skill in forecasting the area of general precipitation for this event as indicated by the display of 24-h QPF produced by the AVN, NGM, and Eta, Fig. 20. The heavier precipitation amounts over the higher terrain are underforecast by the coarser resolution AVN and NGM models. The manual QPFs produced by the HPC and the 10 separate WFOs are shown in Fig. 21. The CNRFC does not routinely modify the WFO mosaic, except in the first six hours when they correct for the amount of precipitation that has already fallen.

There was very little difference in skill between the manual forecasts and NWP model guidance for precipitation amounts less than 1 inch. However, model skill dropped for the heavier precipitation intervals for the 6-h QPF forecasts since model resolution is not sufficient to resolve the details of the orographic forcing. Manual intervention to improve the QPF product is readily apparent when examining the MAE, Fig. 22.

In particular, the QPF forecasts from the WFOs were much better than any of the model or statistical guidance for all of the precipitation categories. This is probably related to the WFO forecasters familiarity with their 4 to 6 forecast sites they are responsible for, and the PRISM data, which utilizes climatology to map these points to a high resolution grid which accounts for terrain effects. The HPC QPF forecasts showed slight improvement over the model forecasts, especially for the areas of moderate precipitation. The volumetric bias scores, Fig. 23, shows a trend for both the model and manual QPFs to overforecast. This is especially true of the WFO forecast for the higher categories.

Case Summary

This event typifies what was observed from the overall objective comparative verification statistics for the CNRFC. For this area, the WFO produces the most skillful forecast, especially for the higher categories. The contribution of the PRISM to this skill level has been discussed. The HPC demonstrates skill at or better than NWP. It would appear that both from this case study and the overall CNRFC statistics, that the HPC is cognizant of the terrain influences along the West Coast, however because HPC forecasts spatially averaged precipitation instead of point or maximum rainfall, the HPC product underestimates rainfall in the heaviest categories. It is not clear at the present time that it is valid to compare point rainfall forecast with a spatially averaged rainfall forecast. Further analysis must be performed on the CNRFC data to determine the best method for comparing these types of forecasts.

c. Questionnaires

The WFO and RFC questionnaires were distributed and collected by each regional representative on the QPF Process Assessment Team. MICs and HICs were instructed to complete the questionnaires in a manner which accurately reflects the status of the QPF process at each office. Response from the field was exceptional, particularly in light of the fact that offices were only given about two weeks to complete the questionnaires. A total of 101 out of 117 WFOs (86%) and all 13 RFCs returned questionnaires, with full participation from Eastern and Western Region.

The questionnaires focused on five primary issues: (1) experience with QPF; (2) QPF production and coordination; (3) verification; (4) training; and, (5) forecast process perceptions. Not surprisingly, responses varied considerably among the regions.

Experience with QPF

The average number of years WFOs have been producing QPF for their supporting RFCs is nearly 5 nationwide. In general, Eastern and Western Region WFOs have more experience than their Southern, Central, or Alaska counterparts. The national RFC-average for the routine use of HAS-mosaicked QPFs is 3.4 years. Two RFCs, Lower Mississippi and Northwest, do not produce HAS mosaics of QPF while the OHRFC has generated QPF mosaics for 7 years. Interestingly, a large majority of the RFCs (11 of 13) have staff members other than HAS forecasters work the HAS function, and at more than half of the RFCs the entire staff rotates through the HAS function. Nationwide, 62% of the RFC staff who perform the HAS function are meteorologist qualified, and other data from the Office of Hydrology indicates that all current HAS forecasters are meteorologist qualified. While experience varies from months to decades, the vast majority of WFOs and RFCs have routinely generated and/or utilized QPFs for at least two years.

QPF Production and Coordination

The majority of WFOs (67%) rated QPF as either one of the most or the most difficult meteorological parameter they forecast. This is not surprising given the inherent complexity of the precipitation forecast problem, which is directly attributable to the fact that the advective transport of atmospheric variables is multi-scale, convection initiation mechanisms are multi-scale, and the interaction of these physical and dynamical processes is multi-scale and highly nonlinear.

Most WFOs (79%) spend 30 minutes or less per forecast issuance producing QPFs in non-flooding situations. Forecast production time is the aggregate time spent on QPF preparation (meteorological analysis) and product generation, and represents the time *beyond* that required to produce the historical forecast package. WFOs usually spend more time on QPF preparation than product generation. During flooding situations, the majority of WFOs (76%) produce additional (non-scheduled) QPFs, with the request most often originating at the RFC. Additionally, WFOs spend more time producing QPFs in flooding situations. In fact, the majority of WFOs (65%) require 15-45 minutes to produce QPFs during flooding situations. It is interesting that most WFOs spend less than 15 minutes coordinating QPFs in both non-flooding (98%) and flooding (65%) situations, particularly given that a substantial number (31%) of WFOs must coordinate with two or more RFCs. The approximate average aggregate time per forecast spent on QPF production and coordination at the WFO is 25 minutes in non-flooding situations and 40 minutes in flooding situations.

The majority of RFCs (10 of 13) responded that it was fairly easy to mosaic/reconcile WFO-provided QPFs for routine operations, while the same number responded that it was moderately difficult in flood events. During routine operations, 12 of 13 of RFCs indicated that very little modifications to the WFO QPF are made by HAS forecasters. However, for flood events, 6 of 13 of RFCs indicated that moderate modifications were required by the HAS forecasters in order to provide more temporally and spatially coherent precipitation patterns for input to NWSRFS. Consistent with this response, most RFCs (9 of 13) require less than 30 minutes per forecast cycle to mosaic and reconcile WFO-produced QPFs in routine operations, and (8 of 13) require 30-60 minutes during flood events. Forecast coordination typically (12 of 13 RFCs) requires less than 30 minutes for routine events, but there was a wider range in responses for flood events with HAS forecasters most often (5 of 13 RFCs) requiring 30 to 45 minutes. The average aggregate time spent per forecast on mosaicking, reconciling, and coordinating QPFs at the RFC is roughly 35 minutes in non-flooding situations and 65 minutes in flooding situations.

A query of HPC personnel revealed that on average two HPC forecasters require a combined total of approximately 8 hours per forecast cycle to produce and coordinate QPFs for the CONUS in both non-flooding and flooding situations. Consequently, a per forecast comparison of the total resources (hours) expended per issuance to produce and coordinate a CONUS QPF in non-flooding situations reveals totals of approximately 8 h, 47.5 h (114 x 25 min), and 7 h (12 x 35 min) for the HPC, WFOs, and RFCs, respectively, which corresponds to a HPC:WFO:RFC relative labor expenditure of 1.1:6.8:1.0. In flooding situations, the totals are approximately 8 h, 76 hours (114 x 40 min), and 13 h (12 x 65 min) for the HPC, WFOs, and RFCs, respectively, or a HPC:WFO:RFC relative labor expenditure of 1.0:9.5:1.6. The differences in these times would be substantially greater if WFOs outside the Western Region extended the range of their forecasts from 24 to 72 hours as required by the RFCs.

Most WFOs and all RFCs use QPF software applications which were not nationally-developed and are not nationally-supported. Consistent with Section 2 of this report, the majority (73%) of WFOs utilize the PC-based WinQPF software application, 19% use the UNIX-based Mountain Mapper software application, and only 3% utilize AWIPS. The vast majority of WFOs (97%) rated these software packages at least satisfactory for the generation of QPF products, but a substantial number (42%) found these tools to be unsatisfactory for coordination purposes. The majority of RFCs (8 of 13) use the UNIX-based HASQPF tool to mosaic and reconcile WFO QPFs, while two RFCs use Mountain Mapper, and two use other locally-developed applications. The Alaska RFC does not mosaic QPF and therefore does not require nor use a mosaicking tool. A majority of the RFCs that mosaic QPF rated these software tools at least satisfactory for mosaicking/reconciling WFO QPFs (10 of 12) and coordination (11 of 12).

Based upon the WFO responses, coordination between the HAS and WFO forecasters is an area of concern. For both non-flooding and flooding situations, many WFOs (42%) are uncertain about the extent to which the HAS forecasters modify WFO QPF input and 39% of WFOs responded that HAS forecasters *never* coordinate modifications when they are made. RFC HAS and WFO forecasters are relegated to using use the telephone as the primary means of coordination, and the majority of RFCs and WFOs rated their collective means of coordination as only somewhat effective or not effective.

Verification

Nearly half of WFOs (49%) compute verification statistics for QPF on routine basis, but nearly a quarter of WFOs (23%) do not compute verification statistics at all. Almost two thirds (63%) do not have a system in place for forecaster feedback. Verification statistics are computed by 9 of 13 RFCs for WFOs, but only 5 of 13 RFCs indicated that statistics are computed for HAS mosaics. Over half (7 of 13) of the RFCs do not have a system in place to provide timely and sufficient feedback to HAS forecasters. Consequently, verification feedback necessary to quantify, calibrate, and improve WFO and HAS forecaster skill is severely lacking.

Training

The questionnaires included a variety of questions on proficiency and training issues. Nearly half (43%) of the WFOs nationally indicated it takes less than 3 months for a forecaster to become proficient at generating QPFs, and 67% revealed that it takes less than 6 months. Thirty-nine percent (5 of 13) of the RFCs indicated that it takes one to 3 months for the HAS forecasters to become proficient to mosaic/reconcile WFO QPF, but 46% (6 of 13) revealed that it takes 3 to 6 months or longer. These results are particularly interesting given the significant seasonal and spatial variability of precipitation over the U.S. and within the domains of many of the RFCs.

Overall, 38% of WFOs participate in training on the impact of QPF in NWSRFS once per year or more, while 48% of WFOs provide training on QPF product generation (software) once per year or more. Additionally, the majority (64%) of WFOs participate in training on QPF preparation (meteorological science) once per year or more. Approximately half (54%) of the WFOs indicated this combination of training met only some of their needs, while 26% felt that it met most of their needs. Among the wide variety of training methods, WFOs rated COMET residence training, regional QPF workshops, and on-station training as being very effective.

The RFC questionnaires also included a variety of questions on training issues. Overall, 46% (6 of 13) of RFCs provide training on the impact of QPF in NWSRFS once per year or more, 39% (5 of 13) participate in training on QPF preparation once per year or more, and 54% (7 of 13) of RFCs provide training on QPF product generation once per year or more. With regard to training methods, RFCs selected COMET residence training, on-station training, and regional QPF workshops as being most effective. All told, 77% (10 of 13) of RFCs indicated the combined training met only some of their needs.

Forecast Process Perceptions

WFO and RFC perceptions of the relative value of each forecast component differed markedly from the verification study results. Contrary to the results of the objective comparative verification, WFOs rate the numerical weather prediction guidance from NCEP as the most valuable component of the QPF process in supporting the NWSRFS, followed by WFO QPF, the HAS QPF mosaic, NCEP/HPC manual products, and MOS guidance. RFCs believe the HAS QPF mosaic is the most valuable component of the QPF process in supporting the NWSRFS, followed by WFO QPF, NWP guidance, NCEP/HPC products, and the MOS guidance.

Regarding the relationship between QPF generation and flood awareness, only 13% of the WFOs indicated they would *not* be as aware of potential flooding situations if they did *not* routinely prepare QPF. This is an important finding particularly when assessing the operational impact and viability of forecast process option C, *Refocusing Activities at the WFOs.*

Based mostly on feedback from the RFCs and river verification, 56% of WFOs felt that QPF improved the accuracy and timeliness of river forecasts, while 31% were not sure. In contrast, and based mainly on river verification, user response, and feedback from the WFOs, 85% (11 of 13) of RFCs felt that QPF improved the accuracy and timeliness of river forecasts. In spite of these responses, relatively few river verification studies are available.

Overall, only 45% of WFOs felt that the improvement in NWS river forecasts relative to the WFO investment in time and resources justifies the requirement for routinely prepared QPF. However, 69% (9 of 13) of RFCs believe that the improvement in NWS river forecasts relative to the HAS forecaster investment in time and resources justifies the requirement for routinely prepared QPF.

V. Conclusions

The following signals related to the viability of the QPF process emerged from an analysis of the objective verification data, the detailed case studies, and responses from the questionnaires.

a. Relative Skill of WFO QPF Mosaic

The mosaicked WFO QPF was found to be less skillful than HPC and model guidance and at or below the skill level of the HAS QPF product for the ABRFC and OHRFC. This is not surprising, since the WFOs indicated QPF is one of their most difficult forecast problems. Furthermore, training to date has met only minimum forecaster needs, and WFO experience with QPF is considerably less than HPC. In fact, the average number of years WFOs have been producing QPF is nearly five nationwide compared to 39 years at HPC. Additional factors which likely contribute to a less coherent and less skillful WFO QPF product include: 1) the structure of the current QPF process enables each WFO forecaster within an RFC's area of responsibility to independently assess and apply a variety of guidance products available from the NWP system, MOS, and HPC; 2) the absence of a capability to display neighboring WFO QPFs hinders coordination and results in inevitable discontinuities across HSA boundaries; and, 3) the lack of timely access to objective verification data makes it difficult for WFO forecasters to calibrate their skill.

For the CNRFC, the WFOs were more skillful than HPC and model guidance. However, two factors may have contributed to the WFO skill. First, identical post-processing of WFO QPF and observed data may have created an artificial correlation. Second, updated WFO QPFs issued during the forecast validation period were included in the verification sample.

b. Misperceptions of Relative Value

The responses from the WFO and RFC questionnaires indicated the WFO QPF product is viewed as a critical part of the forecast process, and that the WFO efforts contributed both spatial resolution and value over the national guidance. This activity, which averages 25 minutes for product generation and coordination with the RFC, was deemed to be a worthwhile use of resources by only 45% of the WFOs. As revealed by the verification results for both the OHRFC and ABRFC, the amalgamation of QPF from several WFOs, resulted in a product that was slightly less skillful than the QPF guidance from HPC. Hence, this level of enhanced resolution generally is not transferred into relative skill for the WFO QPF throughout the RFC domain. In general, the HAS function forecaster at ABRFC and OHRFC removes some of the detail provided by the WFOs in the process of producing a more appropriate QPF for input to the NWSRFS.

An additional finding of importance is associated with the relatively high level of accuracy in the QPF from the AVN as compared with both the Eta and the NGM. The expectation that the Eta should have provided the most accurate QPF was not validated. This could be related to a series of modifications that were introduced last Fall to the analysis system for the Eta, which recently underwent further refinement and adjustment. The need for the provision of timely and consistent feedback related to model performance is evident.

c. Beneficial Human Intervention

The verification study revealed that the NWP system, especially the AVN, produced useful QPF guidance for the hydrologic subdivisions covered by the OHRFC and the ABRFC. Both the AVN and Eta guidance appeared to be adequate to serve as a "first guess" for the QPF process at the CNRFC. However, for a wide variety of moderate to heavy precipitation events throughout the forecast areas of all three RFCs, the expert interpretation of an experienced meteorologist was required to identify and modify the most appropriate guidance for a particular weather pattern. From both the verification results and the case studies, the forecasters at the HPC possess the appropriate level of skill in areas east of the Rocky Mountains to carry out this task. Also, for at least the next few years, it would be imprudent to expect HAS function personnel to bear the full responsibility for this aspect of the QPF process.

As NWP capabilities continue to improve and the hydrologic forecast system evolves, the need for modification and enhancement of QPF by the forecasters should diminish. In the distant future, highly automated, coupled prediction systems that explicitly account for the uncertainties in the atmospheric and hydrologic input variables will be formulated, tested, and implemented. Until that time, the need for meteorological interpretation and assimilation of QPF guidance will be required.

d. Inefficient Forecast Process

Overall, considerable WFO resources related to forecaster training, decisions concerning shift scheduling, product generation, and coordination with other offices and the RFCs, are utilized to generate a QPF for the hydrologic subdivisions which comprise the RFC areas of responsibility. The verification results and case studies indicated that both the NWP system and the HPC guidance resulted in QPF products whose skill is better than or equal to that of the WFOs (except for locations in the West), and these QPFs were spatially coherent and appropriate for modification by the HAS function for input to the NWSRFS. Moreover, as an aggregate, WFOs expend far greater resources in producing QPF than does

HPC and the RFCs. Thus, significant WFO resources are being used for an activity which accrues at best only modest benefits.

While coordination between the WFOs and RFCs is highly desirable on a routine basis, and it is critical during flood events, the emphasis on reconciliation of QPF products is cumbersome and places an untoward burden on the staff at the WFOs and RFCs. Interaction and coordination on local hydrologic problems and improvements to the flash flood program could be more fruitful, especially in light of the fact the vast majority of the WFO responses indicated the local production of QPF for the NWSRFS does not contribute significantly to their awareness of the potential for local flooding.

