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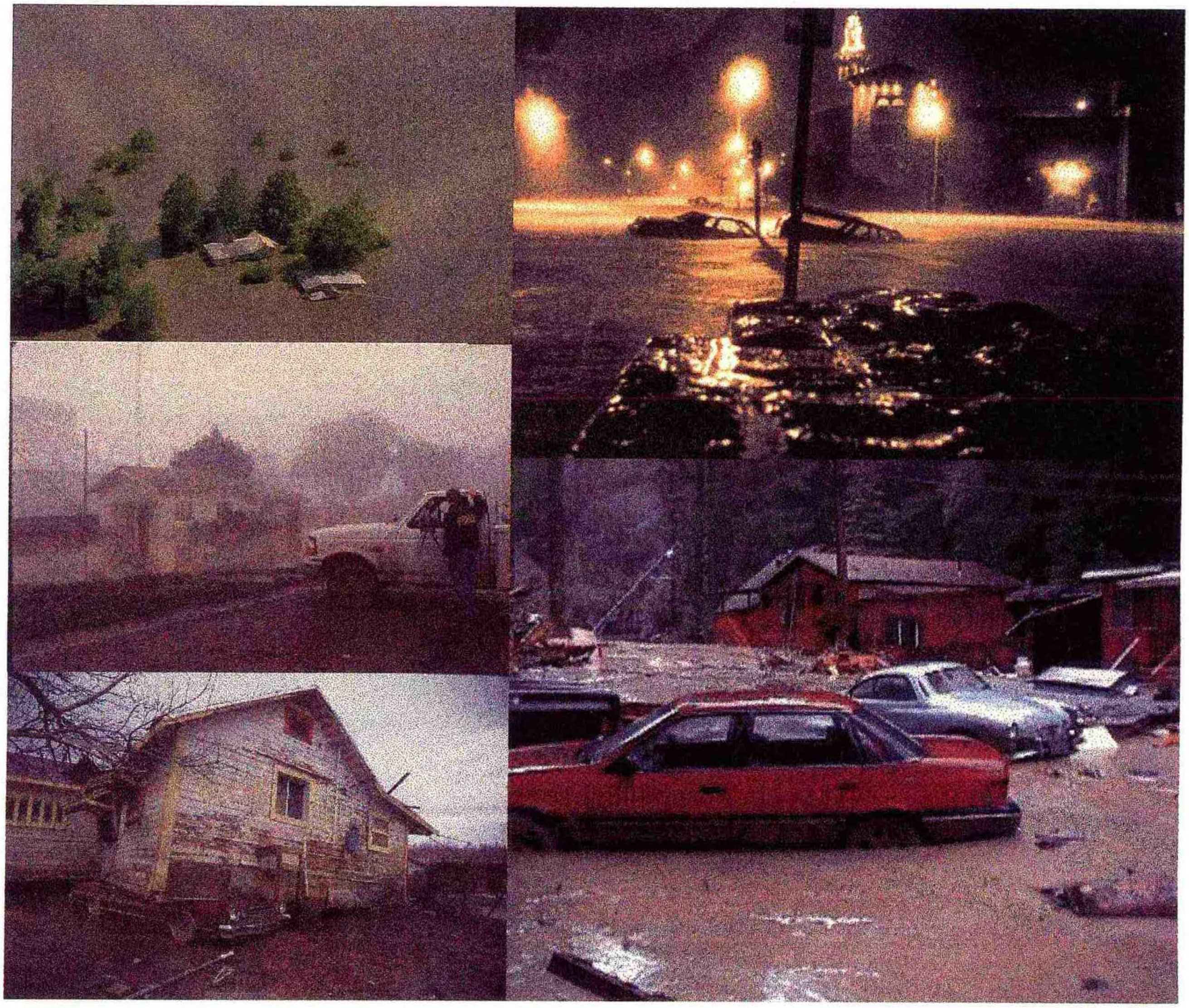
The Modernized End-to-End Forecast Process for Quantitative Precipitation Information: Hydrometeorological Requirements, Scientific Issues, and Service Concepts



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Silver Spring, MD 20910

January 1999

Cover Photographs: *Upper left:* Aerial photograph of flooding in Missouri during The Great Flood of 1993. Photo courtesy of the Federal Emergency Management Agency (FEMA), Andrea Booher, photographer. *Middle left:* California floods, Winter 1997, FEMA Community Relations worker visits with disaster victim in Meridian, CA. Photo courtesy of the FEMA, Andrea Booher, photographer. *Lower left:* House that floated off its foundation in Arboga area during California floods, Winter 1997. Photo courtesy of the FEMA, Andrea Booher, photographer. *Upper right:* Flash flooding along Brush Creek in the Country Club Plaza Shopping District of Kansas City, MO. Intense thunderstorms occurring on 12 and 13 September, 1977, produced record rainfall and destructive flooding in the Greater Kansas City Metropolitan Area. As much as 16 inches of rainfall was recorded in a 26 hour period, and water up to a depth of five feet inundated this shopping plaza. More than 150 automobiles were recovered from Brush Creek and the adjacent public property. The flood claimed 25 lives: 17 of the casualties were occupants of automobiles (NOAA/NWS photo). *Lower right:* Photograph of flood damage in Rio Nido, CA during California Floods of 1998. Photo courtesy of the FEMA, Andrea Booher, photographer.

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Preface

The Hydrometeorological Information Working Group's document entitled *"The Modernized End-to-End Forecast Process for Quantitative Precipitation Information: Hydrometeorological Requirements, Scientific Issues, and Service Concepts"* represents a significant statement and formal commitment, on behalf of the National Weather Service (NWS) and its forecast components, to improve quantitative precipitation forecasts and estimates in support of hydrometeorological services. Furthermore, this document represents the first time the NWS has formally defined the End-to-End (ETE) forecast process for quantitative precipitation information (QPI) and addressed the generation and application of probabilistic quantitative precipitation forecasts (QPFs) for use in operational river and flood forecasting. The projected generation of probabilistic QPFs and their incorporation into the NWS River Forecast System to prepare Advanced Hydrologic Prediction System-based guidance, will enable forecast offices to provide user-requested river and flood warning and forecast products which quantify forecast uncertainty and convey risk.

A modernized ETE framework and supporting requirements are specified, roles and responsibilities are defined, and several scientific and technical issues are outlined to achieve the desired results. I realize the ambitious goals detailed in this plan require that significant resources be made available to resolve critical scientific and technological issues. These include: 1) the development and testing of new forecast methodologies and operational techniques, 2) the implementation of new modeling systems, 3) conducting critical risk reduction activities in all NWS Regions, and 4) providing the training required to implement this modernized ETE Forecast Process for QPI. This document will be used as a basis for seeking the additional funding needed to implement this plan over the next 10 years through the normal budget initiative process associated with the Advance Short Term Warning and Forecast Team.

I gratefully acknowledge the Hydrometeorological Information Working Group (HIWG) for their dedication in generating the visions and goals embodied in this plan. I am especially indebted to Dr. Thomas M. Graziano, Office of Meteorology QPF Program Manager and HIWG Chairperson, for his leadership, and substantial coordination, writing, and editing efforts from the plan's inception to its final draft.

Dr. Louis W. Uccellini
Director, Office of Meteorology

January 1999

Acknowledgments

This quantitative precipitation information concept document represents the collective input of the HIWG, whose membership is listed below. Preliminary and second drafts of this document were disseminated for review and comment in July 1997 and July 1998, respectively. The comments and recommendations of HIWG members were addressed and integrated into this plan.

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Special thanks are also extended to Dr. Louis Uccellini, Greg Mandt, LeRoy Spayd, Dr. Roman Krzysztofowicz, and Tim Helble for their rigorous technical review of this document, and to Linda Kremkau for her many constructive comments during the final editing phase.