VI. Recommendations

The following recommendations will streamline the forecast process and should provide for the more efficient delivery of an improved QPF for input to the NWSRFS.

a. Refocus WFO Activities

From the results presented in Sections IV and V, the committee recommends that all WFOs, except in the Alaska Region and possibly the Western Region, be relieved of producing the QPF product. This will allow the WFO forecaster to concentrate on the office watch/warning program and allow additional time for the provision of new and existing forecast products.

b. Redirect HPC Resources

The assessment team recommends the HPC assume national QPF responsibility in support of NWSRFS. The HPC will provide a seamless, coordinated national QPF product to replace the current product received from a multiplicity of WFOs within each RFC's area of responsibility. Based on the verification results, this product should be as skillful if not better than the WFO mosaic the RFCs are currently receiving. Modifications must be made to HPC's QPF product generation software, product format, forecast range, temporal resolution, and frequency of product issuance in order to meet the needs of the RFCs.

c. Empower HAS Function

The committee recommends that the HAS function take a more active role in the QPF process. The HAS forecaster will be required to review and analyze model output, the HPC QPF, and surrounding WFO forecast products to produce a QPF for the RFC domain. For the HAS function to assume an augmented role in QPF analysis and generation, additional training and enhanced software support tools are necessary.

d. Establish National Precipitation Verification Unit

The committee recommends the establishment of a National Precipitation Verification Unit. One of the most important components of an effective national QPF program is a comprehensive objective comparative verification system. In support of the QPF Assessment Team, implementation of a nationally-approved precipitation verification system (Office of Meteorology 1999) was accelerated for a subset of RFCs. This system must be implemented over the CONUS with verification data made available in a timely fashion to all forecasters.

VII. Implementation Process

Implementation of the team recommendations will involve changes to activities of the HPC and the RFCs, additional training, and the implementation of a national QPF verification system.

An explanation of these changes is provided along with an implementation outline.

a. HPC

Product Schedules

The HPC must expand their product suite to include QPF products through day 3 for both the 0000 and 1200 UTC forecast cycles. For QPFs covering the 1200-1200 UTC forecast cycle, a preliminary 24-h day 1 graphical product will be issued by 0615 UTC, with the final 6-h day 1 through day 3 graphical, gridded and text products issued by 1030 UTC. For the 0000-0000 UTC forecast cycle, a preliminary 24-h day 1 graphical QPF product will be issued by 1800 UTC, with the final 6-h day 1 through day 3 graphical, gridded and text products issued by 2030 UTC. This product schedule will enhance HPC support for the NWSRFS and expand HPC's support of WFOs and other partners and customers.

Product Generation and Formats

The HPC must generate GRIB-encoded gridded QPFs (and SHEF-formatted point (text) QPFs for Western Region RFCs) at 6-h temporal resolution through day 3. The 6-h QPF grids will be continuous rather than the present categorical forecasts to better meet the needs of the HAS forecasters for input to NWSRFS. Currently, the HPC QPF product depicts isohyets at pre-specified intervals beginning with .25 inches. The revised HPC product will additionally delineate areas of measurable precipitation and be provided to the RFCs on the 4-km HRAP grid in a GRIB format compatible with HASQPF. Western Region RFCs will receive HPC QPFs for pre-specified points in SHEF format, which can be utilized directly by Mountain Mapper. In addition, the HPC will continue to issue graphical QPF products both for 6-h and 24-h totals through day 3 for both the 1200 and 0000 UTC forecast cycles.

Currently the HPC uses the NAWIPS/NMAP product generation tool. This allows the HPC forecaster to draw isohyets which can be converted to a grid by using standard graph-to-grid routines. In the future, AWIPS (Build 5.x) should provide the functionality for the HPC (and HAS forecasters) to produce or edit QPF products. In fact, the AWIPS Interactive Forecast Preparation System (IFPS) QPF functionality requirements as specified in the QPI Plan (Office of Meteorology 1999) encompass and expand upon the salient characteristics of WinQPF, Mountain Mapper, HASQPF, and NMAP, and the operational implementation of these capabilities will eliminate the need for the development and maintenance of multiple grid editing applications within the NWS (i.e., all forecasters will utilize the same AWIPS application). The IFPS tool (currently under development) will provide the functionality on AWIPS to initialize (with model output), edit, and generate a gridded QPF product in a format consistent with RFC requirements, and should allow meteorological fields and data currently viewed within D2D to be underlaid to support the QPF forecast process.

For RFC-requested QPF product updates, the HPC will for the first time be placed in an event-driven rather than a schedule-driven mode. The HPC must accommodate RFC requests for updates with existing NCEP FTE resources. Updates to HPC QPF will be issued as a CONUS product, which will be provided to all RFCs. When an RFC requests an update, the HPC will send an ADMINISTR message to all other RFCs to notify them that an update is being prepared. It is assumed that updates would be provided at a frequency of no more than every 6 hours.

Coordination with HAS Function

The HPC will coordinate directly with HAS forecasters at the RFC. HAS coordination with the WFOs will be streamlined yet will remain a critical element of the QPF process, particularly preceding and during significant hydrometeorological events. Routine coordination and communication between HPC forecasters and the RFC HAS function will primarily be achieved via forecast discussion products (such as the HPC PFD and the HAS HMD) and telephone calls. Direct conversation between HPC and HAS forecasters will enable the HPC to review model diagnostics and convey HPC forecaster confidence in the QPF products. Since the HPC will produce a seamless, nationally consistent QPF product, resources currently utilized by the HAS forecasters to resolve differences between neighboring WFO QPFs can be used by the HAS to tailor the HPC QPF product to their RFC domain. The HAS forecaster will modify the HPC gridded (or point) QPF as necessary.

For significant hydrological events, point to multi-point phone coordination is paramount and a system similar to the Tropical Prediction Center "hurricane hotline" and/or "blast-up" teleconferencing should be utilized. Conference calls with affected offices have been effective. Generally, it will be most efficient for HPC and the HAS function forecasters at the RFCs to first coordinate the QPF and its potential impact on the NWSRFS. This should be followed by HAS-initiated coordination between the RFC(s), affected WFOs, and HPC, as necessary.

An HPC implementation outline is provided. Completion dates are specified with respect to Corporate Board Approval (CBA):

CBA + 1 month - **Coordinate with each RFC to standardize the format of the QPF grid and point forecasts**. Confirm product delivery times with RFCs (for 1200-1200 UTC forecast cycle, preliminary 24-h day 1 product issuance at 0615 UTC and final 6-h day1 through day 3 graphical and gridded products issuance at 1030 UTC; for the 0000-0000 UTC forecast cycle, preliminary 24-h day 1 product issuance at 1800 UTC and final 6-h day 1 through day 3 graphical and gridded products issuance at 2030 UTC. **Action:** HPC, OM, OH, Regions

CBA + 1 month - **Submit proposal to NCEP Director defining resources required by HPC to assume national QPF responsibility** (i.e., reallocate existing FTE's within NCEP for up to 3 additional positions in HPC/FOB) or review HPC products suite to eliminate or streamline some products. **Action:** HPC, NWSEO, HR

CBA + 2 month - **Seek approval by NWS management for NCEP/HPC FTE reallocation or product restructuring**. Begin process of implementation. **Action**: HPC, NWSEO, HR

CBA + 2 month - **Establish requirements for NMAP software enhancements** for QPF product development and submit to the NCEP Central Operations (NCO). **Action**: HPC

CBA + 2 months - **Establish a Product Inventory List (PIL) for each 6-hourly HPC QPF product and submit to the Data Review Group (DRG) to obtain (35) WMO headers.** Coordinate with AWIPS Program Office for transmittal of these grids (files) over the Satellite Broadcast Network or Wide Area Network. **Action:** HPC, OM, OSO

CBA + 4 months - **Establish procedures for coordination** between HPC and RFCs**. Action:** HPC, OH, Regions

CBA + 4 months - **Establish backup procedures** for the HPC QPF utilizing the HAS function in each RFC. **Action:** OH, HPC, RFC, Regions

CBA + 5 months - **Implement HPC NAWIPS (NMAP) software modifications** to: 1) improve the interpolation scheme; 2) display running totals of 6 hours QPF for 24, 48, and 72 hour forecasts; and, 3) convert GEMPAK grid to RFC-defined HRAP grid and point forecasts for transmission to RFCs. **Action:** HPC, NCO.

CBA + 6 months - **Test the NMAP graph-grid formulation and grid production** on the Product Development Desk for a subset of RFCs (ABRFC, OHRFC, MARFC) using the 1200 UTC QPF cycle. Send grids via ftp. Test coordination procedures with the three RFCs. **Action:** RFCs, HPC, Regions

CBA + 6 months - **Conduct risk reduction with the CNRFC** to perform objective comparative verification of the HPC and WFO QPF products. The WFO product will be used operationally. The HPC QPF will be ingested into Mountain Mapper and modified by the HAS. The WFO, HPC and HAS gridded forecasts will be saved and evaluated using the verification methods used in this report. The HAS will request updates to the QPF from both the WFOs and the HPC. The final QPF from each will be verified. Verification should be done on a near real-time basis to test the national verification system and to expedite the verification of this risk-reduction. If the HPC/HAS forecasts are shown to be as good or better than the WFO forecasts, the HPC will assume responsibility for QPF in the Western Region beginning the fall of 2000. **Action**: HPC, CNRFC, WRH

CBA + 6 months - **Implement approved HPC FTE restructuring. Action**: HPC, HR

CBA + 6 months - **Invoke new HPC QPF product schedule,** which includes continuous 6-hourly QPFs through a range of 72 hours for both the 1200 and 0000 UTC forecast cycles. **Action:** HPC

CBA + 7 months - **Begin five month OT&E** to send QPF gridded/text products to all CONUS RFCs via ftp or AWIPS WAN/SBN for both the 1200 and 0000 UTC cycle. Confirm all requested updates can be completed in a timely fashion. **Action:** HPC, RFCs, Regions

CBA + 12 months - **Implementation complete**. HPC/RFC HAS officially assumes NWS QPF production for all areas but AR and possibly WR. **Action:** HPC, RFCs, Regions

CBA + 3 years - **Complete operational testing of PQPF procedures** in support of RFC probabilistic stream flow prediction. **Action:** OM, HPC, RFCs, Regions

b. HAS

QPF Responsibility

The HAS function forecasters will modify the HPC QPF guidance as necessary. The HAS forecasters continue to play a critical role in the QPF process as they will have ultimate responsibility for the QPF input to NWSRFS. The HAS must make every effort to tailor the HPC QPF to the RFC forecast domain to best meet the needs of the NWSRFS.

Coordination with HPC and WFO's

Since the HAS forecaster will be responsible for modifying the HPC QPF and for updates to the QPF during the first 6-h period, it will be their responsibility to coordinate significant changes with the HPC and associated WFOs. *The elimination of the QPF requirement for the WFOs does not reduce the need for close coordination between the WFO and RFC, particularly when either flash flooding or main stem river flooding is forecast or occurring.*

QPF/QPS to the WFOs

The servicing RFC must provide the QPF (either point data or gridded product) and QPS (basin means in text format), generated for input to the NWSRFS, to the affected WFOs as part of the normal forecast cycle. This will allow the local WFO to continue to provide these products to partners and customers.

Data Archive/Verification

All RFCs must routinely archive in a consistent format (i.e., Netcdf) and send the following products/data via AWIPS WAN/SBN to the National Precipitation Verification Unit (NVU) at NCEP: 1) hourly, gridded Stage III (or equivalent - e.g., Mountain Mapper) precipitation analyses; 2) 24-h precipitation gage observations for both the 1200-1200 UTC and 0000-0000 UTC forecast cycles (i.e., RFC HYD bulletin); and, 3) gridded HAS-modified QPF (see *Section d).* These data must be sent to the NVU as soon as they are available to ensure timely verification data are provided to forecasters.

Process Enhancements and Standardization

As is the case for the HPC, it is extremely important to provide the HAS function the essential tools to support the QPF process. For the next two years it is envisioned that the HASQPF or Mountain Mapper software will be the primary tools used by the HAS to modify the HPC QPF. However, in the near future (i.e., AWIPS Build 5.x time frame) the HAS function will require more robust editing tools and software enhancements to facilitate QPF production and coordination as specified in the QPI Plan (Office of Meteorology 1999).

c. Training for HPC and HAS

Training is essential for implementing the aforementioned recommendations and improving the QPF process. COMET's Hydrometeorology Course is currently the most focused and relevant QPF/NWSRFS training provided to operational RFC and WFO hydrologists, HAS forecasters, and WFO hydrologic focal points. In light of the recommendation to increase the QPF responsibility of the HPC and the HAS function forecasters, it is important both groups of forecasters attend this course within two years after CBA. Three sessions of the COMET Hydrometeorological Course are scheduled for fiscal year 2000. Priority should be given to RFC staff members and HPC QPF forecasters. However, during the implementation phase of this plan, HPC QPF forecasters will need training on the basic operations of NWSRFS and the impact of QPF. A more focused COMET residence QPF training course, similar to the scheduled SOO QPF Symposia, is necessary for HAS function and HPC forecasters and should be delivered no later than 2001. Course topics should include critical elements of the COMET QPF PDS (Professional Development Series). Periodically, it would also be beneficial for HPC personnel to provide on-site QPF training at RFCs and for HAS personnel to train HPC forecasters on evolution of NWSRFS.

d. Verification of QPF

CONUS implementation of the nationally-approved QPF verification program requires:

CBA + 3 months - **Establish a Product Inventory List (PIL) for each 6-hourly HAS QPF product** (through day 3) and submit to the Data Review Group (DRG) to obtain (12) WMO headers. Coordinate with the AWIPS Program Office for transmittal of these grids (files) over the SBN or WAN. **Action**: OH, Regions, RFCs, OSO, OM

CBA + 4 months - **Ensure all RFCs routinely send: 1) hourly, gridded Stage III (or equivalent -** e.g., Mountain Mapper) precipitation analyses; 2) **24-h precipitation gage observations** for both the 1200-1200 UTC and 0000-0000 UTC forecast cycles (i.e., RFC HYD bulletin); and, 3) **gridded HAS-modified QPF** products via AWIPS WAN/SBN to the National precipitation Verification Unit (NVU) at NCEP (NOTE: during some or all months of the year, certain sections of the U.S. lack observed validation data). **Action**: Regions, RFCs, NVU, OH, OSO

CBA + 6 months - In conjunction with HPC issuances, **begin operational testing of the verification program for selected RFC domains** (ABRFC, OHRFC, and MARFC). **Action:** NVU

CBA + 9 months - **Expand verification effort to include all CONUS RFCs** and the 0000 UTC forecast cycle products. **Action**: NVU

CBA + 12 months - **Make operational the National Precipitation Verification Unit. Action:** NVU, OM, Regions

Through FY 2002 - **Develop, evaluate, and implement precipitation verification strategies** for the utilization of PQPF. Continue research and development of improved verification methodologies in coordination with the research community. Coordinate efforts to improve QPE for input to NWP modeling and verification of precipitation forecasts. Action: OH, OM, NVU, HPC, EMC, CPC, RFCs, Regions *e. Policy*

The national QPF vision and plan is specified in the strategic planning document entitled "The Modernized End-to-End Forecast Process for Quantitative Precipitation Information: Hydrometeorological Requirements, Scientific Issues, and Service Concepts" (Office of Meteorology 1999). This document must be modified to account for the assessment team recommendations. In particular, Chapter 6 (Weather Forecast Office Products and Requirements) will require substantial changes. A revised QPI Plan should be available for review no later than five months after CBA. It is also recommended more uniform operational policies regarding the QPF process be formulated and implemented in the form of Operations Manual Letters and Regional Operations Manual Letters.

VIII. Benefits

a. Short-term Benefits

The simplified QPF process recommended will produce a variety of short-term benefits. The benefits are:

- more effective use of NWS human resources;
- improved QPF input for the NWSRFS;
- streamlined QPF product coordination;
- a more simplified and nationally consistent QPF process;
- timely and comprehensive verification feedback; and,
- focused and tractable requirements for training and applications software.

Refocusing the efforts at the WFOs will allow forecaster resources to be utilized in a more productive manner. One of the immediate and distinct short-term benefits is the reduction in the workload by eliminating the requirement for QPF products issued by WFO. Forecasters will have additional time to devote to new products being proposed for incorporation into the standard WFO forecast product suite. In flooding situations, when MICs indicated up to an hour of additional time was spent on QPF, the WFO forecaster can instead concentrate on the potential for flash flood conditions and the need for watches and warnings.

The revised QPF process will result in improved input to the NWSRFS because it uses the "forecast funnel" approach of moving from the larger scale to a regional scale, resulting in a more logical forecast process. Eliminating the need of the HAS forecaster to mosaic individual WFO QPFs and reconcile discrepancies between offices through coordination will provide more focus on the hydrologic situation. Also, modification of the QPF guidance will be accomplished by the staff at the RFC with a working knowledge of the responses of individual river basins.

Empowering the HAS function forecasters will focus the coordination activities and allow time to assess the impact of the QPF on the NWSRFS. Currently, coordination by the HAS at the RFC is a complex task. By eliminating WFO QPF mosaic, the coordination efforts of the RFC can be focused on HPC's guidance. This will foster interaction between experts dedicated to making QPF forecasts and experts producing the river forecasts.

Another short-term benefit is a move toward national consistency in the QPF program. By using HPC as the primary source of guidance, all CONUS RFCs will be working with the same format of guidance.

This will promote consistency in the tools used to develop QPF products at RFCs. Ensuring consistent data archival will provide data for verification studies and establish a more comprehensive verification data base, which includes all RFCs.