List of Acronyms and Abbreviations

6LPE	Six-Layer Primitive Equation
ABR	Average Basin Rainfall
ABRFC	Arkansas-Red Basin River Forecast Center
ACARS	ARINC Communications Addressing and Reporting System
AFOS	Automation of Field Operations and Services
AHOS	Automated Hydrologic Observing System
AHOS-T	Automated Hydrologic Observing System - Telephone
AHPS	Advanced Hydrologic Prediction System
AKRFC	Alaska River Forecast Center
ALERT	Automated Local Evaluation in Real Time
AMS	American Meteorological Society
AR	Alaska Region
ARINC	Aeronautical Radio, Incorporated
ASOS	Automated Surface Observing System
ASTWF	Advance Short Term Warning and Forecast
AVN	Aviation (run of the NCEP NWP models)
AWC	Aviation Weather Center
AWHPS	Area Wide Hydrologic Prediction System
AWIPS	Advanced Weather Interactive Processing System
BAMI	Bay Area MESONET Initiative
BPP	Bayesian Precipitation Processor
BIS	Bayesian Informativeness Score
BOR	Bureau of Reclamation
BS	Brier Score
BS_c	Climatological Brier Score
CBRFC	Colorado Basin River Forecast Center
CCF	Coded Cities Forecast
CFSO	Critical Flood Support Office
CGT	Central Guidance Threat
CI	Cooperative Institute
CNRFC	California-Nevada River Forecast Center
COMET	Cooperative Program for Operational Meteorology, Education and Training
CONUS	Continental United States
COOP	Cooperative Observer Program
COS-21	Composite Observing System for the 21st Century
COTS	Commercial Off-The-Shelf
CPC	Climate Prediction Center
CR	Central Region
CRH	Central Region Headquarters
CS	Calibration Score

List of Acronyms and Abbreviations -- Continued

CSI	Critical Success Index
CSTAR	Collaborative Science, Technology, and Applied Research
CWA	County Warning Area
D2D	Display 2-Dimensions
DCP	Data Collection Platform
DEM	Digital Elevation Model
DHR	Digital Hybrid-Scan Reflectivity
DMSP	Defense Meteorological Satellite Program
DOH	Development and Operations Hydrologist
DSM	NWSFO Des Moines, IA
EM	Emergency Manager
EMC	Environmental Modeling Center
ER	Eastern Region
ERH	Eastern Region Headquarters
EPP	Ensemble Precipitation Processor
ES	Efficiency Score
ESDIM	Environmental System Data and Information Management
ESP	Ensemble Streamflow Prediction
ESRI	Environmental System Research Institute
ETE	End-to-End
FAR	False Alarm Rate
FEMA	Federal Emergency Management Agency
FFG	Flash Flood Guidance
FFT	Flash Flood Threat
FMAP	Forecast Mean Areal Precipitation
FMAT	Forecast Mean Areal Temperature
FOB	Forecast Operations Branch
FSL	Forecast Systems Laboratory
FY	Fiscal Year
GCIP	GEWEX Continental-Scale International Project
GCM	Global Circulation Model
GDSS	Gage Data Support System
GEO	Geostationary Earth Orbiting
GEWEX	Global Energy and Water Cycle Experiment
GFE	Graphical Forecast Editor
GIS	Geographic Information System
GMOD	Grid Modification
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning Satellite

List of Acronyms and Abbreviations -- Continued

GSM	Global Spectral Model
GUI	Graphical User Interface
HAS	Hydrometeorological Analysis and Support
HDP	Hourly Digital Precipitation
HIWG	Hydrometeorological Information Working Group
HP	High Precipitation
HPC	Hydrometeorological Prediction Center
HPB	Heavy Precipitation Branch
HPW	Heavy Precipitation Workshop
HRAP	Hydrologic Rainfall Analysis Project
HRL	Hydrologic Research Lab
HSA	Hydrologic Service Area
HSD	Hydrologic Services Division
HSS	Heidke Skill Score
HYD	Hydrologist
IB&WC	International Boundary and Water Commission
ICWF	Interactive Computer Worded Forecast
IFFA	Interactive Flash Flood Analyzer
IFLOWS	Integrated Flood Observing and Warning System
IFP	Interactive Forecast Preparation
IFPS	Interactive Forecast Preparation System
IFWG	IFPS Forecaster Working Group
IHABBS	Integrated Hydrologic Automated Basin Boundary System
IMOST	Integrated MAR Operations and Services Team
IR	Infrared
LAMP	Local AWIPS MOS Program
LAPS	Local Analysis and Prediction System
LCG	Local Climatological Guidance
LCRA	Lower Colorado River Authority
LEO	Lower Earth Orbiting
LES	Lake Effect Snow
LFM	Limited-area Fine Mesh
LMRFC	Lower Mississippi River Forecast Center
LWX	NWSFO Sterling, VA
MAE	Mean Absolute Error
MAP	Mean Areal Precipitation
MAR	Modernization and Associated Restructuring
MBRFC	Missouri Basin River Forecast Center
MCC	Mesoscale Convective Complex

List of Acronyms and Abbreviations -- Continued

McIDAS	Man-computer Interactive Data Access System
MD	Mesoscale Discussion
ME	Mean Error
MESONET	Mesoscale Observation Network
MM5	Mesoscale Model version 5
MOS	Model Output Statistics
MRF	Medium Range Forecast
MSM	Modernization Systems Management
NAOS	North American Atmospheric Observing System
NASA	National Aeronautics and Space Administration
N-AWIPS	NCEP Advanced Weather Interactive Processing System
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCRFC	North Central River Forecast Center
NERFC	Northeast River Forecast Center
NESDIS	National Environmental Satellite Data and Information Service
NEXRAD	Next Generation Weather Radar
NGM	Nested Grid Model
NHWC	National Hydrologic Warning Council
NLDN	National Lightning Detection Network
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NOS	National Ocean Service
NPPU	National Precipitation Prediction Unit
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NSC	NOAA Science Center
NSF	National Science Foundation
NSSL	National Severe Storms Laboratory
NVU	National Verification Unit
NWP	Numerical Weather Prediction
NWRFC	Northwest River Forecast Center
NWS	National Weather Service
NWSFO	NEXRAD Weather Service Forecast Office
NWSH	National Weather Service Headquarters
NWSMC	National Weather Service Modernization Committee
NWSO	NEXRAD Weather Service Office
NWSRFS	National Weather Service River Forecast System

List of Acronyms and Abbreviations -- Continued

OAR	Office of Oceanic and Atmospheric Research
OH	Office of Hydrology
OHRFC	Ohio River Forecast Center
OM	Office of Meteorology
ONR	Office of Naval Research
ORA	Office of Research and Applications
ORPG	Open Radar Product Generator
OSD	Office of Systems Development
OSDPD	Office of Satellite Data Processing and Distribution
OSF	Operational Support Facility
OSO	Office of Systems Operations
PBZ	NWSFO Pittsburgh, PA
PC	Personal Computer
PDT	Prospectus Development Team
POD	Probability of Detection
POES	Polar Operational Environmental Satellite
PoP	Probability of Precipitation
PPS	Precipitation Processing Subsystem
PQPF	Probabilistic Quantitative Precipitation Forecast
PR	Pacific Region
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PRSF	Probabilistic River Stage Forecast
PSU	Pennsylvania State University
PW	Precipitable Water
QPB	Quantitative Precipitation Branch
QPE	Quantitative Precipitation Estimate
QPF	Quantitative Precipitation Forecast
QPI	Quantitative Precipitation Information
RAFS	Regional Analysis and Forecast System
RAP	Research Applications Program
RASS	Radio-Acoustic Sounding Systems
RCM	Radar Coded Message
REEP	Regression Estimation of Event Probability
RFC	River Forecast Center
RFG	River Forecast Group
RH	Relative Humidity
RLX	NWSFO Charleston, WV
RMSE	Root Mean Square Error
RPG	Radar Product Generator

List of Acronyms and Abbreviations -- Continued

RPS	Ranked Probability Score
RSM	Regional Spectral Model
RUC	Rapid Update Cycle
RVF	River Forecast
SAAS	Southwestern Association of ALERT Systems
SAB	Satellite Analysis Branch
SBN	Satellite Broadcast Network
SC	Sufficiency Characteristic
SCAN	System for Convection Analysis and Nowcasting
SCS	Soil Conservation Service
SCTI	SCAN CWA Threat Index
SHEF	Standard Hydrometeorological Exchange Format
SIM	Satellite Information Message
SOO	Science and Operations Officer
SPC	Storm Prediction Center
SPD	Supplemental Precipitation Data
SPE	Satellite Precipitation Estimate
SR	Southern Region
SREF	Short-Range Ensemble Forecasting
SRH	Southern Region Headquarters
SSD	Scientific Services Division
SSHPS	Site-Specific Hydrologic Prediction System
SSM/I	Special Sensor Microwave/Imager
SST	Severe Storm Threat
SWI	Soil Wetness Index
TBD	To Be Determined
TDL	Techniques Development Laboratory
TDWR	Terminal Doppler Warning Radar
TVA	Tennessee Valley Authority
UCAR	University Corporation for Atmospheric Research
UDFCD	Urban Drainage and Flood Control District
URL	Uniform Resource Locator
USACE	United States Army Corps of Engineers
USAF	United States Air Force
USDA	United States Department of Agriculture
USGCRP	U.S. Global Change Research Program
USGS	United States Geological Survey
USWRP	United States Weather Research Program

List of Acronyms and Abbreviations -- Continued

UTC	Universal Time Coordinated
UVA	University of Virginia
VIL	Vertically Integrated Liquid
WAN	Wide Area Network
WCC	Water and Climate Center
WDSS	Warning Decision Support System
WFB	Weather Forecast Branch
WFO	Weather Forecast Office
WHFS	WFO Hydrologic Forecast System
WR	Western Region
WSFO	Weather Service Forecast Office
WSI	Weather Services International
WSO	Weather Service Office
WSOM	Weather Service Operations Manual
WSR-88D	Weather Surveillance Radar - 1988 Doppler
WRF	Weather Research and Forecasting
WWRP	World Weather Research Program

Executive Summary

Flash and river floods are one of the most economically devastating and deadly weather-related hazards. For the 30-year period ending in 1995, floods have claimed an average of 136 lives per year compared to 85 by lightning, 73 by tornadoes, and 25 by hurricanes (Office of Meteorology, 1997). Reductions in the number of fatalities associated with these natural hazards in recent years reflect the initial operational benefits derived from the National Weather Service (NWS) Modernization and Associated Restructuring (MAR) (Friday, 1994). *However, the number of people impacted by floods and their economic cost continue to increase with industrialization and the increased inhabitation of flood prone regions (National Research Council, 1996).* News reports of the personal tragedy inflicted by floods are becomingly increasingly more commonplace. More than 75 percent of all Presidential Disaster Declarations result from flooding, and several hundred thousand Americans are evacuated from their homes each year (NOAA, 1995). The average annual cost of flood damage during the 10-year period ending in 1997 (adjusted for inflation) exceeded 4.6 billion dollars, and this cost rose to an average in excess of 8 billion dollars for the latter 5 years of this period (F. P. Richards, 1998, personal communication). Just recently, flood damage resulting from The Northeast Flood of January 1996, The Northwest Flood of February 1996, The Western U.S. Flood of January 1997, The Ohio Valley Flood of March 1997, and The Red River of the North Flood of April 1997, exceeded one billion dollars each (F. P. Richards, 1998, personal communication). Floods impact all fifty states of the United States and occur during all seasons of the year. Consequently, some of the most important public products issued by NWS field offices include flood and flash flood watches and warnings and main-stem river forecasts. The most important observed and/or forecast parameters required to produce NWS hydrometeorological forecast and warning products are quantitative precipitation estimates (QPEs) and quantitative precipitation forecasts (QPFs). The aggregate of QPEs and QPFs is referred to as quantitative precipitation information (QPI). In recognition of the potential service benefits of QPFs, improving QPFs has recently been identified as one of the top science priorities of the NWS (Uccellini, 1996a; Uccellini, 1998), the United States Weather Research Program (USWRP) (Fritsch et al., 1998), and the World Weather Research Program (WWRP) (Carbone, 1997), and improving QPEs and QPFs is recognized as a significant challenge facing the NWS and the meteorological community over the next 10 years. In light of these facts, and the increasing burden being shouldered by state and local officials to ensure public safety and mitigate the impact of flooding events, the NWS is actively engaged in activities to improve hydrometeorological services (Zevin, 1994; Office of Hydrology, 1996; Uccellini, 1996a; Office of Hydrology, 1997; Graziano, 1998; Wernly and Uccellini, 1998; Fread et al., 1999).

The purpose of this QPI concept document is to specify an operational framework which efficiently and effectively couples advanced meteorological and hydrological prediction on the short- through long-ranges. The terms short-, medium-, and long-range correspond to the following time spans: 0-3 days; 4-14 days, and 15 days or longer, respectively. This plan was developed in coordination with, and approved by, all NWS components and will be reviewed triennially by the HIWG to ensure the proposed forecast process continues to reflect and most efficiently meet the needs of NWS forecasters, partners, and customers. Furthermore, coordination must continue with the Integrated MAR Operations and Services Team (IMOST) to ensure consistency with other NWS programmatic and modernization activities. Through the full implementation of this strategic plan, the NWS will improve the accuracy, reliability, resolution, information content, temporal span and timeliness of hydrometeorological and hydrologic forecasts and warnings provided to the nation. Incremental improvements in products and services will be accompanied by appropriate end user notification. A companion implementation plan, which will detail the many ongoing and planned activities which must be completed to modernize the forecast process for QPI and incorporate the necessary forecaster and end user training, is currently being developed. In response to requirements from a diverse user community, and in light of the service-science linkage which forms the basis of the modernized NWS, field offices plan to advance and expand current NWS services to include the routine generation and use quantitative precipitation and river forecast products which quantify forecast uncertainty and convey risk (Zevin, 1994; Fread et al., 1995; Office of Hydrology, 1996; Office of Hydrology, 1997; Fread, 1998; Graziano, 1998; Krzysztofowicz, 1998a,b; Schaake and Larson, 1998). Recent national forums and publications wherein end users have articulated a requirement for probabilistic hydrometeorological forecast products include:

- the 1995 NWS Emergency Management Forum,
- the 1996 NWS Fifth National Heavy Precipitation Workshop,
- the 1997 Second National Conference and Exposition of the National Hydrologic Warning Council (NHWC) incorporating the Tenth Annual Conference of the Southwestern Association of ALERT Systems (SAAS),
- the 1997 Workshop on Climate Variability and Water Resource Management in the Southeastern U.S. sponsored by the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the United States Geological Survey (USGS),
- the 1998 Special Symposium on Hydrology sponsored by the American Meteorological Society (AMS),
- the 1998 NWS Modernized Product Development Workshop, and
- NOAA Natural Disaster Survey Reports and Service Assessments from 1993 to the present.

The generation of value-added QPFs lends itself particularly well to a probabilistic approach and format. The broad spectrum of space and time scales on which precipitation organizes and occurs makes precipitation amount one of the most -- *if not the most* -- difficult predictands and a major source of uncertainty in hydrologic forecasting (Krzysztofowicz, 1993; NRC, 1996). The inherent complexity of the precipitation forecast problem 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 non-linear.