A national QPF verification program with direct feedback to the RFCs, will help standardize the verification process. An important tool in improving QPF forecasts is timely distribution of consistent verification results. Answers to the questionnaires indicated verification data are available, but are not necessarily being shared with all of the forecasters providing the QPF. Also, the RFCs are using a variety of verification techniques. The implementation of a national QPF verification system will aid in this process. Verification data will provide feedback to the HAS function forecaster so they can work to improve QPF input.

The proposed modifications will simplify QPF training requirements. Training can be focused on specific applications of QPF. WFO forecasters will focus training on applying QPF to flash flood forecasting. QPF training to support river forecasting will be tailored for personnel at HPC and the RFCs. Also, with increased coordination between HPC and RFCs, the hydrologists at RFCs will sensitize the HPC forecasters to the responses of the river models. Although the majority of personnel currently performing the HAS function are meteorologist qualified, the proposed change in QPF process will require HAS function personnel to acquire an enhanced understanding of the performance of the QPF guidance products.

An added benefit of redirecting HPC resources is the expansion of QPF product availability to year round and twice per day. Further, HPC will produce QPF guidance in 6 hour increments out to 72 hours for the CONUS. Increasing the temporal coverage of the products will benefit a variety of partners and customers. Adjustments by the HAS function to the products issued by HPC will facilitate the inclusion of this guidance into the NWSRFS. The proposed process enhancements and standardization will streamline the QPF production process and provide more time to concentrate on improved services.

b. Long-term Benefits

The modifications to the current QPF process will also bring long-term benefits by encouraging a more streamlined evolution of the process with time. The proposed modified QPF process will facilitate infusion of science and technology. As new techniques of determining QPF for river models are developed, fewer people will need to be trained on these new techniques since this new technology will be directed toward the HPC and RFCs. A streamlined process for software maintenance and enhancement will be possible. By concentrating on HPC and the RFCs, a reduced number of personnel will be involved. Therefore, fewer resources will need to be allocated to the development and implementation of new, probabilistic forecasting procedures associated with the AHPS.

IX. Summary

The assessment team carefully examined the ongoing process to produce QPF for input to the NWSRFS. This review indicated the current QPF process utilizes WFO resources in the Eastern, Central, and Southern Regions in an inefficient and somewhat ineffective manner. Therefore, recommendations have been made to correct the deficiencies. While the analysis revealed similar inefficiencies for the Western Region, the comparative verification study was inconclusive. Hence, a phased, one-year transition to a more focused and streamlined QPF process should be pursued in conjunction with an additional evaluation for the Western Region.

The revised and simplified QPF process will strengthen the partnership among personnel at HPC and the RFCs. The restructured process will require the forecasters at HPC to provide HAS function personnel with properly formatted QPF guidance twice per day for 6-h periods through 72 hours. The HAS function will be responsible for updating at least the first 6 hours of each forecast cycle and for adjustments to HPC products to accommodate the unique needs of each RFC. HPC forecasters will coordinate with HAS function personnel during both routine and flood events and HPC will provide updated QPF guidance when necessary.

Although the assessment recommends removal of the WFO component from the QPF process, there may be WFOs who provide the most skillful product for their local area (the team did not evaluate the skill of *individual* WFO QPFs).

The revised QPF process must include the implementation of a national verification system, the prototype of which has been devised and tested during the past four months in conjunction with this assessment.

X. Acknowledgments

Brett McDonald, the incumbent in the Office of Meteorology funded COMET Post Doctoral position at HPC, was responsible for implementation of the prototype for the national verification system.

The team wishes to thank the management and personnel at the OHRFC, ABRFC, and CNRFC for outstanding data acquisition support for the comparative verification study.

Letitia Koether and Marc Saccucci of TDL prepared the verification charts.

XI. Reference

Office of Meteorology, 1999: The Modernized End-to-End Forecast Process for Quantitative Precipitation Information: Hydrologic Requirements, Scientific Issues, and Service Concepts. National Weather Service, NOAA, U.S. Department of Commerce, 187 pp.

XII. Figures

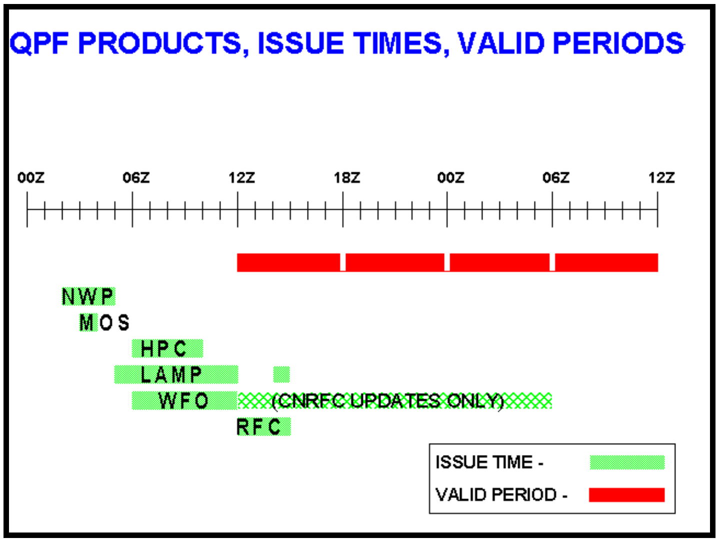


Figure 1. Issue times (green shading) for various QPF products as indicated, which are valid during the 1200 to-1200 UTC period (shaded red). NWP includes QPF output from the AVN, Eta, and NGM models produced by NCEP. All products are for 6-h valid periods, except HPC also produces a 24-h product.

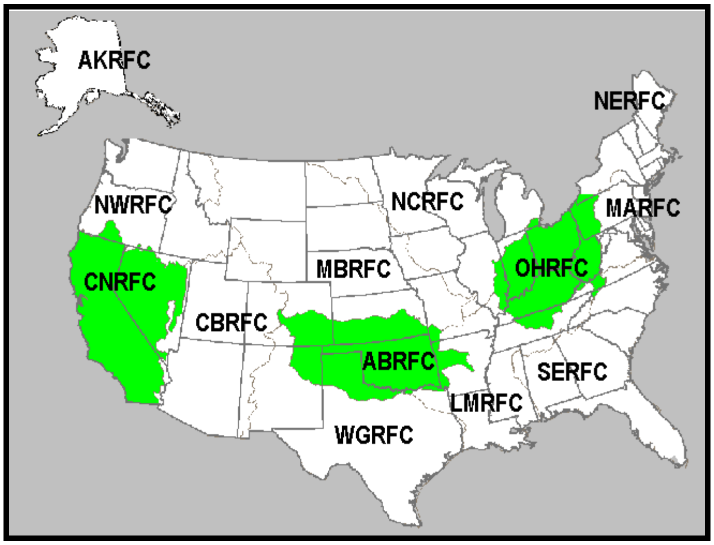


Figure 2. RFC areas (green shaded) involved in the verification. CNRFC, ABRFC, and OHRFC stand for California-Nevada RFC, Arkansas-Red Basin RFC, and Ohio RFC, respectively.

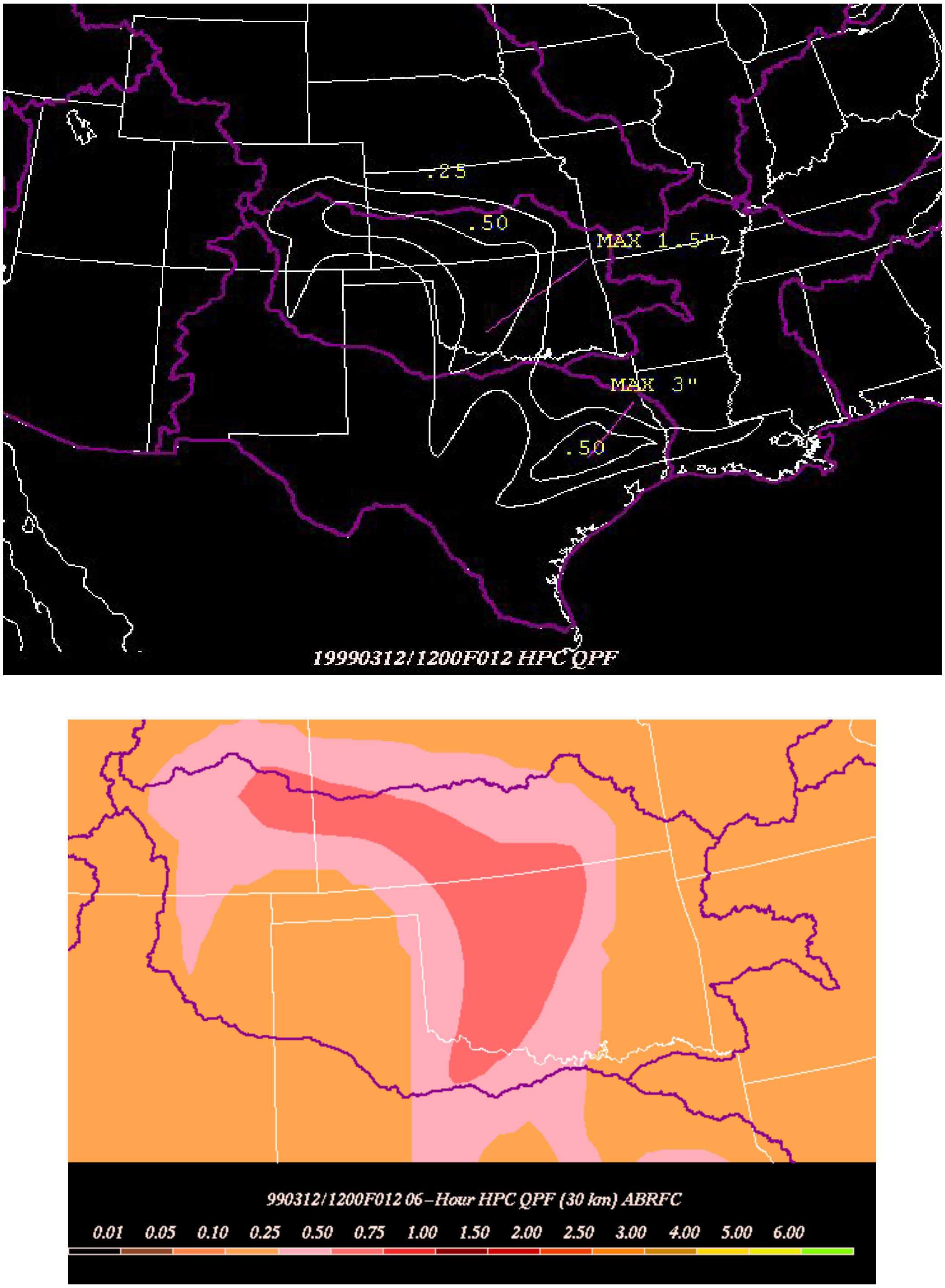
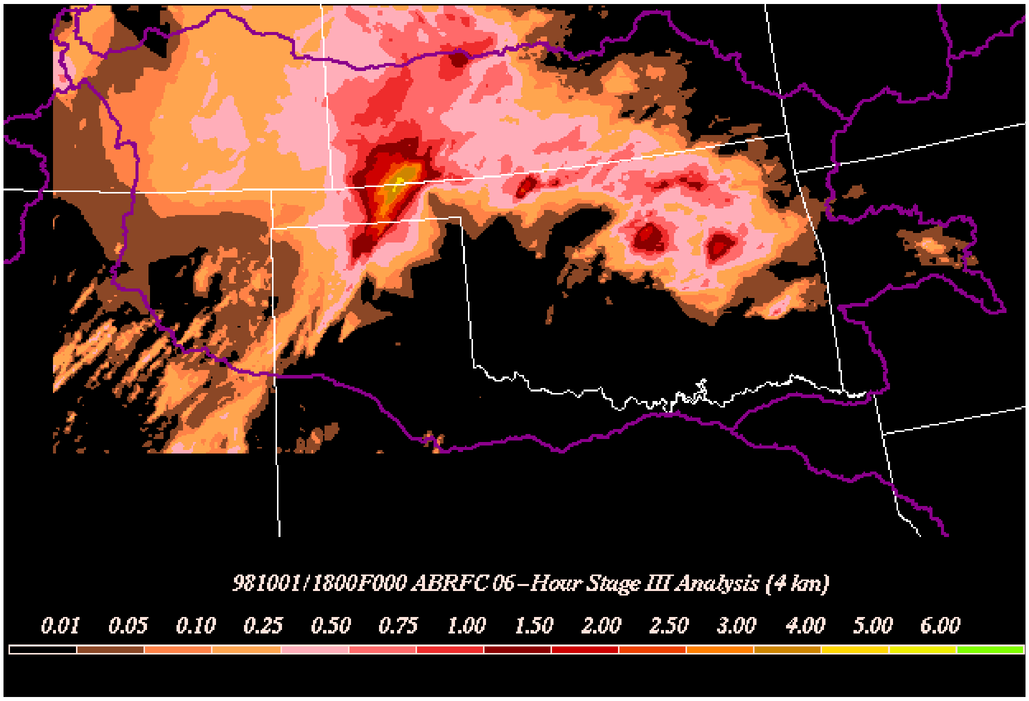


Figure 3. HPC national 6-h QPF graphic (cropped) including RFC boundaries (top), and the contoured representation of the corresponding gridded product (bottom) for the ABRFC area. Precipitation amounts are in inches. In the bottom figure, note that all gridpoint values less than 0.25 inch do not fall below 0.10 inch.

Figure 4. 30-km verification grid shown for the ABRFC area, where gridpoints within the bounded RFC service area are circled.



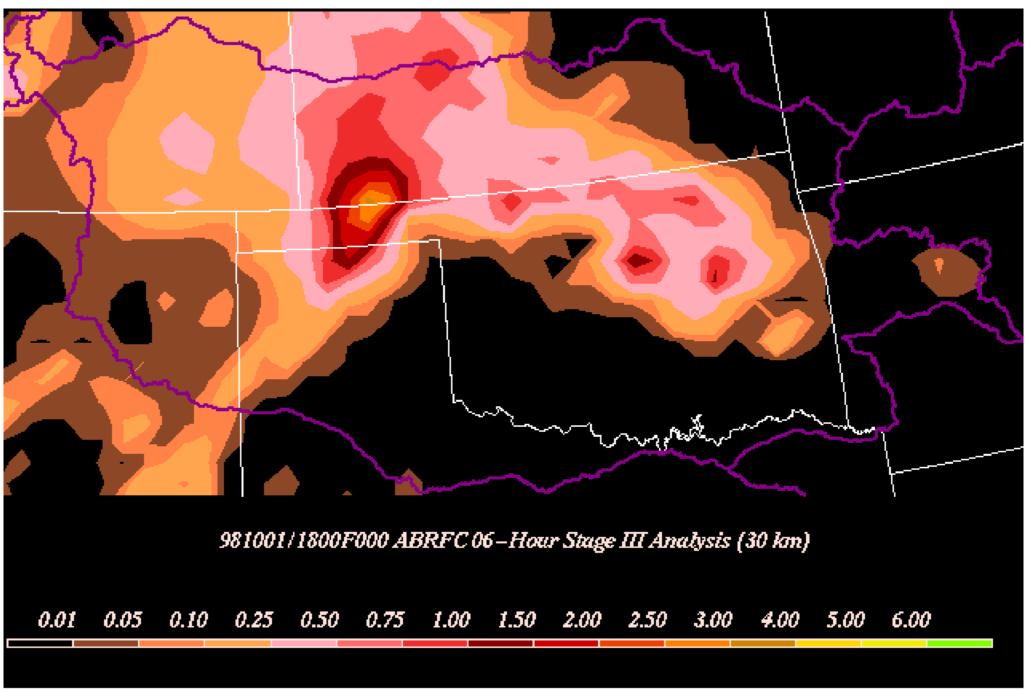
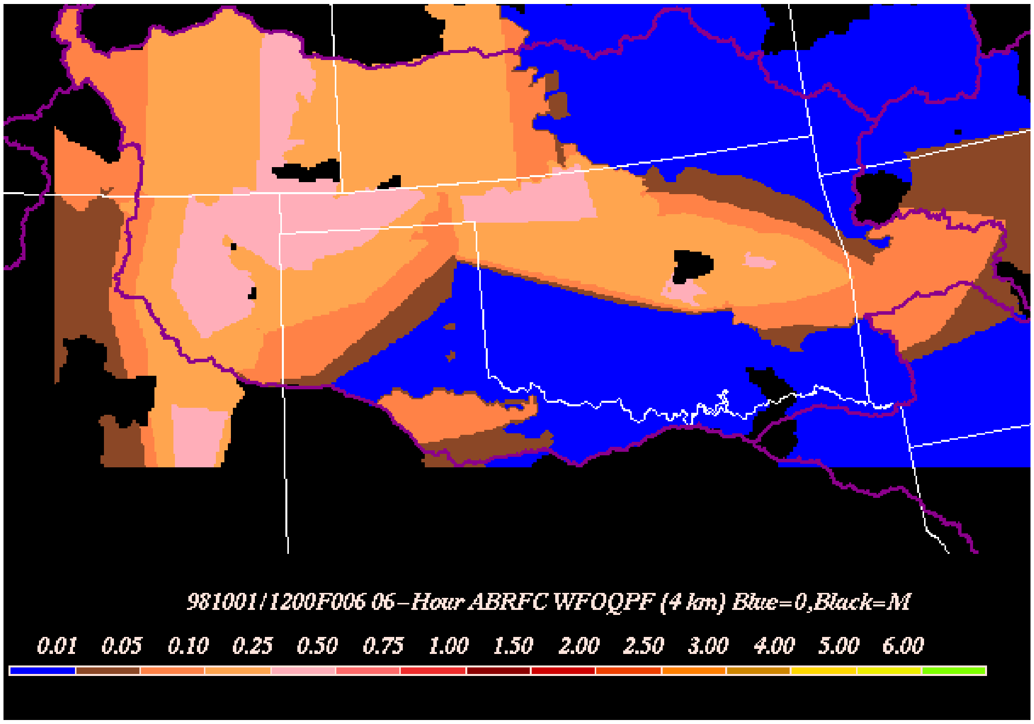


Figure 5. Raw (top) and smoothed (bottom) Stage III precipitation analysis for the 6-h period ending 1 October 1998, 1800 UTC. Precipitation amounts are in inches.