Krzysztofowicz and Drake (1992), Krzysztofowicz (1993), and Zevin (1994) have shown that a probabilistic format for QPFs enables forecasters to quantify the uncertainty associated with the predictand. Furthermore, Krzysztofowicz (1983) and Alexandridis and Krzysztofowicz (1985) have shown that the (economic) value of probabilistic forecasts is always at least as large as that of their deterministic counterparts and the potential economic gain from probabilistic forecasts (relative to deterministic forecasts) is directly correlated with the degree of uncertainty about the predictand. In light of these results and the inherent complexities and associated forecaster uncertainty in quantitatively forecasting rainfall amount, the benefits of adopting and implementing a probabilistic format for QPFs could be very large.

The incremental implementation of improved and expanded NWS hydrometeorological services, which include improving the accuracy and extending the range of our hydrometeorological forecasts and a transition to stochastic forecasting, is planned to occur over the next 5-10 years. The incremental implementation of value-added probabilistic QPFs (PQPFs) is planned to begin with the Hydrometeorological Prediction Center (HPC) of the National Centers for Environmental Prediction (NCEP) and Weather Forecast Offices (WFOs) which support River Forecast Centers (RFCs) utilizing the Advanced Hydrologic Prediction System (AHPS). *The many requirements which must be satisfied along with the scientific and technological issues which must be resolved, to improve hydrometeorological services and enable the NWS to implement probabilistic forecasting nationally, are specified.* The resolution of these technological and scientific issues requires a sustained and aggressive applied research effort conducted under the auspices of the USWRP and the Collaborative Science, Technology, and Applied Research (CSTAR) Program. Performing this applied research, conducting associated risk reductions and training, and implementing new modeling systems, requires funding via the normal budget initiative process associated with the Advance Short Term Warning and Forecast (ASTWF) Team. Risk reduction activities must be conducted in all NWS Regions and at the HPC of NCEP to fully test new forecast methodologies, operational techniques, and forecast products based on this applied research to ensure they meet the needs of NWS forecasters, partners, and customers. Furthermore, these risk reductions will enable the NWS to assess associated resource requirements to ensure enhanced services can be provided with projected staffing and computational capabilities.

For over a decade, users, such as Emergency Managers (EMs) and state and local officials, have recognized and articulated an increasing need for NWS hydrometeorological guidance products which quantify forecast uncertainty. Probabilistic forecast and warning guidance will enable local officials to weigh forecast probability and lead time vs. potential flood severity to utilize resources most effectively to preserve life and property (Zevin, 1994). Furthermore, short- through long-range probabilistic streamflow guidance, which accounts for the uncertainty in future atmospheric and land surface events, will enable water resource managers to make more informed decisions regarding the utilization of water and the operation of water systems. The provision of this short- through long-range guidance is particularly important and its potential socioeconomic benefit is very large, given that the demand for water for domestic hydropower, industrial, and agricultural applications exceeds its available supply in some regions of the country (U.S. Global Change Research Program, 1997).

The primary mission of NOAA's NWS Hydrologic Services Program is to provide advanced, short-range river and flood forecasts and warnings for the protection of life and property, and basic hydrologic forecast information for the Nation's economic and environmental well-being, including short- through long-range forecast information for water resource management. In support of these missions, and to improve hydrometeorological services, this QPI concept document applies an End-to-End (ETE) Forecast Process (Uccellini et al., 1995; Uccellini, 1996a; Wernly and Uccellini, 1998) and capitalizes on the technological and scientific advances implemented through the NWS MAR. The ETE Forecast Process is comprised of many steps which include collecting and assimilating observations, running numerical weather prediction (NWP), statistical, and hydrologic models, preparing forecasts and warnings, and coordinating these products with a diverse user community.

The Hydrometeorological Information Working Group (HIWG) has the specific charge to establish and update operational requirements for QPI and observational data in support of river and flash flood forecasting and to define the roles, responsibilities, and relationships of the components of the ETE Forecast Process for QPI. HIWG is chaired by the Office of Meteorology (OM) and membership includes representatives from the NWS Regions, the Office of Systems Development (OSD), the Office of Hydrology (OH), NCEP, and the National Environmental Satellite Data and Information Service (NESDIS). The HIWG applied a requirements concept to the QPI problem by inverting the ETE Forecast Process and systematically working in reverse order from the end user to articulate specific requirements on various forecast components within the NWS, and to specify and address the scientific and technical issues which form a basis for the anticipated advances. The collective input of the HIWG serves as the basis for this QPI document. This document complements other NWS documents, such as the "Hydrometeorological Service Operations for the 1990's" (Office of Hydrology, 1996) and the "Office of Meteorology 1996-2005 Strategic Operating Plan" (Uccellini, 1996a), and provides details of the ETE Forecast Process for QPI, heretofore, not fully addressed.

The NWS MAR program provides a physical and technical support environment wherein greatly improved collaboration, coordination, communication and integration are achieved between and within the hydrology and meteorology components of the NWS. The implementation of advanced remote sensing technologies, such as the Weather Surveillance Radar 1988-Doppler (WSR-88D), the Automated Surface Observing System (ASOS), Doppler wind profilers, improved Geostationary Operational Environmental Satellites (GOES), and lightning detection networks, provides a broader spectrum of observations at unprecedented temporal and spatial scales. The advent of advanced operational atmospheric and hydrologic data assimilation techniques and higher resolution, numerical-model based ensemble prediction and statistically-based forecast models will more effectively integrate and utilize these observational data. These observational and modeling systems should provide improved QPE and QPF products and hydrometeorological guidance to personnel at HPC and the Storm Prediction Center (SPC) of NCEP, WFOs, and RFCs located throughout the United States. The implementation of the Advanced Weather Interactive Processing System (AWIPS) (Friday, 1994) and its associated grid editing software, communications infrastructure, and local software applications should enable NWS field personnel to generate, coordinate, and issue more accurate, site-specific, and timely hydrometeorological forecast and warning products. Critical

WFO AWIPS software applications for assessing and predicting the areal potential for flash flooding and preparing watch and warning products include the WFO Hydrologic Forecast System (WHFS) (Roe et al., 1998) and the System for Convection Analysis and Nowcasting (SCAN) (Smith et al., 1998). These improvements, coupled with the implementation of the next generation NWS River Forecast System (NWSRFS), AHPS, modernized Flash Flood Guidance (FFG), and stochastic and distributed hydrologic modeling at RFCs, should yield improved hydrometeorological services to the public in the modernized NWS (Office of Hydrology, 1996).

As determined by the HIWG and as detailed in this plan, 1) the technological benefits of the NWS MAR program combined with the operational implementation of applied research planned to be conducted under the auspices of the USWRP and the CSTAR Program, and 2) funding via the normal budget initiative process associated with the ASTWF Team, are necessary and should enable the NWS to modernize the ETE Forecast Process for QPI and achieve the following projected forecast goals:

5-Year QPI Goals

- Increase the skill of the Day 1 operational NWP model QPFs by 50 percent.
- Increase the skill of the Day 2 and Day 3 operational NWP model QPFs by one day (i.e., increase skill of Day 2 QPF to current Day 1, and increase skill of Day 3 to current Day 2).
- Add value to the operational NWP model QPFs at each subsequent step of the NWS ETE Forecast Process (i.e., HPC, WFOs, RFCs).
- Introduce forecaster-prepared, value-added PQPFs through Day 3 for use in AHPS[3].
- Improve the nationally-averaged lead time of flash flood warnings by more than 30 percent (from 45 minutes[4] to 60 minutes).

Meeting these QPI goals will impact each component of the forecast process and place new requirements on their associated partners (i.e., RFCs, WFOs, HPC, Statistical Guidance, NWP models, observations). Associated service goals, also based upon USWRP and CSTAR Program applied research and ASTWF funding, and achievable via the integration of these research benefits into AWIPS and the implementation of a Modernized ETE Forecast Process which includes AHPS, are projected to be as follows:

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[3] *The introduction of PQPFs will be focused on, but not limited to, HPC and WFOs which support RFCs utilizing AHPS.*

[4] *Nationally-averaged lead time for flash flood warnings issued in 1997 (Paul Polger, personal communication, 1998)*

10-Year Hydrometeorological Service Goals

- Introduce AHPS short- through long-range site-specific, probabilistic river stage forecasts (PRSFs) at RFCs utilizing value-added PQPFs[5].

- Prepare, issue, and verify PQPFs and hydrologic forecast and warning products at WFOs nationwide.

- Extend the range of forecaster-prepared, value-added QPFs/PQPFs produced by the HPC and WFOs and assimilated by the RFC through Day 3[6].

- Provide improved and expanded centrally-produced Model Output Statistics (MOS) QPF/PQPF guidance products based on operational NWP models, including global and regional ensembles.

- Implement statistically-based models, expert systems, and other techniques on AWIPS to provide high resolution, short-range, statistical QPF/PQPF guidance products. These guidance products, coupled with advanced decision assistance and product preparation tools such as SCAN and WHFS, will enable WFOs to more accurately and efficiently assess and predict the areal potential for flash flooding.

- Implement improved data assimilation techniques, improved and higher resolution regional mesoscale NWP models, regional and stormscale NWP models, and a regional ensemble prediction system at the Environmental Modeling Center (EMC) of NCEP.

- Expand the real-time use and integration of QPEs, based on various sources of in situ and remotely sensed data, utilizing continuing advances on verifying, optimally merging, and quality controlling gage, radar, and satellite estimates.

- Improve the real-time access, integration, and utilization within AWIPS of surface rain gage data, and data from new and improved observing technologies.

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[5] *National implementation of AHPS is contingent upon the approval and continuance of funding. The transition to probabilistic river forecasting is contingent upon 1) the implementation of AHPS, 2) the development, successful testing, documentation, and implementation of methodologies which produce short-range PRSFs and accurately quantify and account for hydrologic uncertainties, and 3) regional risk reductions wherein a quantitative assessment of associated resource requirements is conducted to ensure enhanced services can be provided with projected staffing and computational capabilities.*

[6] *The incremental extension of the range of forecaster-prepared QPFs/PQPFs (from Day 1 to Day 2, and from Day 2 to Day 3) is contingent upon forecaster skill exceeding that of the operational NWP models by an amount to be specified by the HIWG in the forthcoming companion implementation plan.*

- Implement 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 ETE Forecast Process. Verification data will be utilized to ensure the ETE Forecast Process represents the most efficient use of resources to produce quality QPI for hydrologic services.

As a first step toward national implementation, the NWS commenced a two-year risk reduction exercise in September of 1998 to develop and test AWIPS-compatible probabilistic QPF and river forecast methodologies and to begin to specify a probabilistic ETE framework. The original concept for this probabilistic risk reduction exercise was discussed and supported by the HIWG during July 1996. This risk reduction exercise is an OM, OH, and Eastern Region Headquarters (ERH) coordinated CSTAR Program effort with the University of Virginia (UVA), which builds upon previous collaborative development efforts between the NWS Eastern Region (ER) and UVA. Additionally, the HPC of NCEP, the Techniques Development Laboratory (TDL) of the OSD, the Ohio River RFC (OHRFC), and NWSFOs in Pittsburgh, PA and Charleston, WV of ER were actively engaged in planning, and are participating in, this important activity. This risk reduction enables the NWS to begin to test new forecast methodologies, operational techniques, and forecast products and perform a quantitative resource assessment to ensure enhanced services can be provided with projected staffing and computational capabilities. Results from this exercise and similar risk reduction exercises projected for other NWS Regions, integrated with the results of a recently completed PRSF risk reduction exercise (Office of Hydrology, 1997), parallel and planned CSTAR and USWRP applied research and development efforts, and HIWG workshops, will be utilized to formulate a modernized ETE hydrometeorological forecast system.

This strategic plan reflects a partnership amongst the various organizations that comprise the modernized ETE Forecast process to meet the requirements of a diverse user community and ensure a national implementation over the next 10 years.

The Modernized End-to-End Forecast Process for Quantitative Precipitation Information: Hydrometeorological Requirements, Scientific Issues, and Service Concepts

1.0. Introduction

1.1. Overview

The primary mission of the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) Hydrologic Services Program (Fread et al, 1995; Larson et al., 1995; Stallings and Wenzel, 1995; Office of Hydrology, 1996) is to provide:

- advanced, short-range river and flood forecasts and warnings for the protection of life and property, and
- basic hydrologic forecast information for the Nation's economic and environmental well-being, including short- through long-range forecast information for water resource management.

In support of these hydrometeorological missions of the NWS, this quantitative precipitation information (QPI) concept document applies an End-to-End (ETE) Forecast Process (Uccellini et al., 1995; Uccellini, 1996a; Wernly and Uccellini, 1998) comprised of many steps which include collecting and assimilating observations, running NWP, statistical, and hydrologic models, preparing value-added forecasts and warnings, and coordinating these products with a diverse user community. The application of this process enables the NWS to capitalize on the technological and scientific advances implemented through the Modernization and Associated Restructuring (MAR) (Friday, 1994; NOAA, 1996) to:

- articulate specific requirements on various forecast components within the NWS (River Forecast Centers, Weather Forecast Offices, National Centers), and,
- specify and address the scientific and technical issues which form a basis for the anticipated advances.

The purpose of this QPI concept document is to specify an operational framework which efficiently and effectively couples advanced meteorological and hydrological prediction on the short- through long-ranges. The terms short-, medium-, and long-range correspond to the following time spans: 0-3 days; 4-14 days, and 15 days or longer, respectively. This plan was developed in coordination with, and approved by, all NWS components and will be reviewed triennially by the Hydrometeorological Information Working Group (HIWG) to ensure the proposed forecast process continues to reflect and most efficiently meet the needs of NWS forecasters, partners, and customers.

Furthermore, coordination must continue with the Integrated MAR Operations and Services Team (IMOST) to ensure consistency with other NWS programmatic and modernization activities. Through the full implementation of this strategic plan, the NWS will improve the accuracy, reliability, resolution, information content, temporal span and timeliness of hydrometeorological forecasts and warnings provided to the nation. Incremental improvements in products and services will be accompanied by appropriate end user notification. In response to user requirements, and in light of the service-science linkage which forms the basis of the modernized NWS, field offices plan to routinely generate and use quantitative precipitation and river forecast products which quantify forecast uncertainty (Zevin, 1994; Fread et al., 1995; Office of Hydrology, 1996; Krzysztofowicz, 1997; Schaake and Larson, 1997; Fread, 1998; Graziano, 1998; Krzysztofowicz, 1998a,b; Schaake and Larson, 1998; Fread et al., 1999). The transition to stochastic forecasting will occur over the next 5-10 years, and the specific requirements which must be satisfied, the scientific and technological issues which must be resolved, and the associated development activities and operational testing necessary to support a national implementation, are specified in this QPI concept document.