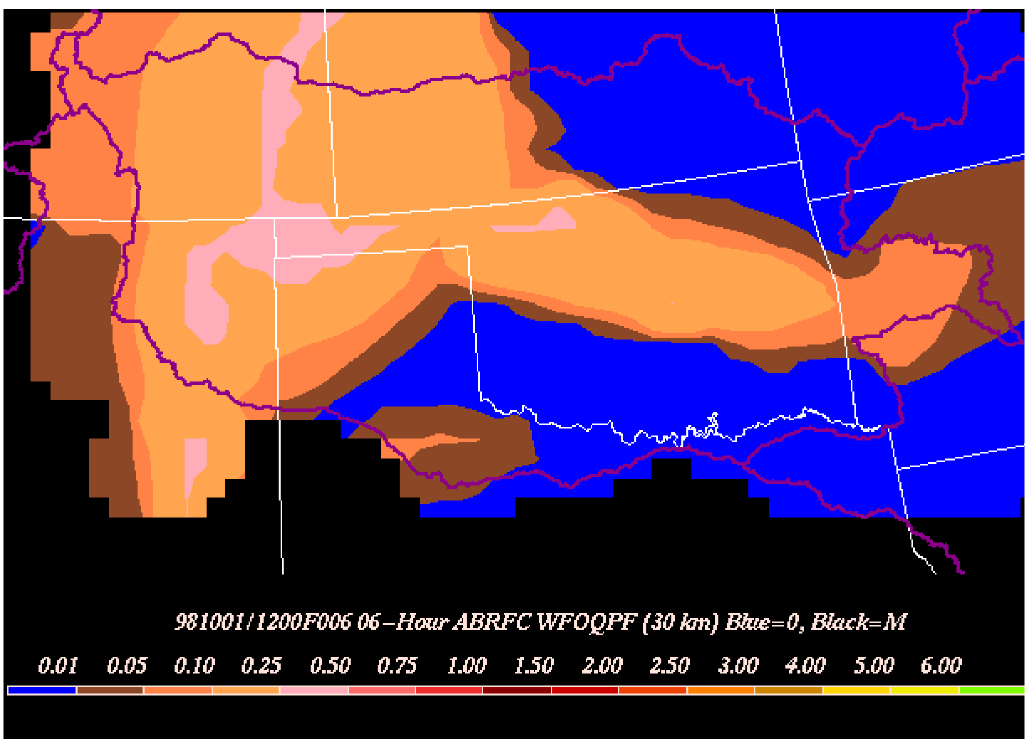


Figure 6. Raw (top) and smoothed (bottom) WFO QPF product for the 6-h period ending 1 October 1998, 1800 UTC. Precipitation amounts are in inches.

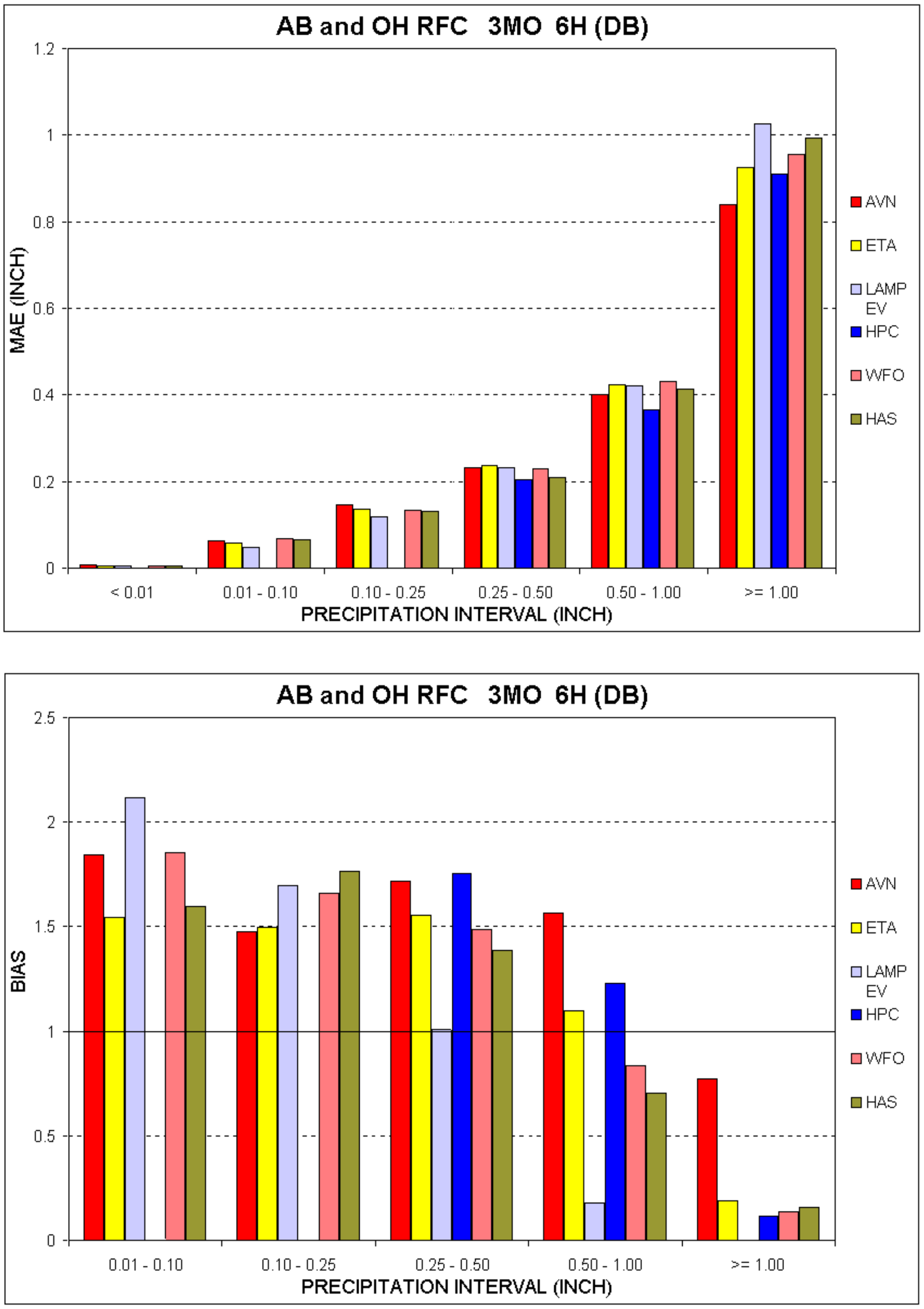


Figure 7. MAE (top) and bias (bottom) for the ABRFC and OHRFC areas combined for 6-h QPF products during 1 January - 31 March, 1999 (3-mo period). The products are identified in the legend along the right margin. The notation "EV" below the LAMP identifier denotes that the forecast precipitation is the expected value product and the notation"DB" in the title stands for the "double-both" accounting method used in the score computations (see Appendix A). Note that bias chart does not include the precipitation interval <0.01 inch.

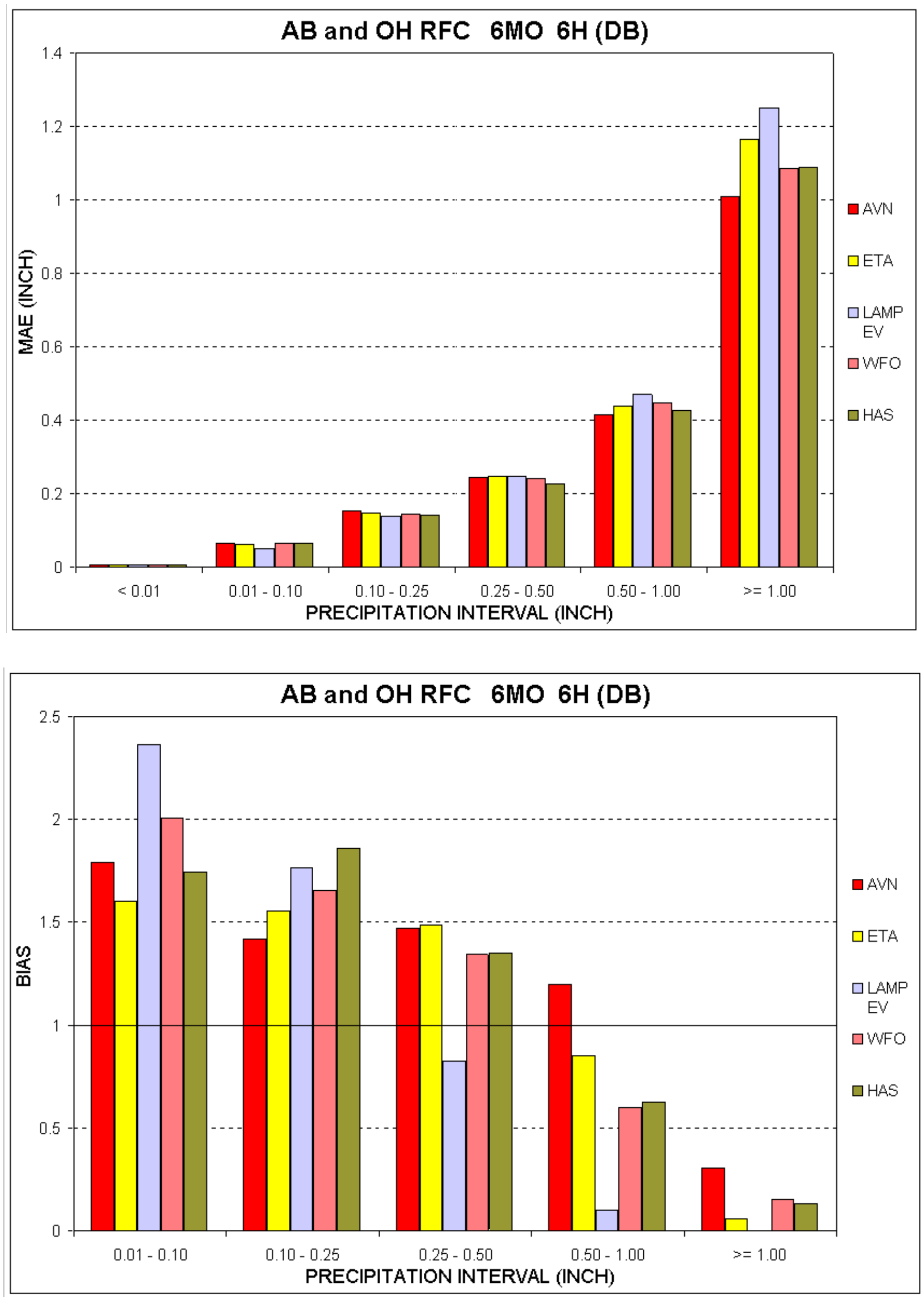
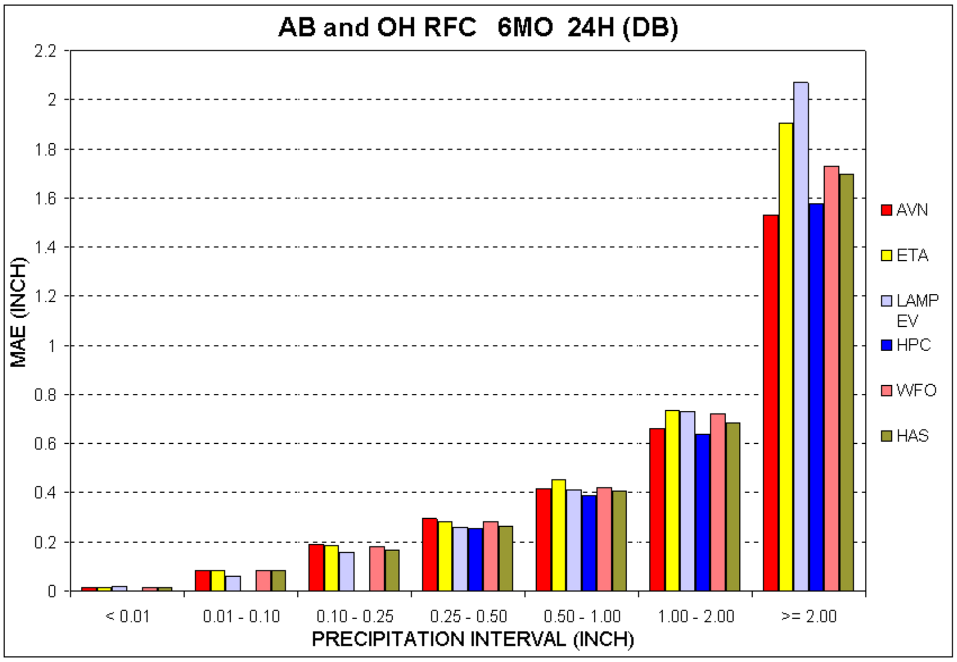


Figure 8. As in Fig. 7 for 1 October 1998 - 31 March 1999 (6-mo period) and with HPC excluded.



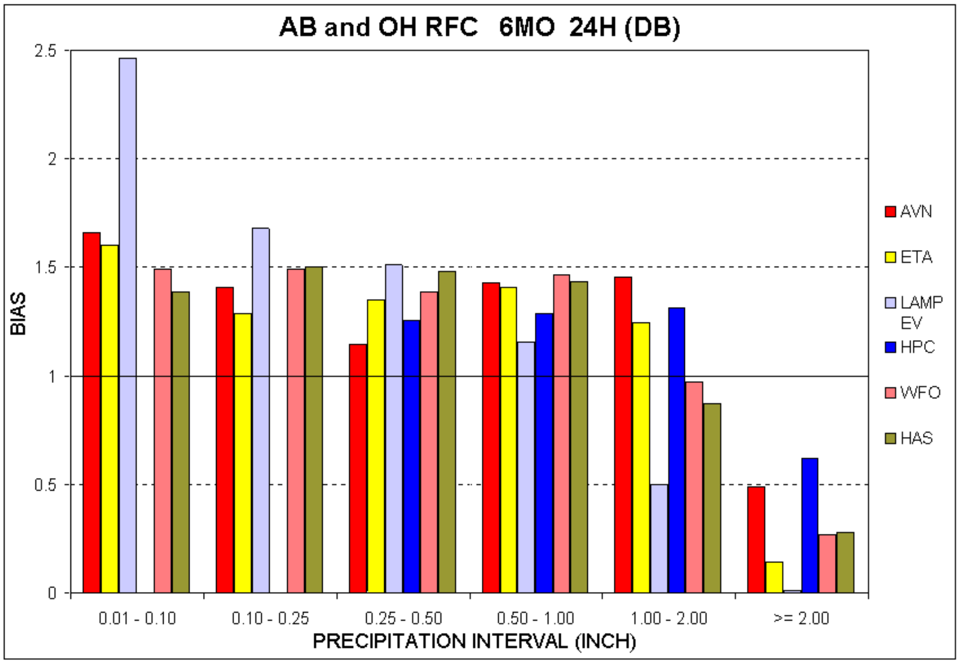
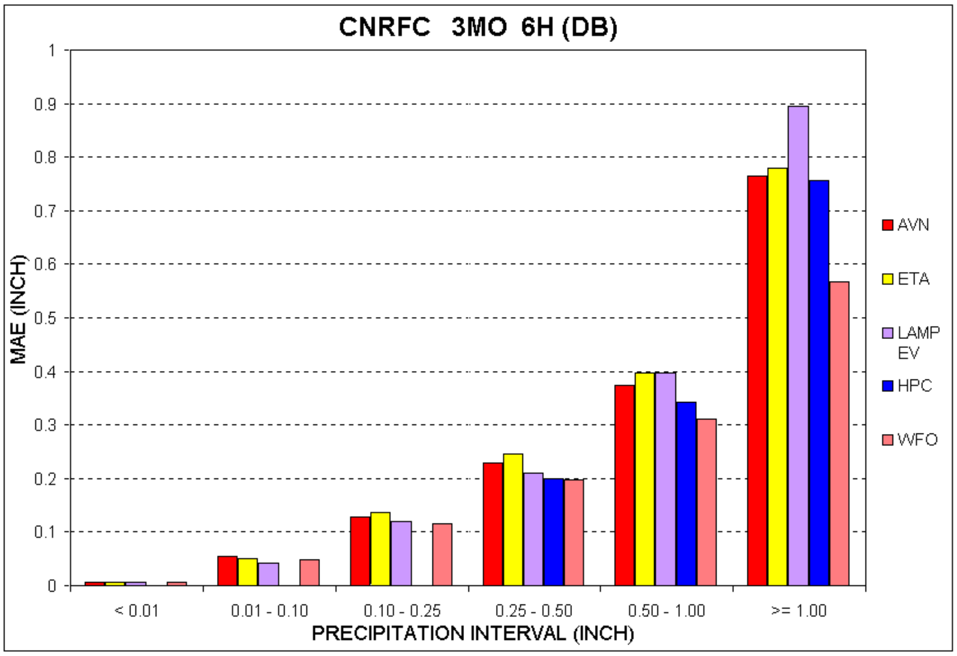


Figure 9. As in Fig. 7 for 24-h QPF products and 1 October 1998 - 31 March 1999 (6-mo period).



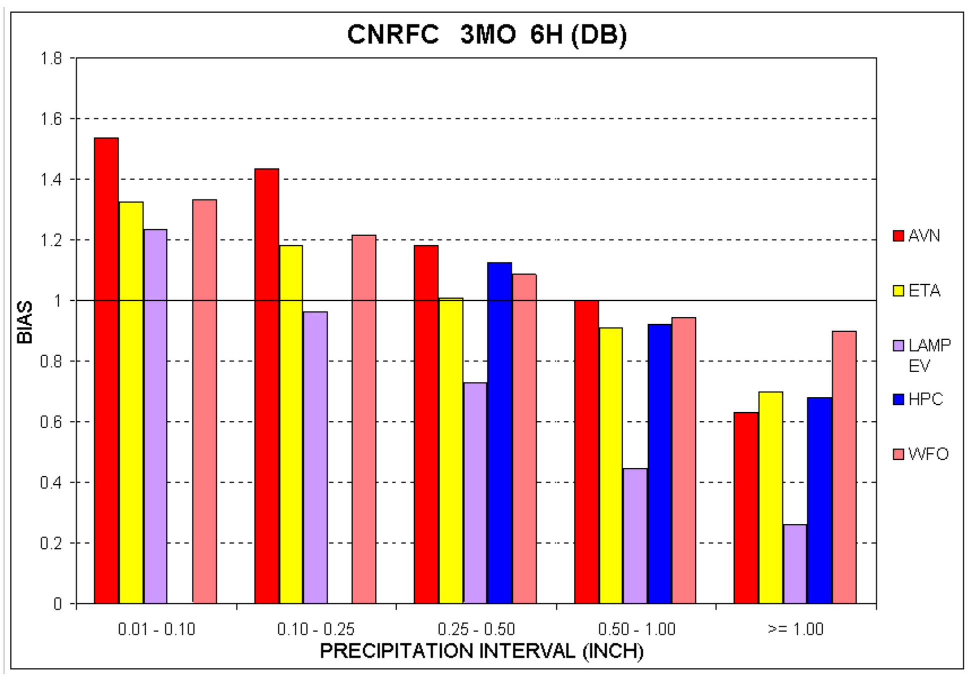
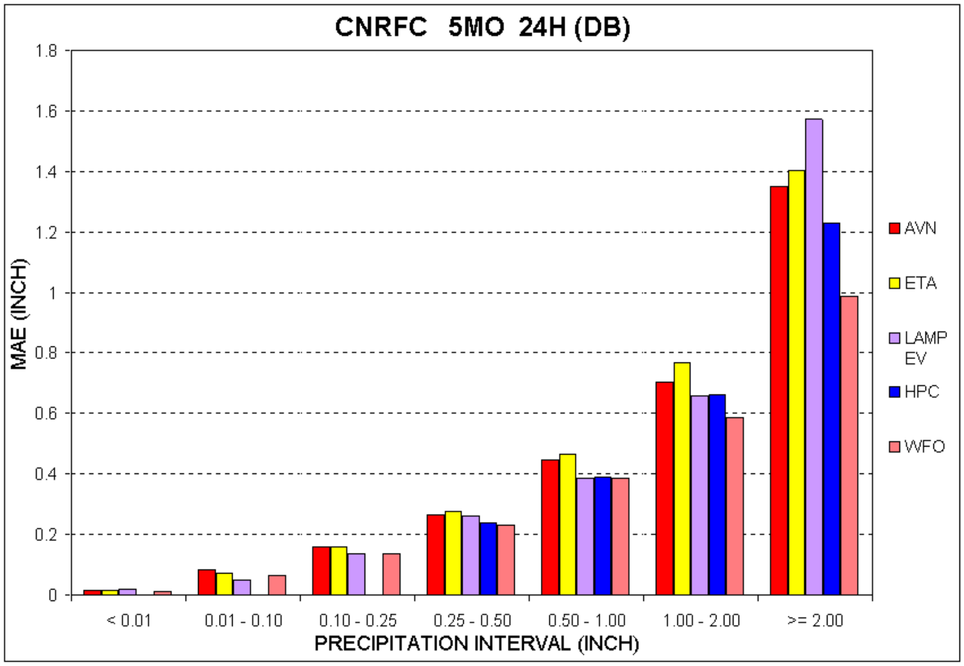


Figure 10. As in Fig. 7 for CNRFC , 1 January 1999 - 31 March 1999 (3-mo period), and with HAS excluded.



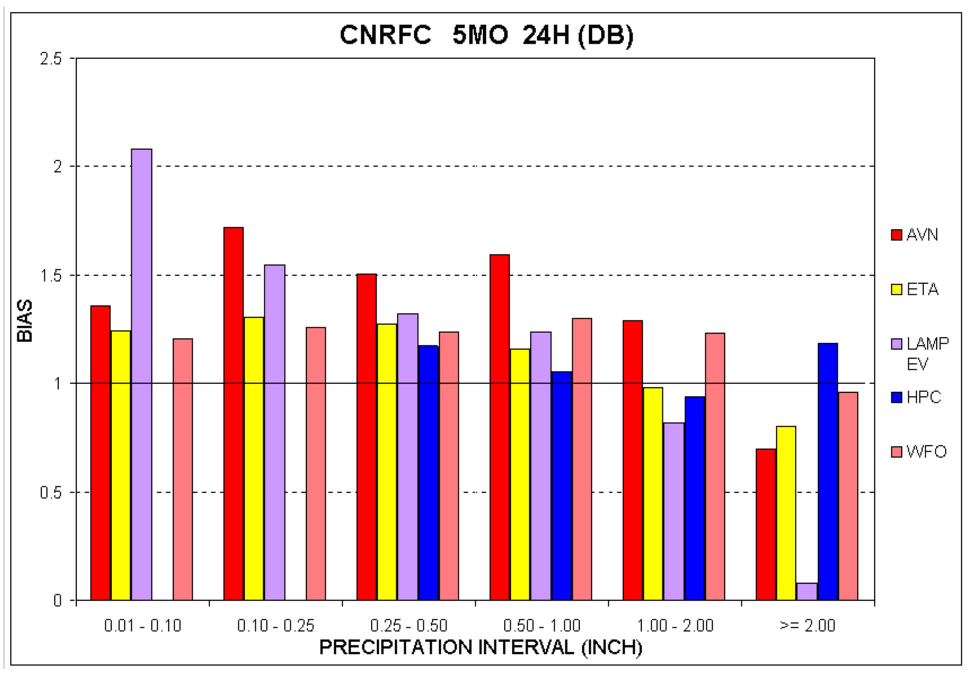


Figure 11. As in Fig.7 for CNRFC, the 24-h QPF products, 1 November 1998 - 31 March 1999 (5-mo period), and with HAS excluded.

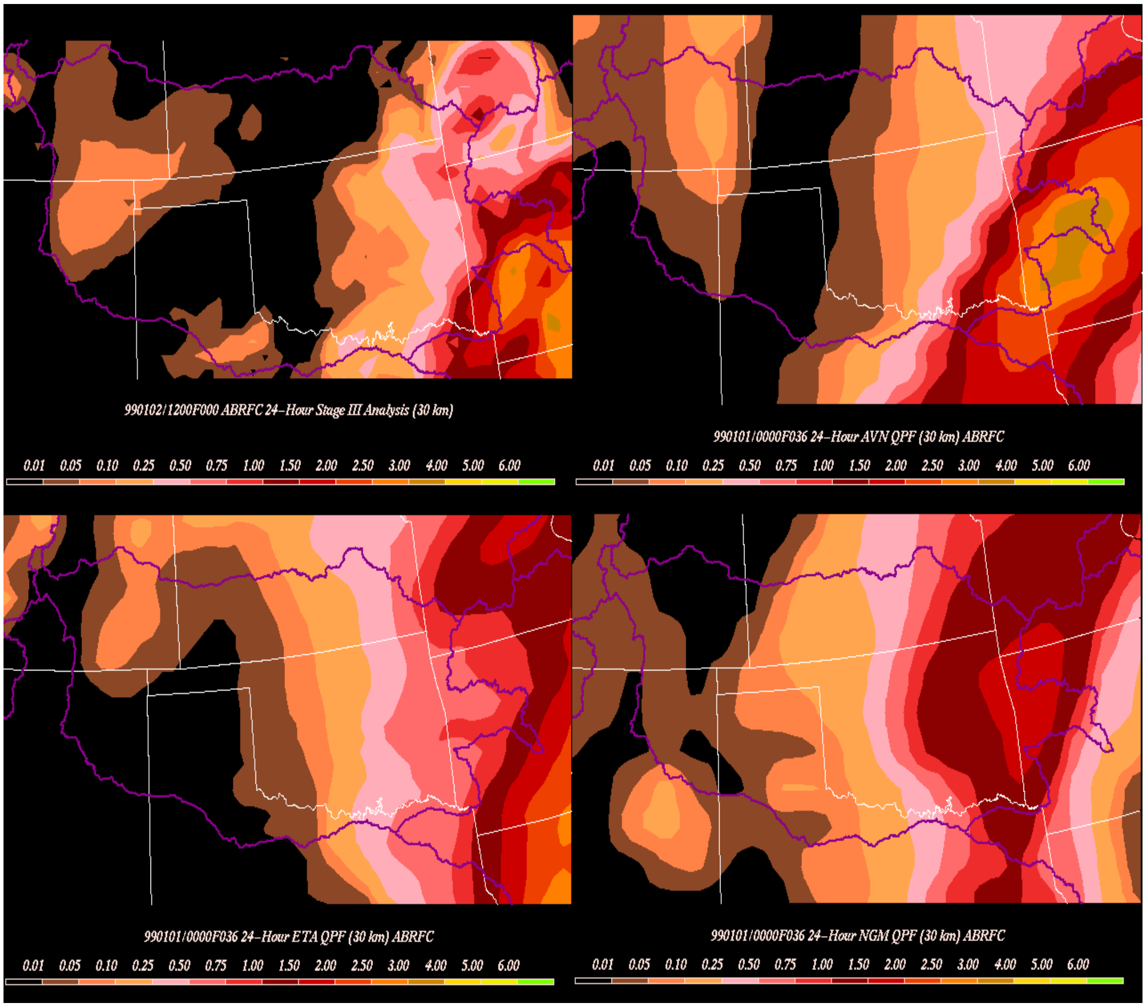


Figure 12. Starting in upper left corner and moving clockwise, Stage III observed precipitation product, 24-h AVN QPF, 24-h NGM QPF, and 24-h Eta QPF for the period 1200-1200 UTC January 1-2, 1999.

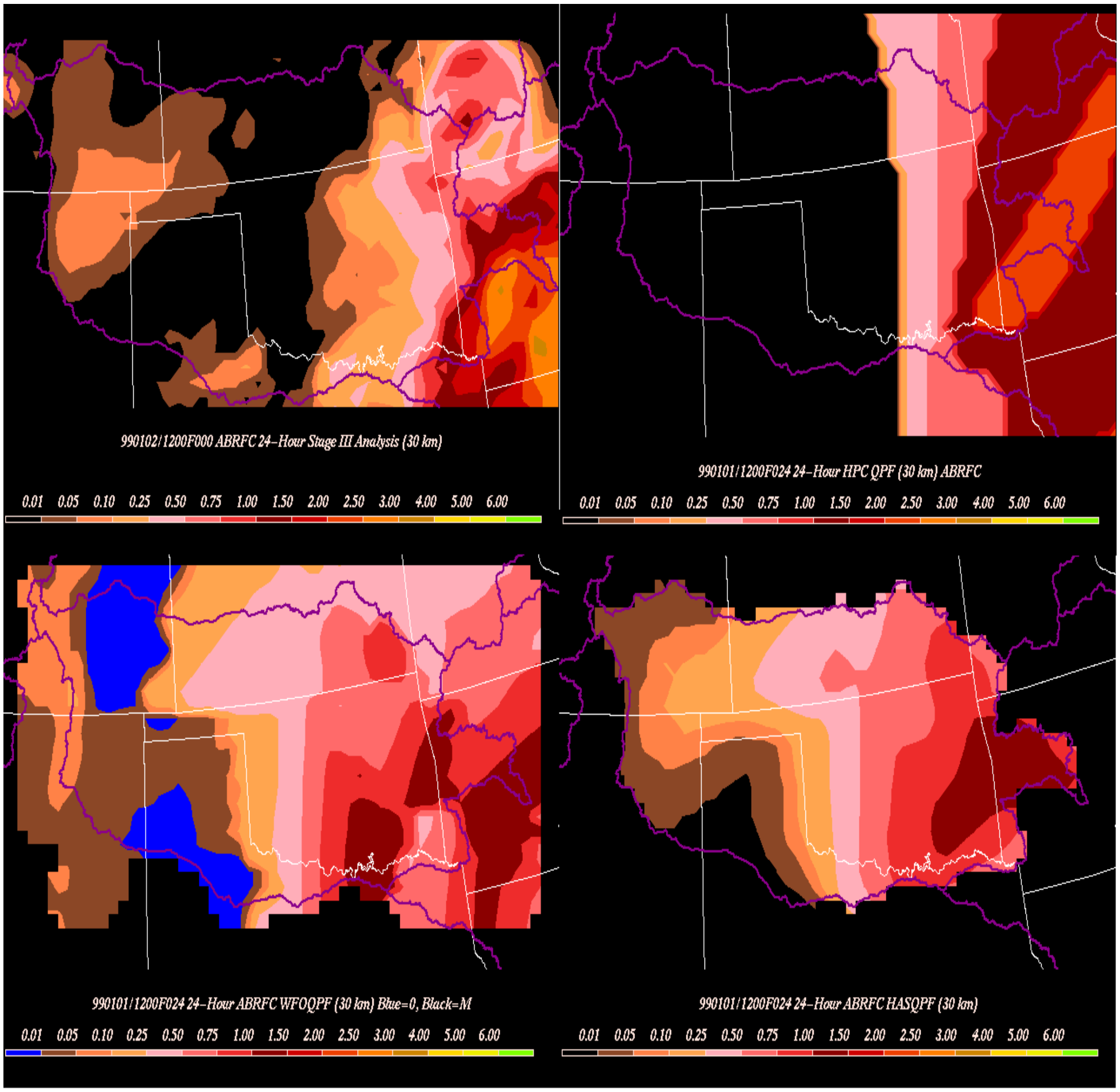


Figure 13. Starting in the upper left corner and going clockwise, observed Stage III data, manually produced HPC, HAS modified WFO mosaic, and WFO mosaic (based on input from 12 WFOs) QPF, valid from 1200 UTC 1 January to 1200 UTC 2 January 1999. The blue shading in the WFO mosaic simply denotes where the forecaster issued a QPF of zero.

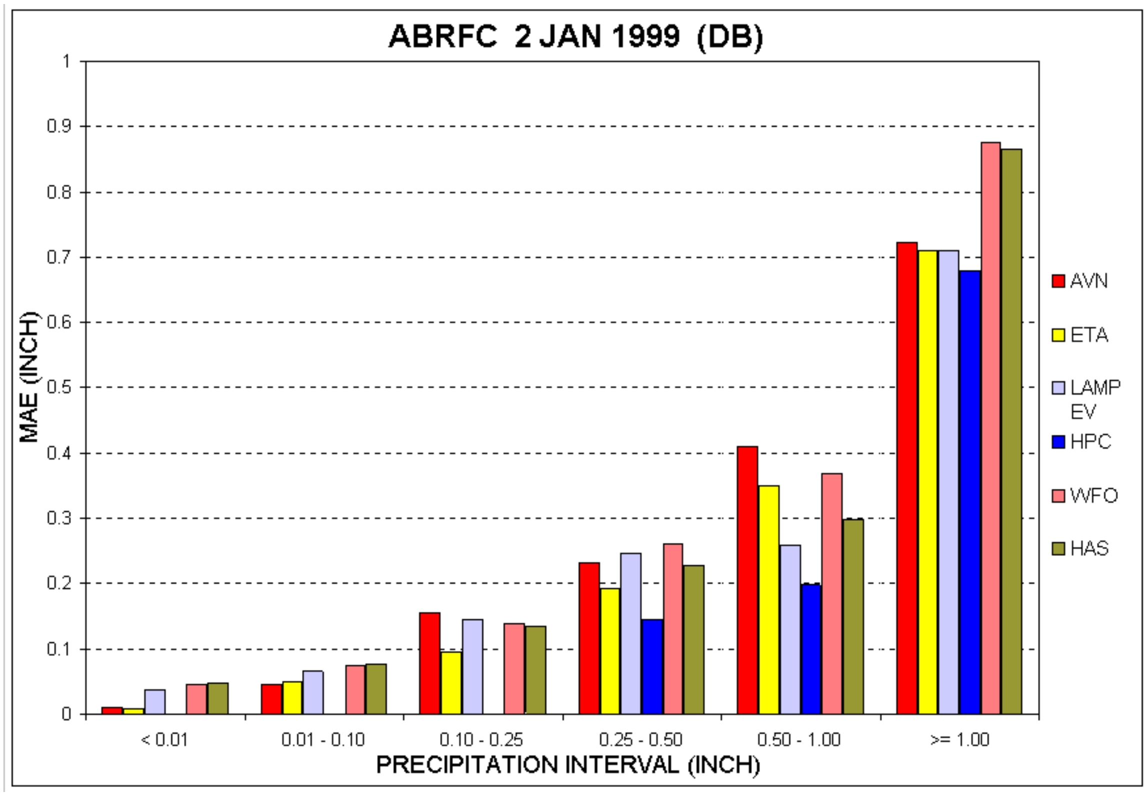


Figure 14. Graph of mean absolute error (MAE) versus specified precipitation interval for January 2, 1999 over the ABRFC domain using the four 6-h forecasts combined. Both the observed and forecast data are used in the sample. The legend on the right denotes the color coding used.