The NWS MAR program provides a physical and technical support environment wherein greatly improved collaboration, coordination, communication, and integration are achieved between and within the hydrology and meteorology components of the NWS. The implementation of advanced remote sensing technologies, such as:

- the Weather Surveillance Radar 1988-Doppler (WSR-88D), also known as Next Generation Weather Radar (NEXRAD);
- the Automated Surface Observing System (ASOS);
- Doppler wind profilers;
- improved Geostationary Operational Environmental Satellites (GOES); and
- lightning detection networks;

provides a broader spectrum of observations at unprecedented temporal and spatial scales. The advent of advanced operational atmospheric and hydrologic data assimilation techniques and higher resolution, numerical-model based ensemble prediction and other statistical forecast systems will more effectively integrate and utilize these observations. These observational and modeling systems should provide improved quantitative precipitation estimate (QPE) and quantitative precipitation forecast (QPF) products (i.e, QPI) and hydrometeorological guidance to personnel at the Hydrometeorological Prediction Center (HPC) and the Storm Prediction Center (SPC) of the National Centers for Environmental Prediction (NCEP), Weather Forecast Offices (WFOs), and River Forecast Centers (RFCs). The implementation of the Advanced Weather Interactive Processing System (AWIPS) and its associated grid editing software, communications infrastructure, and local software applications should enable NWS field personnel to generate, coordinate, and issue more accurate, site-specific, and timely hydrometeorological forecast and warning products. Critical WFO AWIPS decision assistance and product preparation applications for assessing and predicting the areal potential for flash flooding and preparing watch and warning products include the WFO Hydrologic Forecast System (WHFS) (Roe et al., 1998) and the System for Convection Analysis and Nowcasting (SCAN) (Smith et al., 1998). These improvements, coupled with the implementation of the next generation NWS River Forecast System (NWSRFS), the Advanced Hydrologic Prediction System (AHPS), modernized Flash Flood Guidance (FFG), and stochastic and distributed hydrologic modeling at RFCs, should yield improved hydrometeorological services to the public in the modernized NWS (Office of Hydrology, 1996).

Figure 1: Flooding from Hurricane Fran at Point of Rocks, Maryland, on September 9, 1996, during flood crest. The flood stage is 16 feet and a crest of 36.33 feet was recorded. (Photo courtesy of Barbara Watson, NWSFO, Sterling, Virginia)

Fundamental to modernized NWS hydrometeorological operations, and in direct support of main-stem probabilistic river stage forecasting (PRSF) within AHPS, will be the generation and dissemination of value-added, QPFs/PQPFs through Day 3 by forecasters in the National Precipitation Prediction Unit (NPPU) of the Forecast Operations Branch (FOB) of HPC, WFO forecasters, and Hydrometeorological Analysis and Support (HAS) forecasters at RFCs. The HAS forecaster at the RFC will mosaic the QPF/PQPF products prepared by all WFOs whose forecast domain intersects an RFC's area of hydrologic responsibility. In fulfillment of this duty, and to ensure that spatially and temporally consistent QPFs/PQPFs are input into the NWSRFS, the HAS forecaster will coordinate and edit WFO QPFs/PQPFs to reconcile differences in the forecasts across the boundaries between WFOs. Considerable training will be required to effect this NWS-wide transition to stochastic forecasting.

1.2. Document Organization

This document first addresses in section 2, the process of establishing the operational requirements which define the roles, responsibilities and associated products for each component of the Modernized ETE Forecast Process for QPI. Section 3 provides a historical perspective and the current status of QPF in the NWS regions, while section 4 provides background information on pioneering NWS efforts to produce PQPFs and the details of current efforts to develop an AWIPS-compatible operational PQPF methodology and a probabilistic (stochastic) ETE framework.

Sections 5 through 10 specify the production of and/or the requirements for QPI, for each component of the ETE Forecast Process, necessary to satisfy end user requirements for hydrometeorological forecast and guidance products. The "production" refers to the output of the forecast component together with a discussion of how and why it is produced. The "requirements" pertain to what is needed by the NWS forecast component -- the input. Finally, section 11 describes current NWS verification procedures and outlines a framework and the requirements for a national verification program applied to every component of the forecast process, and section 12 summarizes the primary QPI forecast and hydrometeorological service goals of this plan. This QPI Concept document does not specifically address training requirements or aspects of the modernization which are more general in nature and are covered in other planning documents. A companion QPI implementation plan, which will incorporate the necessary forecaster and end user training, is currently being developed.

Figure 2: Flash Flood event in Cheyenne, Wyoming on August 1, 1985. Over six inches of rain fell in just more than three hours, turning Dry Creek into a raging torrent. The flood claimed twelve lives: ten were swept away in automobiles. (Photo courtesy of FEMA/ Wyoming Emergency Management Agency).

The production of QPI and its application within all components of the NWS ETE Forecast Process (i.e., NCEP, WFOs, and RFCs) along with the planned national production of PQPFs and hydrologic products, is a complex and largely new process of sufficient importance to warrant this document. This document is intended to complement other NWS documents, such as the "Hydrometeorological Service Operations for the 1990's" (Office of Hydrology, 1996) and the "Office of Meteorology 1996-2005 Strategic Operating Plan" (Uccellini, 1996a), and to provide details of the ETE Forecast Process for QPI, heretofore, not fully addressed. Further, this QPI Concept document will form the basis of a national implementation plan to be formulated over the next several months in coordination with the NWS components of the ETE Forecast Process for QPI.

1.3. Background and Impetus for Change

Measured in terms of socioeconomic impact, flash and river floods are one of the most devastating and deadly weather-related hazards. For the 30-year period ending in 1995, floods have claimed an average of 136 lives per year compared to 85 by lightning, 73 by tornadoes, and 25 by hurricanes (see table 1) (Office of Meteorology, 1997). Reductions in the number of fatalities associated with these natural hazards in recent years reflect the initial operational benefits derived from the NWS MAR. *However, the number of people impacted by floods and their economic cost continue to increase with industrialization and the increased inhabitation of flood-prone regions (National Research Council, 1996).* News reports of the human tragedy inflicted by floods are becoming increasingly more commonplace. More than 75 percent of all Presidential Disaster Declarations result from flooding, and several hundred thousand Americans are evacuated from their homes each year (NOAA, 1995). The average annual cost of flood damage during the 10-year period ending in 1997 (adjusted for inflation) exceeded 4.6 billion dollars, and this cost rose to an average in excess of 8 billion dollars for the latter 5 years of this period (F. P. Richards, 1998, personal communication). Just recently, flood damage resulting from The Northeast Flood of January 1996, The Northwest Flood of February 1996, The Western U.S. Flood of January 1997, The Ohio Valley Flood of March 1997, and The Red River of the North Flood of April 1997, exceeded one billion dollars each (F. P. Richards, 1998, personal communication). Floods impact all fifty states of the United States and occur all seasons of the year. Consequently, some of the most important public products issued by NWS field offices include flood and flash flood watches and warnings (by WFOs) and main-stem river forecasts (by RFCs). In light of these facts, and the increasing burden being shouldered by state and local officials to ensure public safety and mitigate the impact of flooding events, the NWS is actively engaged in activities to improve hydrometeorological services.

Table 1. Annual average loss of life directly attributable to hazardous weather. (Office of Meteorology, 1997)

Natural Hazard	*Annual Average Fatalities*		
	10-year Average (1986-1995)	*30-year Average (1966-1995)*	*50-year Average (1946-1995)*
Extreme Heat	133[1]	**[3]	**[3]
River / Flash Floods[4]	82	136	115
Lightning	68	85	127
Winter Storms[5]	49	**[3]	**[3]
Tornadoes	42	73	97
Extreme Cold	34[2]	**[3]	**[3]
Hurricanes	13	25	39

[1] The vast majority of heat-related deaths during this ten-year period (1,021 of 1,325) occurred in 1995.

[2] This value represents an 8-year average. Data on extreme cold-related fatalities are not available prior to 1988.

[3] Data are not available for this period.

[4] Beginning in 1988, data for flash and river flood floods were archived independently. These data reveal that for the eight year period ending in 1995, 72 percent of the flood-related deaths (471 of a total 655) have been caused by flash flooding.

[5] Winter storms represent the combined effects of heavy snow, blizzards, ice storms, and avalanches.