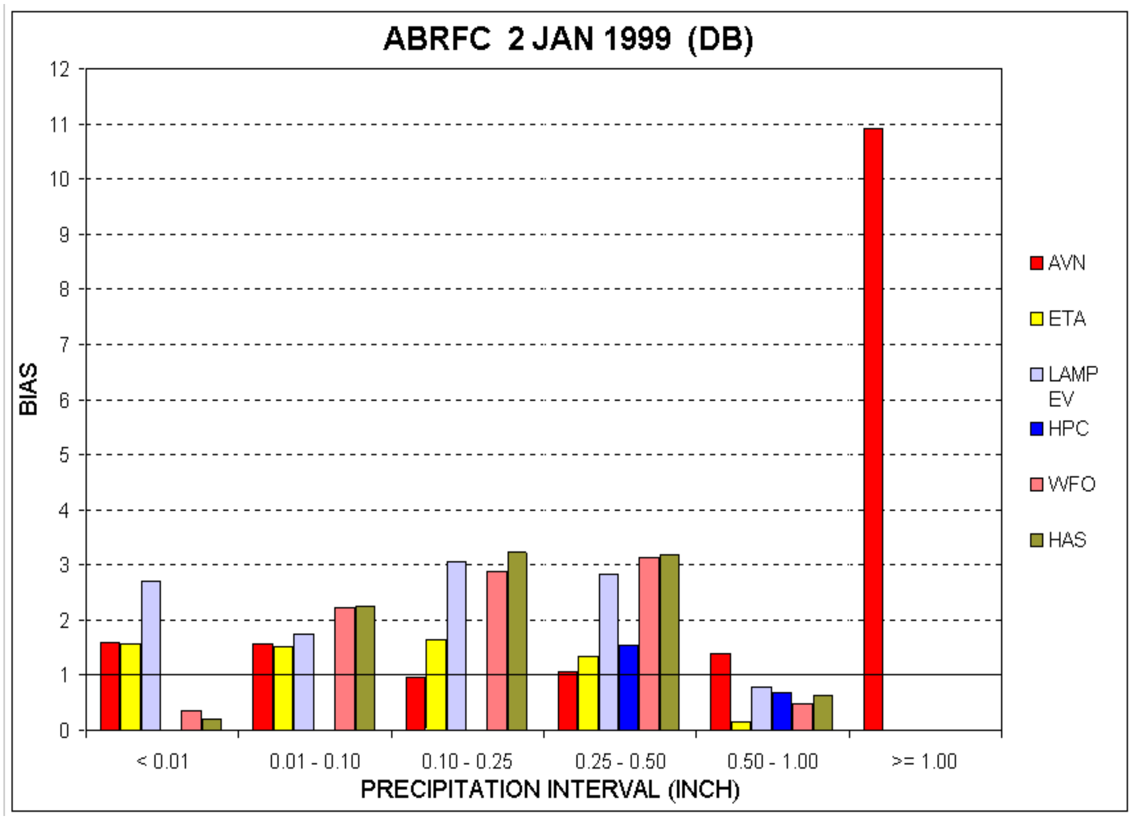


Figure 15. Volumetric bias for each product analyzed for the 2 January, 1999 case study.

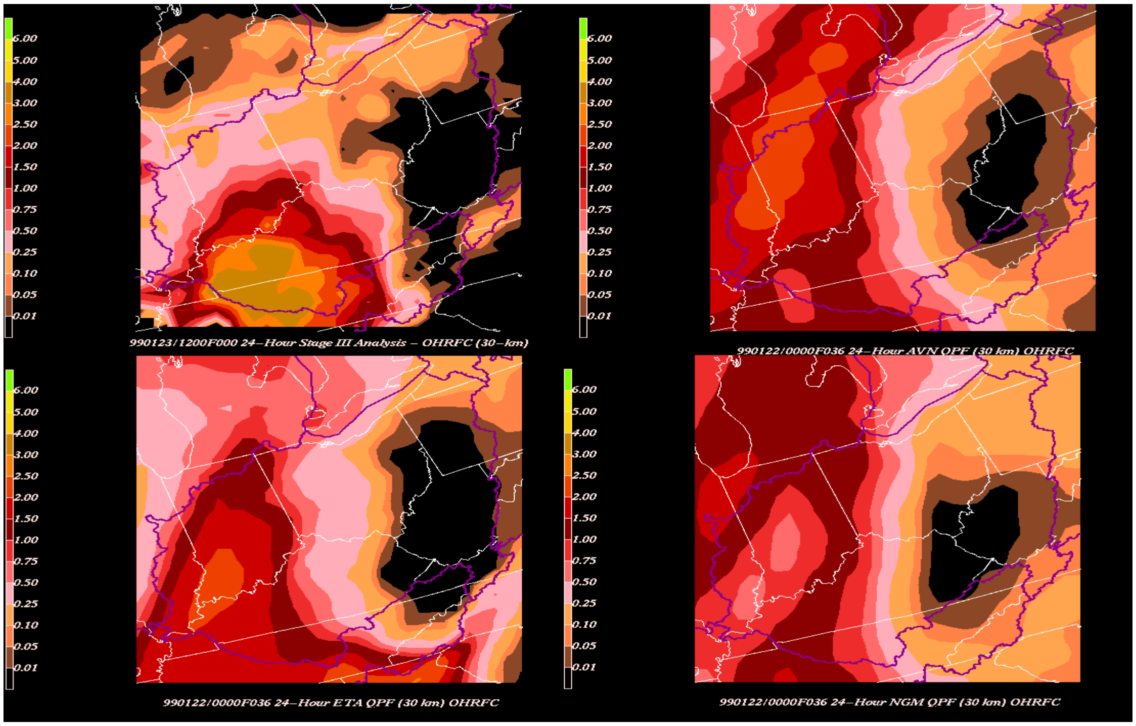


Figure 16. Starting in upper left corner and moving clockwise, Stage III precipitation product, 24-h AVN QPF, 24-h NGM QPF, and 24-h Eta QPF for the period 1200 UTC 22 January to -1200 UTC 23 January 1999.

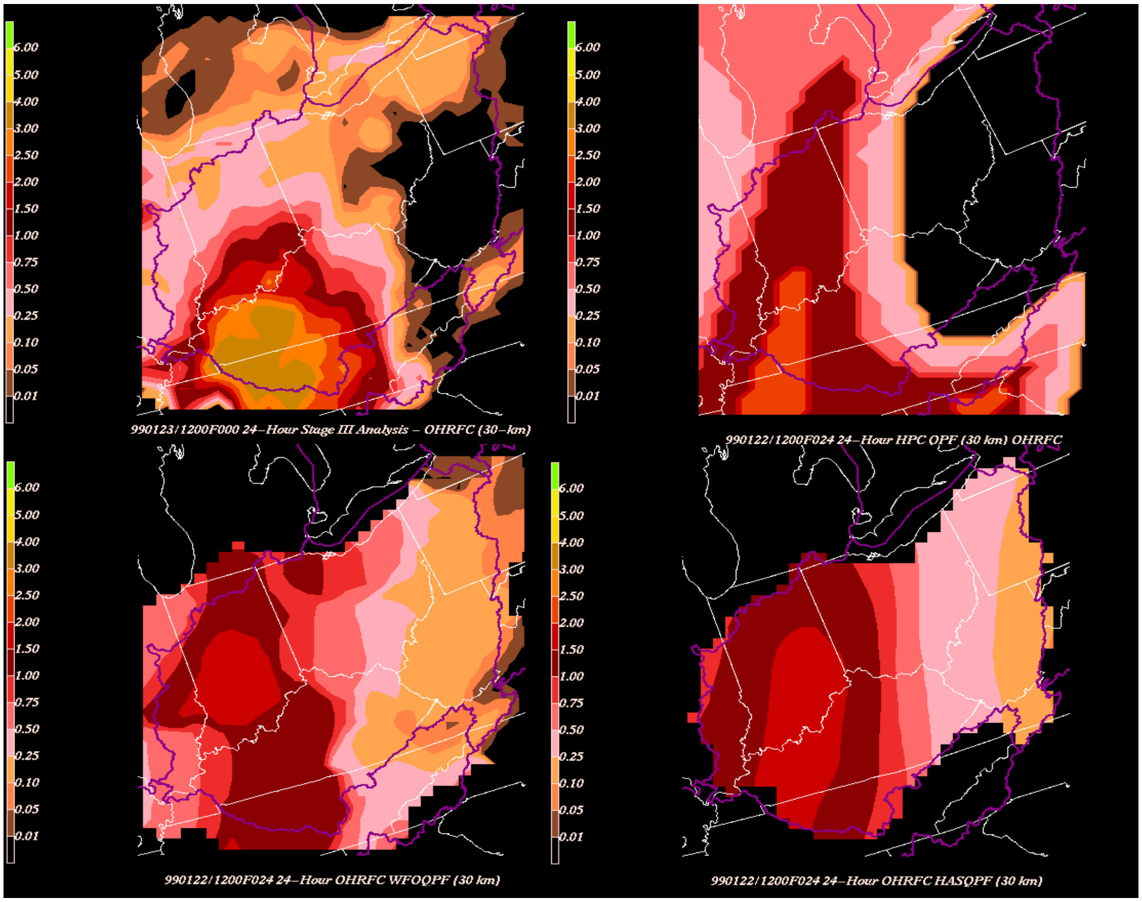


Figure 17. Beginning in upper left and moving clockwise, Stage III precipitation product, HPC manual 24-h QPF, HAS modified 24-h QPF mosaic, and WFO mosaic (based on input from 14 WFOs) QPF, valid from 1200 UTC 22 January to 1200 UTC 23 January 1999.

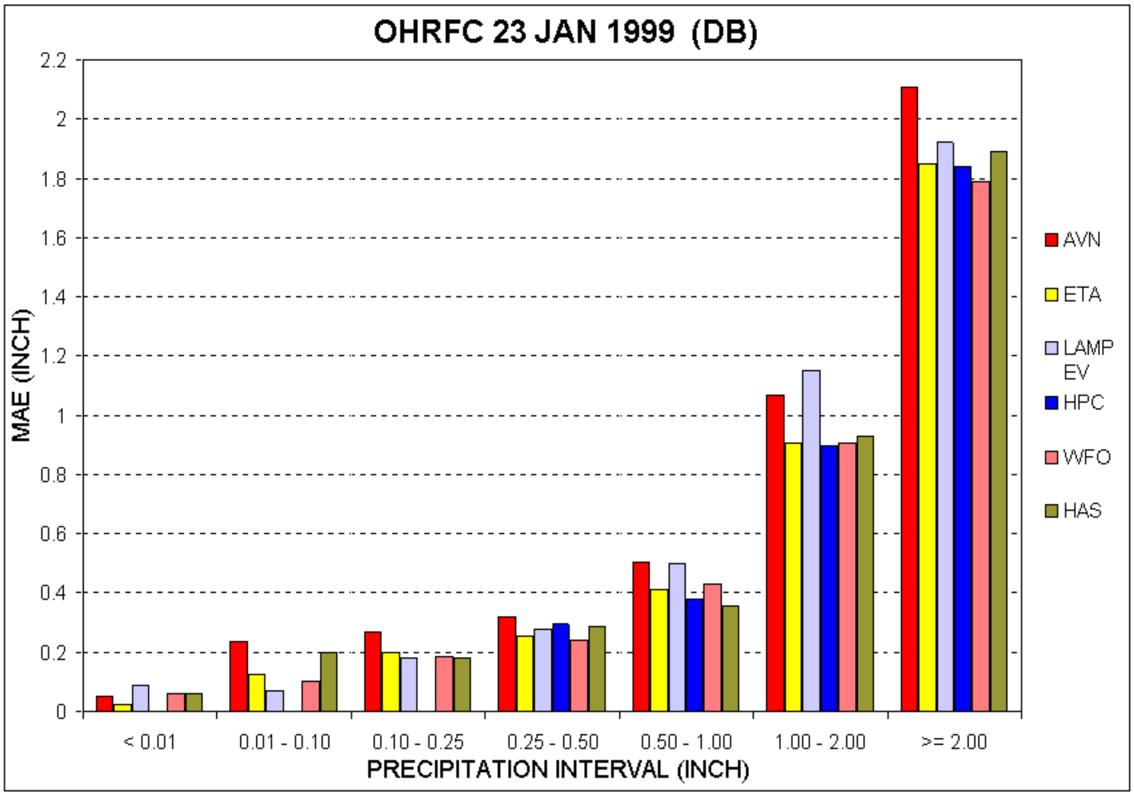


Figure 18. MAE versus discrete precipitation intervals combining the four 6-h QPFs for the various QPF products evaluated for the 23 January case study.

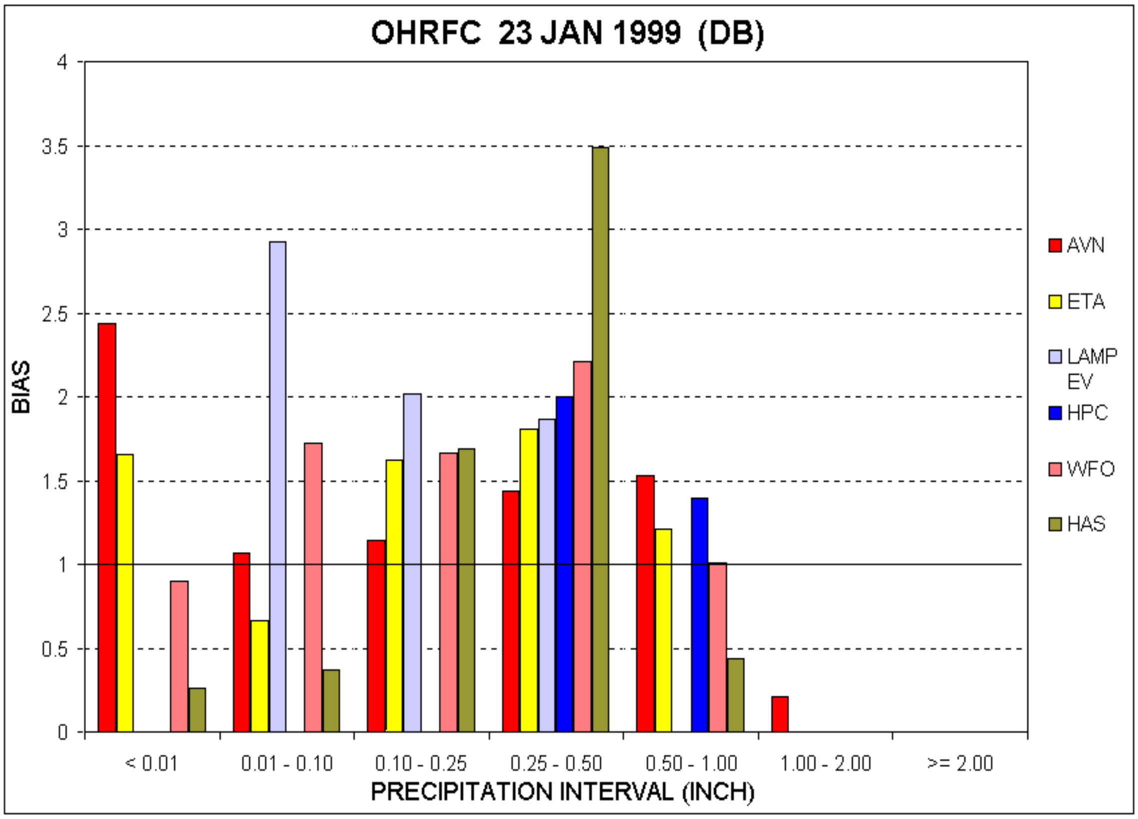


Figure 19. Volumetric bias for each product analyzed for the 23 January 1999 case study. The volumetric bias is zero for all forecasts in the highest interval because forecasts of 2 inches or more were not indicated for any 6-h period for each of the products examined.