Precipitation is the most important observed and/or forecast input to the NWS's hydrometeorological forecast and warning operations although other parameters, such as temperature, potential evaporation, and snowpack, are also important. The routine generation and use of WSR-88D-based QPEs, QPFs, and probabilistic QPFs (PQPFs) in hydrologic models will improve flood prediction and warning (Davis and Drzal, 1991; NRC, 1991; Krzysztofowicz and Drake, 1992; Krzysztofowicz, 1993; Krzysztofowicz et al., 1993; Zevin, 1994; Krzysztofowicz, 1995; Office of Hydrology, 1996; NRC, 1996; Davis and Jendrowski, 1996; Office of Hydrology, 1997; Schaake and Larson, 1997; Davis, 1998; Graziano, 1998; Jendrowski and Davis, 1998; Krzysztofowicz, 1998a,b; Roe, et al., 1998; Schaake and Larson, 1998). Accurate and timely quantitative precipitation estimates and forecasts are critical for modernized NWS hydrometeorological operations and the production of WSR-88D-based QPEs and QPFs/PQPFs are slated to be a key element in future flood and flash flood operations. Additionally, QPEs and QPFs are critical for monitoring and forecasting heavy snowfall. Heavy snow events claim lives, cripple transportation, and often have a prolonged and profound economic impact (see figures 3 and 4) (Fair and Feit, 1978; Faich and Rose, 1979; Glass et al., 1979: Griffin, 1979; Helburn, 1982). Furthermore, through the subsequent release of its liquid water content, snowfall can have a significant impact on flood prediction, as evidenced by The Northeast Flood of January 1996 (NOAA, 1997a) where the rapid ablation of a significant snowpack exacerbated the impacts of a heavy rain event, yielding devastating results. Similarly, the recent and disastrous Red River of the North Flood of April 1997 was primarily the result of the rapid melting of a snowpack with an unusually high liquid water content, although the lead-time was much greater.

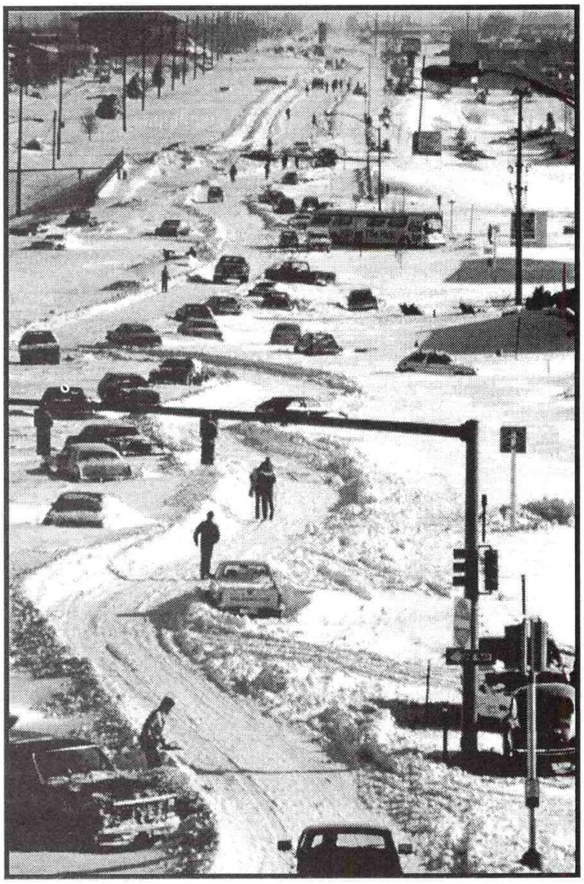

Figure 3: Heavy snow strands commuters in Denver, Colorado. On December 24, 1982, a blizzard dumped two to three feet of snow in the Denver metropolitan area bringing ground and air traffic to a halt, temporarily isolating the city from the outside world. (Photo courtesy of J. Wiesmueller, NWSFO Sterling, Virginia)

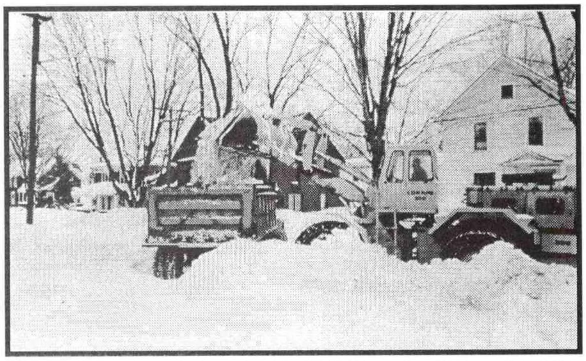

Figure 4: Snow removal activities in the wake of a significant winter storm (Photo courtesy of the American Red Cross)

1.4. Significance and Overarching Goals

In recognition of potential service benefits, improving QPFs has recently been identified as a top science priority of the NWS's Collaborative Science, Technology, and Applied Research (CSTAR) Program (Uccellini, 1996a; Uccellini, 1998), the United States Weather Research Program (USWRP) (Fritsch et al., 1998), and the World Weather Research Program (WWRP) (Carbone, 1997). Furthermore, the participating organizations collectively recognize that improving QPEs and QPFs is one of most significant challenges facing the NWS and the meteorological community over the next decade.

The CSTAR Program is the umbrella program for the NWS's collaborative applied research activities through programs such as the Cooperative Program for Operational Meteorology, Education and Training (COMET) Outreach Program (http://www.comet.ucar.edu/outreach/index.htm), NOAA Cooperative Institutes (CIs), governments labs, and smaller projects at local WFOs. The USWRP is an interagency research program whose goal is to improve the specificity, accuracy, and reliability of weather forecasts for disruptive, high impact weather. The agencies participating in the USWRP are NOAA, the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Office of Naval Research (ONR).

As detailed in this plan, 1) the technological benefits of the NWS MAR program combined with the operational implementation of applied research planned to be conducted under the auspices of the USWRP and the CSTAR Program, and 2) funding via the normal budget initiative process associated with the Advance Short Term Warning and Forecast Process, are necessary and should enable the NWS to modernize the ETE Forecast Process for QPI and achieve the following projected forecast goals:

5-Year QPI Goals

- Increase the skill of the Day 1 operational numerical weather prediction (NWP) model QPFs by 50 percent.
- Increase the skill of the Day 2 and Day 3 operational NWP model QPFs by one day (i.e., increase skill of Day 2 QPF to current Day 1, and increase skill of Day 3 to current Day 2).
- Add value to the operational NWP model QPFs at each subsequent step of the NWS ETE Forecast Process (i.e., HPC, WFOs, RFCs).
- Introduce forecaster-prepared, value-added probabilistic QPFs (PQPFs) through Day 3 for use in AHPS[1].

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[1] *The introduction of PQPFs will be focused on, but not limited to, HPC and WFOs which support RFCs utilizing AHPS.*

- Improve the nationally-averaged lead time of flash flood warnings by more than 30 percent (from 45 minutes[2] to 60 minutes).

Meeting these QPI goals will impact each component of the forecast process and place new requirements on their associated partners (i.e., RFCs, WFOs, HPC, Statistical Guidance, NWP models, observations). Associated service goals, also based upon USWRP and CSTAR Program applied research and ASTWF funding, and achievable via the integration of these research benefits into AWIPS and the implementation of a Modernized ETE Forecast Process which includes AHPS, are projected to be as follows:

10-Year Hydrometeorological Service Goals

- Introduce AHPS short- through long-range site-specific, probabilistic river stage forecasts (PRSFs) at RFCs utilizing value-added PQPFs[3].

- Prepare, issue, and verify PQPFs and hydrologic forecast and warning products at WFOs nationwide.

- Extend the range of forecaster-prepared, value-added QPFs/PQPFs produced by the HPC and WFOs and assimilated by the RFC, through Day 3[4].

- Provide improved and expanded centrally-produced Model Output Statistics (MOS) QPF/PQPF guidance products based on operational NWP models, including global and regional ensembles.