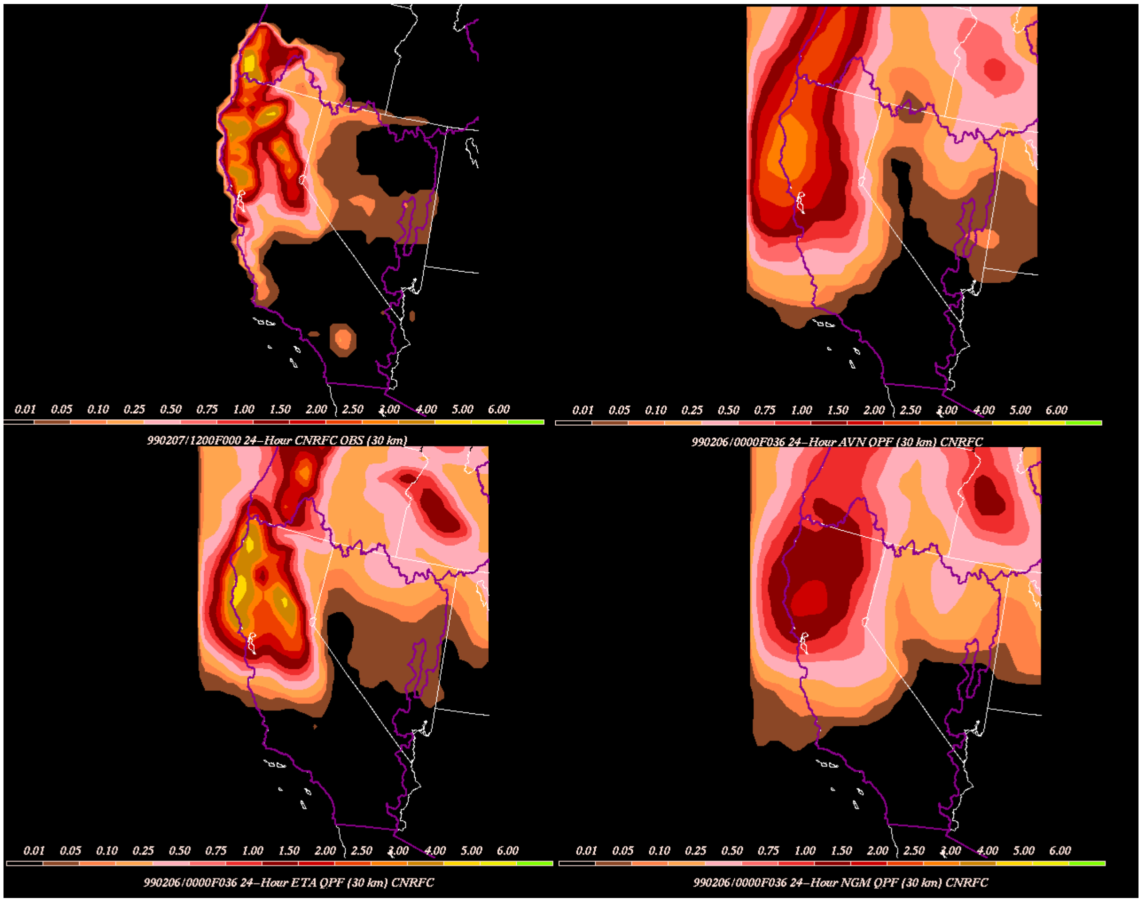


Figure 20. Beginning in upper left corner and moving clockwise, Mountain Mapper rendered 24-h precipitation totals (inches), AVN 24-h QPF, NGM 24-h QPF, and Eta 24-h QPF, all valid for period 1200 UTC 6 February to 1200 UTC 7 February 1999.

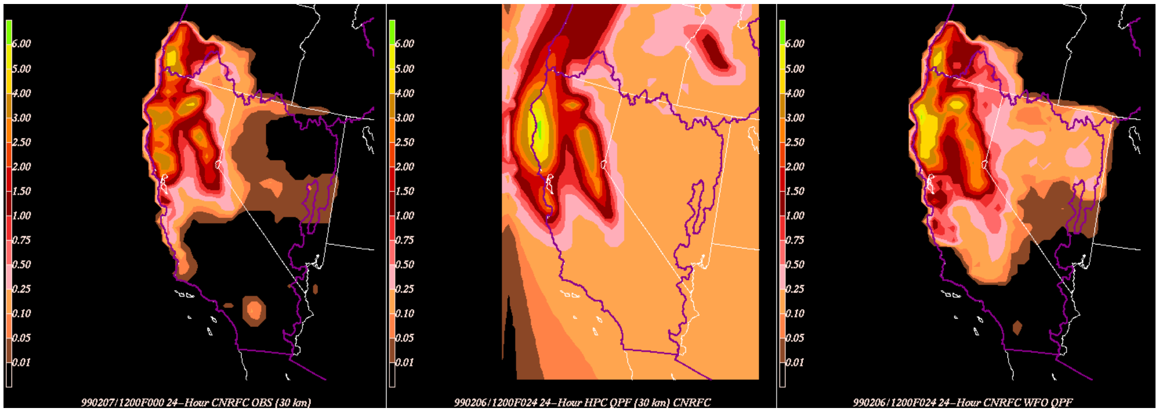


Figure 21. Mountain Mapper rendered 24-h precipitation totals (inches) (left), manually produced 24-h QPFs from the HPC (center) and 10 WFOs (right) for the period 1200 UTC 6 February to 1200 UTC 7 February 1999. The large area between 0 and .25 inches seen in the HPC grid is an artifact of the graph to grid routine. This area is not considered in the verification statistics.

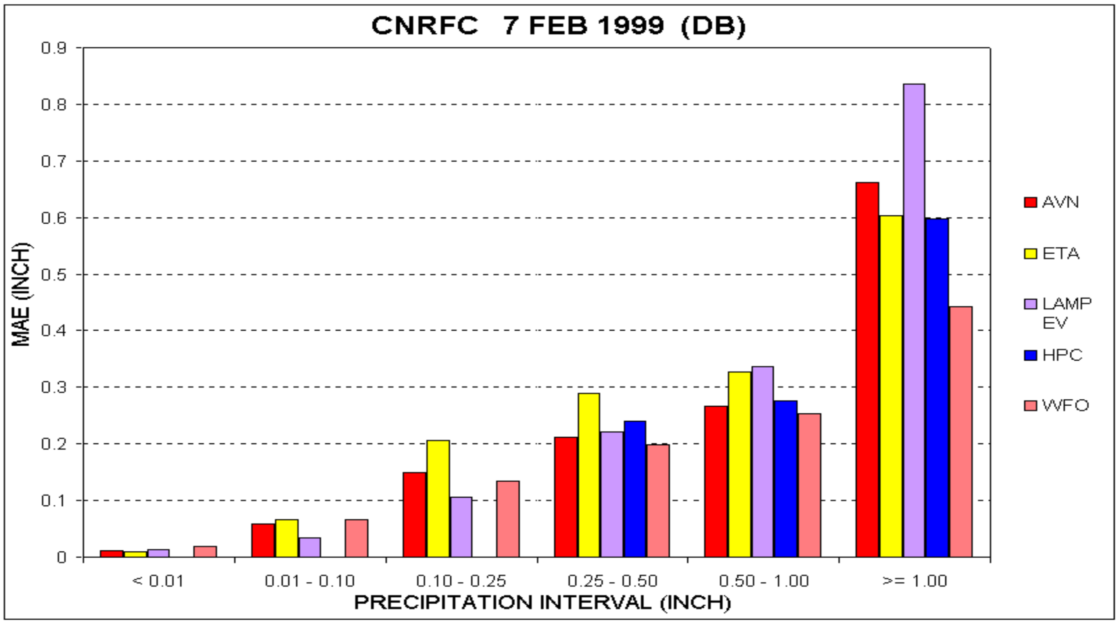


Figure 22. MAE versus discrete precipitation intervals using the combined four 6-h QPF's for the various QPF products evaluated for the 7 February 1999 case study.

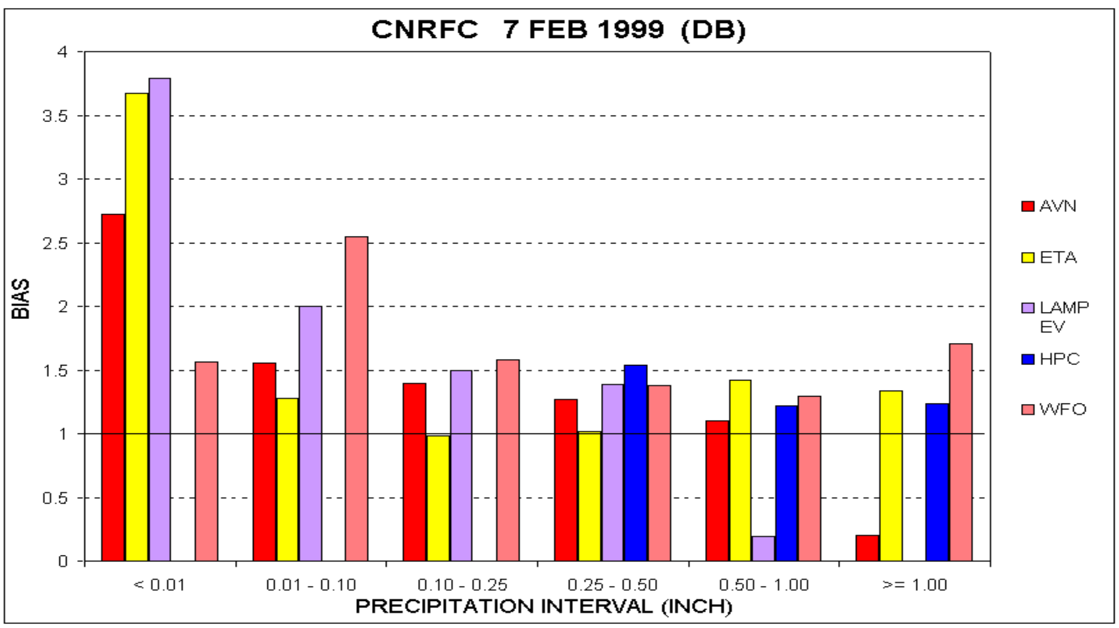


Figure 23. Volumetric bias per discrete precipitation interval for each product analyzed for the 7 February 1999 case study.

XIII. Appendix A: Experiments with the Continuous Scoring Method

A number of important issues and procedural options were considered when the continuous precipitation scoring approach was applied. Here, a series of verification experiments with the continuous method are described to develop the basis for the various choices made for this study. The experiments are based on the 24-h QPF products for the full 6-mo period for the ABRFC and OHRFC areas combined. This ensemble of QPF valid period, period of historical record, and RFC areas was selected for the experiments because the resulting sample was the largest one available in this study.

One of the initial questions considered was: Should the various verification scores be stratified by ranges of precipitation amount, and, if so, what approach to the stratification would be most relevant to the QPF assessment study? A common approach is to stratify forecast accuracy scores against *observed* precipitation, denoted as OBS in this study. The usual practice with the OBS method has been to use cumulative precipitation intervals, i.e., overlapping intervals where each begins with a threshold amount. This approach is illustrated in Fig. A1, where the mean absolute error (MAE) is plotted against observed precipitation amount in the cumulative intervals. A disadvantage to the use of cumulative intervals is the intervals are very broad, especially for the lighter thresholds. Consequently, it is hard to discern how the MAE varies with light, moderate, and heavy precipitation amounts. The alternative use of discrete intervals, illustrated in Fig. A2, provides a solution to this problem. The large error seen in the highest precipitation category in Fig. A2 is no longer averaged with the smaller error in the lighter threshold categories. Note that the MAE in Fig. A1 rises with increasing cumulative precipitation interval in a fairly gradual manner, whereas the MAE variation versus amount illustrated in Fig. A2 exhibits a slow rise over most of the precipitation range and then an abrupt increase at the heaviest interval. A primary advantage of the OBS approach, as applied to the various QPF products, is that the samples within the intervals are identical for all products. The sample matching among the various QPF products for the discrete interval case is illustrated in Fig. A3.

Verification scores based on the OBS approach do not provide information about the performance of the QPF products as a function of the *forecasted* precipitation amount, which is a significant shortcoming. Therefore, a second approach was to stratify the forecast accuracy scores against discrete intervals of *forecasted* precipitation amount. This approach is termed FCST in this study. A plot of the MAE based on the FCST approach is shown in Fig. A4, and the corresponding sample sizes are shown in Fig. A5. A comparison of the MAE for observed precipitation in Fig. A2 with the MAE for forecasted precipitation in Fig. A4 reveals several differences. The general shapes of the two plots are quite different, as the rise in MAE with increasing precipitation amount is more linear in Fig. A4 than it is in Fig. A2. Another difference is that the MAE values for the products relative to one another is similar for some products but not others. In particular, the WFO versus HAS ranking is similar in the two charts with the HAS having equal or lower MAEs than the WFO. However, the ranking of HPC relative to these two products and to the AVN is different in the two figures. The most striking difference in these figures is that the ≥2.0 interval for LAMP has the highest (worst) MAE in the OBS case (Fig. A2) and the lowest (best) MAE in the FCST case (Fig. A4). At least part of the explanation for the apparent discrepancy can be found by examining the corresponding sample size chart (Fig. A5). The latter figure shows that LAMP very rarely forecasted precipitation in this peak interval (only 11 times), whereas the other products had many more forecasts in the interval. Thus, the small sample explains much of the LAMP anomaly in this case. This extreme example underscores a negative aspect of the FCST approach to the scoring stratification; the sample sizes within the precipitation intervals for the different products do not match. Still, the application of both the OBS and FCST approaches is required to achieve a thorough examination of product performance.

A drawback to the use of both the OBS and FCST verification methods is the complexity introduced by the added number of scores to consider for the QPF assessment. A remedy to this problem was to combine the methods during the score computations by scoring each data point twice, denoted for this study as the “double-both (DB)” approach. This approach doubled the overall samples as both the OBS and FCST approaches were combined into a single set of scores. In the score computation, a point is tabulated first for the precipitation interval where the observed amount occurred and second the point is tabulated for the precipitation interval where the forecast amount occurred. Thus, each data point is counted twice, and the samples within the discrete precipitation intervals shown in Fig. A6 are actually a summation of the samples for the OBS and FCST cases shown in Figs. A3 and A5, respectively.

A plot of MAE with the DB approach is shown in Fig. A7. It should be noted the MAEs obtained with the DB method are actually a weighted combination of corresponding MAEs for the OBS and FCST approaches, where the weights are the number of cases in the OBS and FCST intervals. This result can be noted upon careful examination of Figs. A2, A4, and A7. Thus, the DB approach is a proper method for combining the scores from the OBS and FCST approaches into a single set of scores and it streamlines the assessment task based on the continuous scoring system.

Two additional issues arose in regard to the QPF assessment with the continuous scoring system. One involved the determination of which verification measures were sufficient. It was found that among the forecast accuracy measures, the MAE and root-mean-square error (RMSE) provided similar information. The mean error, correlation coefficient, and reduction of variance were not found to be particularly useful, and the bias is not an accuracy measure. Fig. A8 shows the RMSE for the DB approach for comparison with the corresponding MAE in Fig. A7. The two figures indicate the information contained in the two forecast accuracy measures is largely redundant; the RSMEs are slightly larger for all intervals, but the rankings of the products are similar for the two scores, especially for the upper precipitation intervals. Between the two scores, the MAE was chosen as the primary one for the assessment because of its simplicity.

The final issue in regards to the continuous scoring system involves the potential contamination of the HPC scores for observed precipitation ≥0.25 inch. As noted previously, bogus HPC QPFs under 0.25 inch can enter into the OBS (and therefore DB) scoring approach even for observed precipitation in the range of 0.25 inch and beyond. For instance, the distortion in the distribution of the HPC QPF case counts for intervals involving amounts less than 0.25 inch seen in Fig. A5 is a reflection of the bogus QPFs. A check of the number of bogus HPC QPFs in the intervals beyond 0.25 inch for the test sample considered here revealed that 17% of the observed precipitation cases of 0.25 inch and greater were coupled with a bogus QPF. The corresponding percentages within the discrete intervals ranged from 25% for the 0.25-0.50 interval to 2.6% for the ≥2.00 inch interval. Despite these significant percentages of bogus QPFs for intervals beginning with 0.25-0.50 inch and larger, Fig. A2 shows little evidence of contamination of the HPC MAEs. Spurious values do not appear, even for the interval (0.25-0.50 inch) with the largest fraction of bogus QPF. Even more surprising is that Fig. A2 does not show spurious MAEs for HPC for intervals in the range less than 0.25 inch even though the number of bogus QPFs included therein was close to the number of observed precipitation cases. The corresponding bias plot (not shown) clearly displayed evidence of the contamination, but only for observed precipitation intervals in the 0.00-0.25 inch range. This result indicates that the large error contained in the valid QPFs masks the error that results from the bogus forecasts. Thus, the HPC accuracy and bias scores with the continuous scoring system for intervals beyond 0.25 inch were used in the assessment.

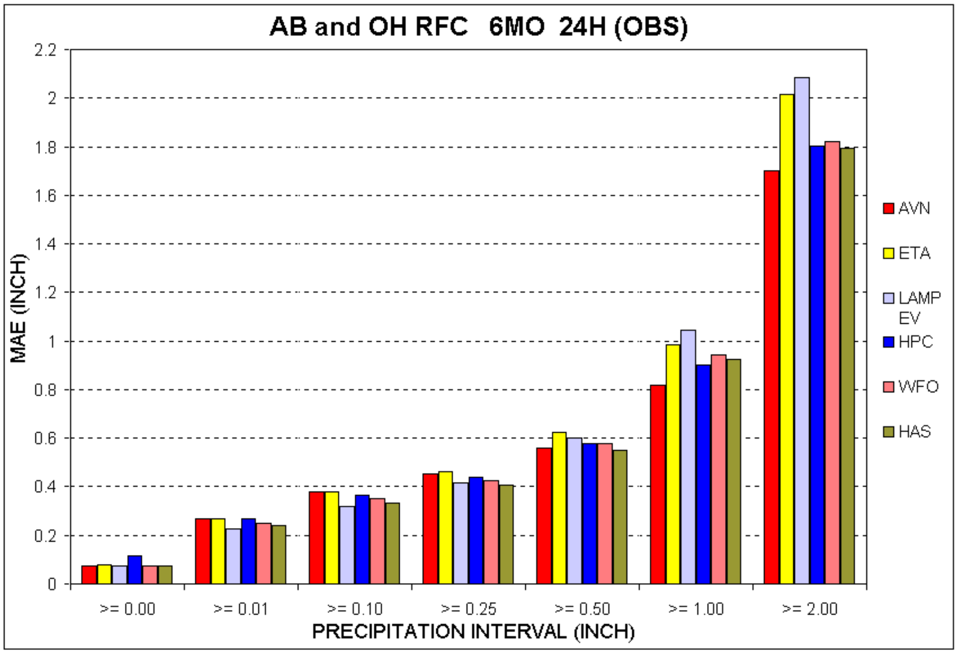


Figure A1. Mean absolute error (MAE) versus observed precipitation amount (OBS approach) in cumulative intervals for the ABRFC and OHRFC areas combined, the 6-mo verification period, and 24-h precipitation amounts.

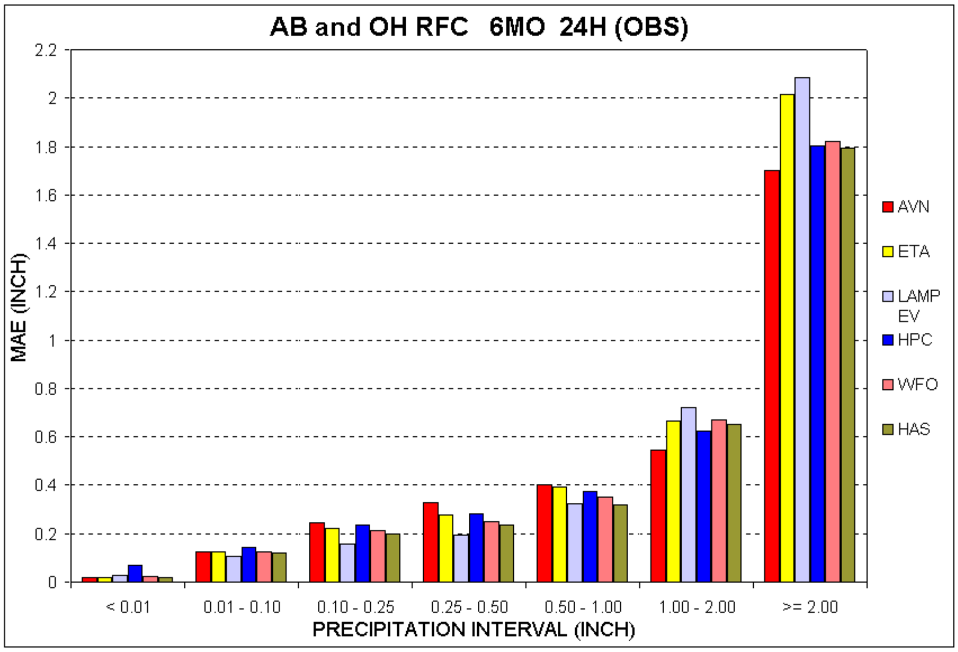


Figure A2. As in Fig. A1 except discrete precipitation intervals are used.

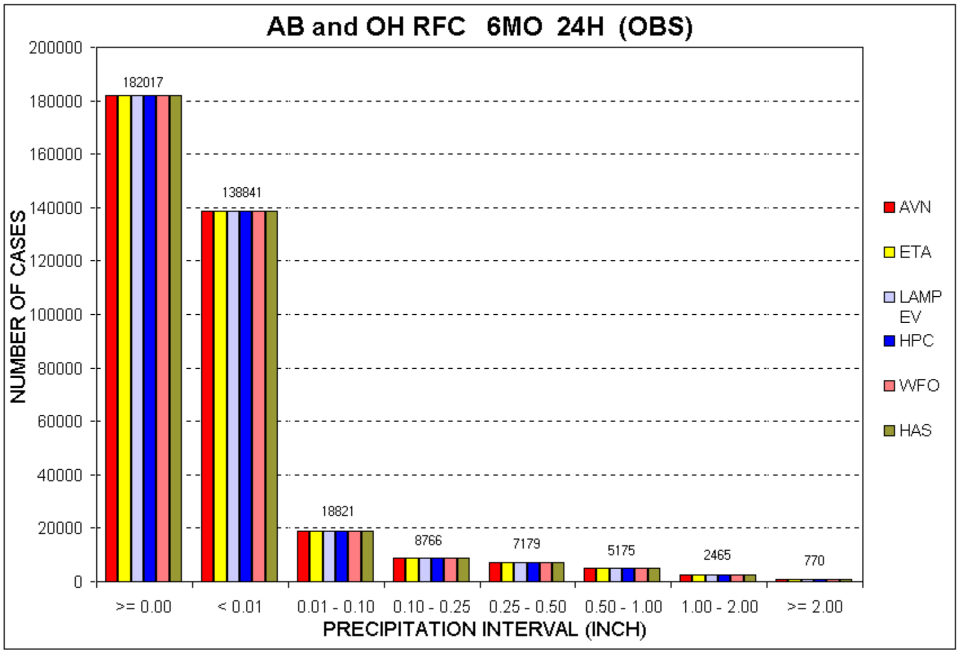


Figure A3. Number of cases within the discrete intervals. The numeral values, which are the same for all products, are plotted above the bars. Otherwise as in Fig. A2.

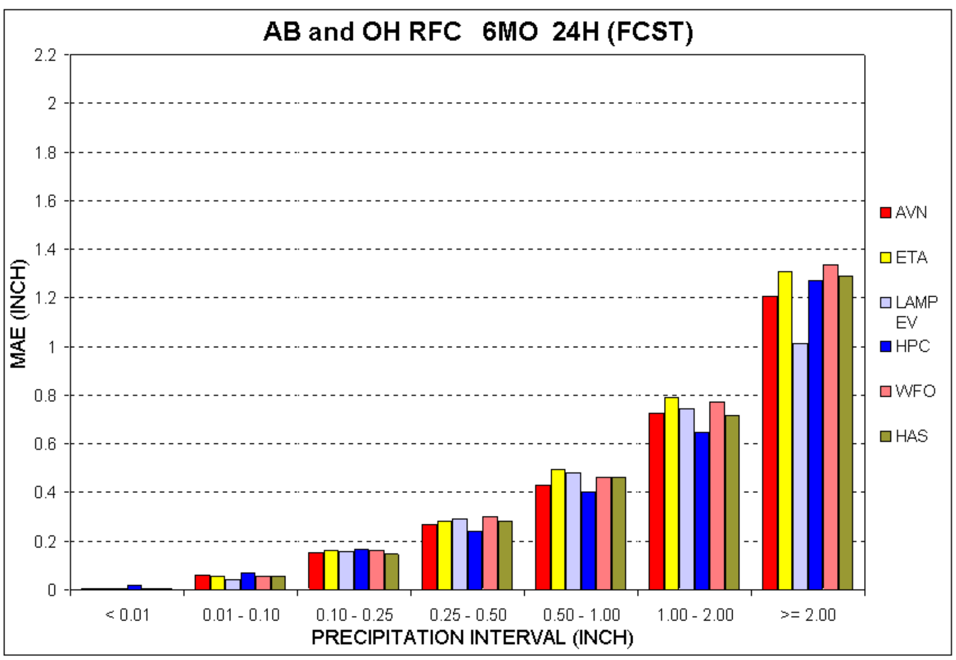


Figure A4. MAE versus forecasted precipitation amount (FCST approach). Otherwise as in Fig. A2.

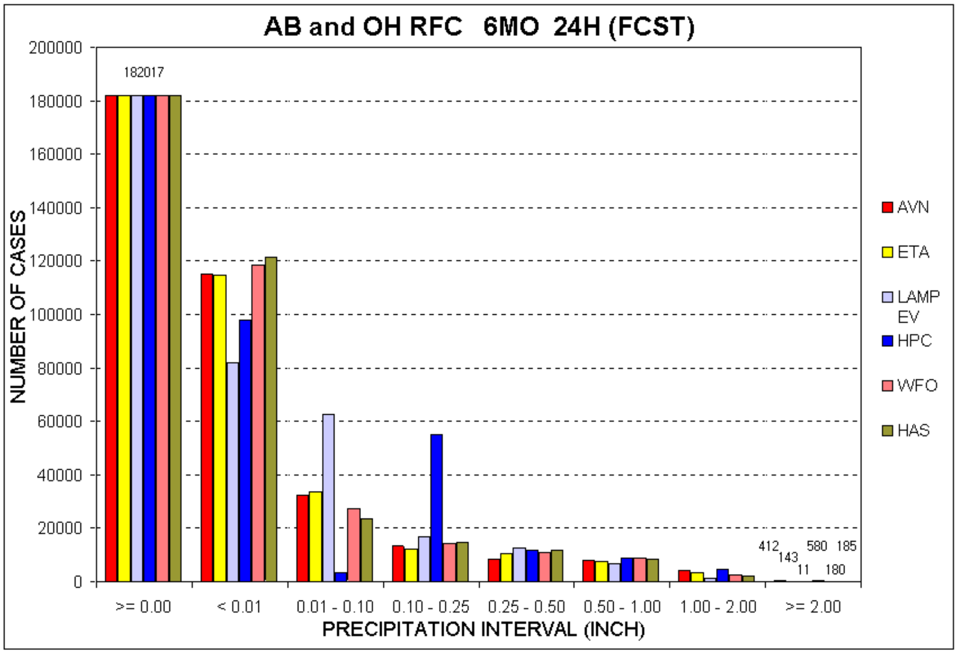


Figure A5. As in Fig. A3 except the samples refer to forecast precipitation amount. The numerical values are shown only for the ≥0.00 inch and ≥2.00 intervals.

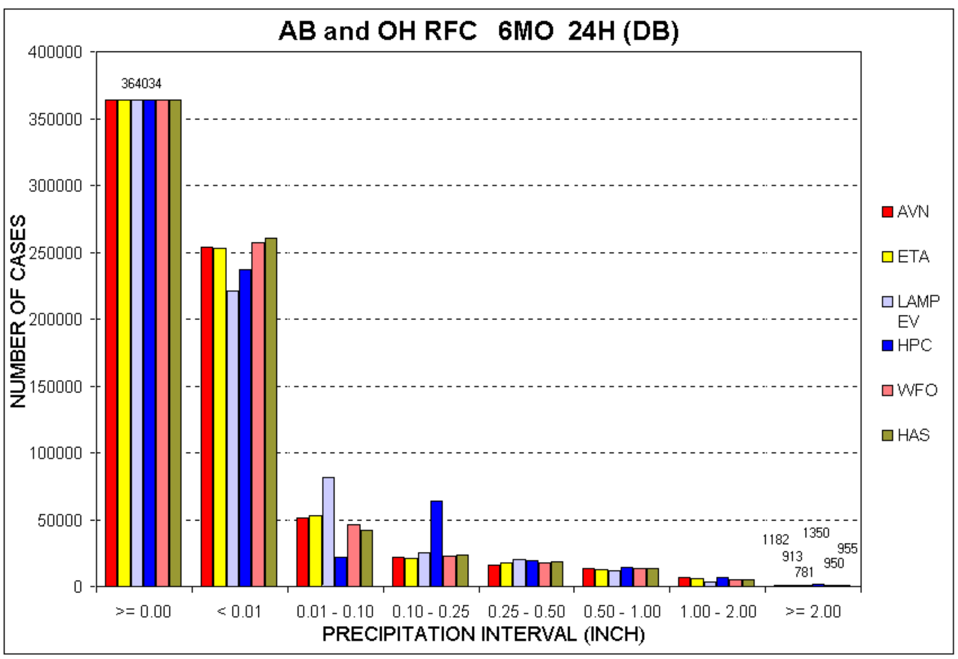


Figure A6. As in Fig. A3 with the DB accounting approach.

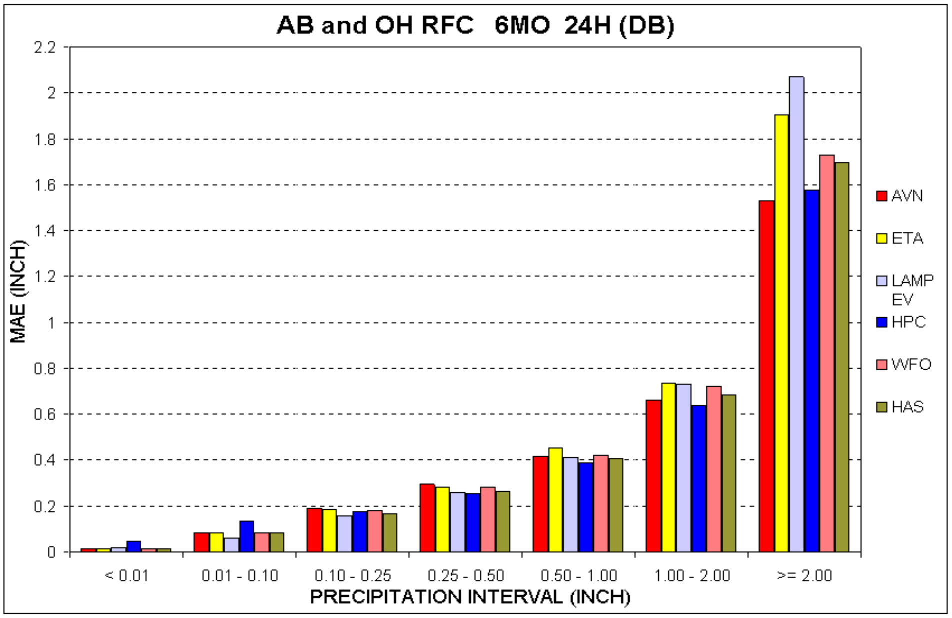


Figure A7. As in Fig. A2 with the “double-both (DB)” scoring approach.

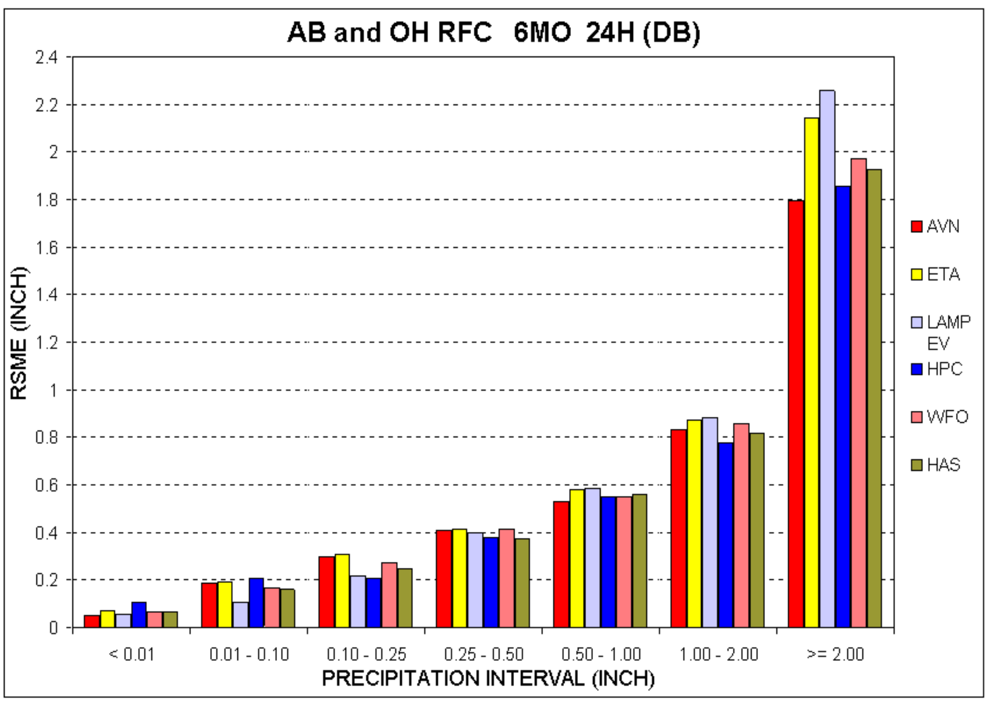


Figure A8. As in Fig. A7 except for root-mean-square error (RMSE). Note that the ordinate scale is slightly different than that in Fig. A7.