- Implement statistically-based models, expert systems, and other techniques on AWIPS to provide high resolution, short-range, statistical QPF/PQPF guidance products. These guidance products, coupled with advanced decision assistance and product preparation tools such as SCAN and WHFS, will enable WFOs to more accurately and efficiently assess and predict the areal potential for flash flooding.

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[2] *Nationally-averaged lead time for flash flood warnings issued in 1997 (Paul Polger, personal communication, 1998)*

[3] *National implementation of AHPS is contingent upon the approval and continuance of funding. The transition to probabilistic river forecasting is contingent upon 1) the implementation of AHPS, 2) the development, successful testing, documentation, and implementation of methodologies which produce short-range PRSFs and accurately quantify and account for hydrologic uncertainties, and 3) regional risk reductions wherein a quantitative assessment of associated resource requirements is conducted to ensure enhanced services can be provided with projected staffing and computational capabilities.*

[4] *The incremental extension of the range of forecaster-prepared QPFs/PQPFs (from Day 1 to Day 2, and from Day 2 to Day 3) is contingent upon forecaster skill exceeding that of the operational NWP models by an amount to be specified by the HIWG in the forthcoming companion implementation plan.*

- Implement improved data assimilation techniques, improved and higher resolution regional mesoscale NWP models, regional and stormscale NWP models, and a regional ensemble prediction system at the Environmental Modeling Center (EMC) of NCEP.

- Expand the real-time use and integration of QPEs, based on various sources of in situ and remotely sensed data, utilizing continuing advances on verifying, optimally merging, and quality controlling gage, radar, and satellite estimates.

- Improve the real-time access, integration, and utilization within AWIPS of surface rain gage data, and data from new and improved observing technologies.

- Implement 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 ETE Forecast Process. Verification data will be utilized to ensure the ETE Forecast Process represents the most efficient use of resources to produce quality QPI for hydrologic services.

1.5. Scientific and Technical Issues

Improving QPFs and QPEs and achieving the aforementioned forecast and service goals represents a significant challenge which requires that the operational and research communities be engaged through the CSTAR Program and the USWRP. The provision of improved QPEs, QPFs and hydrometeorological services requires progress on a spectrum of scientific and technological issues which include:

Observational

- improving the measurement of atmospheric water vapor, wind (momentum), and temperature (mass) profiles,

- developing improved strategies for targeted observations,

- developing automated satellite-based, high resolution, multi-sensor, -channel precipitation estimates for the full spectrum of precipitation producing phenomena (including cold and warm top convection, winter storms, tropical storms, lake effect snow and stratiform cloud systems),

- developing techniques to verify, optimally merge, and quality control in situ and remotely sensed data (e.g., gage, radar, and satellite) for precipitation estimation, *Physical Understanding*

- expanding our understanding of the dynamics of mesoscale convective systems,

- heightening our understanding of cloud microphysical and atmospheric boundary layer processes, and land surface-atmospheric interactions,

Modeling

- developing improved data assimilation techniques, including operational 3- and 4-D variational methodologies,

- improving the parameterization of boundary layer and cloud turbulent and microphysical processes,

- developing enhanced meso- and storm-scale NWP models,

- developing an operational regional short-range ensemble forecasting system (SREF) by determining 1) the sources and relative magnitude of forecast uncertainties and appropriately accounting for these uncertainties, and 2) the optimal combination of ensemble size (i.e., the number of members), model (grid) resolution, model configuration (i.e., variations in model physics and parameterizations), and ensemble composition (i.e., single vs. multiple models) given limited computing resources,

- developing improved techniques for precipitation forecasting in complex terrain where there are a relatively small number of predominantly low elevation observations, and where there is a propensity for more frequent and heavier precipitation events to occur at higher (vs. lower) elevations (these techniques include improved NWP models, simplified models [Rhea, 1998], and statistical methods [e.g., MOS]), and

Techniques

- developing and implementing within AWIPS point and grid initialization, editing, and display capabilities which support the preparation, coordination, and verification of QPFs at all steps of the NWS ETE Forecast Process (see section 2.3.3).

Several additional scientific and technical issues must be resolved prior to implementing a probabilistic ETE hydrometeorological forecast system. These scientific and technological issues include:

Statistical/Modeling

- quantifying and accounting for QPE and QPF uncertainty,

- developing an improved error model to account for the uncertainties in hydrologic modeling,

- determining the effective scale of value-added PQPFs and the developing techniques to downscale these forecasts for input to NWSRFS,

- generating precipitation probability distributions and ensembles of precipitation time series for each NWSRFS mean areal precipitation (MAP) area (MAP areas represent the resolution of the data entered into NWS operational river forecast models),

- developing techniques to derive PQPFs from NCEP global and regional ensembles at hydrologically-relevant spatial and temporal scales,

- developing a methodology to improve the incorporation of climate outlooks/forecasts into long-range hydrologic predictions,

- developing statistical techniques to compensate for biases in the NWP model ensemble-based outputs, to ensure forecast probabilities are well calibrated,

- developing an improved and expanded operational MOS system which provides short-through medium-range QPF guidance to support HPC, WFO, and HAS forecasters (including a transition from point to gridded MOS QPF guidance for all operational NWP models, and an exploration of the utility of alternative and advanced statistical processing techniques),

- developing and implementing within AWIPS statistically-based models, expert systems, and other techniques to provide high resolution, short-range (i.e., 0-6 hour) PQPFs and an automated means of translating these forecasts into probabilities of flash flood occurrence,

- developing appropriate measures of the skill of probabilistic forecasts (i.e., bias, informativeness, etc.),

Techniques

- developing and implementing within AWIPS an operationally efficient methodology for forecasters to specify value-added PQPFs at all steps of the NWS ETE Forecast Process,

- mosaicking QPFs/PQPFs at the RFC,

Service

- performing a quantitative assessment of the resources required to implement PQPF and PRSF methodologies/techniques to ensure enhanced services can be provided with projected staffing and computational capabilities,

- specifying probabilistic hydrometeorological product formats appropriate for a diverse user community,

- developing a flood warning decision system and a user response system, and

- developing and delivering appropriate training to forecasters and end users.

1.6. Applied QPI Research

In October 1996, the USWRP convened Prospectus Development Team (PDT) 8 to identify and delineate emerging research opportunities to improve QPE, QPF, and the hydrological aspects thereof. The PDT 8 meeting summary (Fritsch et al., 1998) is consistent with and expands upon the aforementioned scientific issues and details applied research necessary to improve operational QPE and QPF techniques. Additionally, in January 1998, the USWRP convened PDT 9 to identify and delineate critical scientific and technological issues related to linkages among precipitation estimation, QPF, catchment runoff, and other land surface processes in a coupled meteorological/hydrological framework (Kelvin Droegemeier and James Dungan Smith, personal communication, 1998). While a modest level of USWRP and CSTAR funding has been made available for research on QPI, resolving these technical and scientific issues requires a sustained, aggressive, and expanded applied research effort conducted under the auspices of these programs. Under the auspices of the CSTAR Program, the NWS and the University of Virginia (UVA) are collaboratively developing prototype 1) methodologies and associated software applications which enable forecasters to generate experimental value-added PQPFs and PRSFs, and 2) advanced flood forecast/warning decision assistance tools. Furthermore, the NWS is collaborating with the Research Applications Program (RAP) of the National Center for Atmospheric Research (NCAR), the National Severe Storms Laboratory (NSSL) and Forecast Systems Laboratory (FSL) of the Office of Oceanic and Atmospheric Research (OAR), and the National Environmental Satellite Data and Information Service (NESDIS) to develop SCAN. SCAN is a series of integrated, AWIPS-compatible, advanced software applications to detect, analyze, and monitor convection and generate short-range probabilistic forecasts and warning guidance for flash floods and other hazardous weather (Smith et al., 1997; Smith et al., 1998; also see sections 2.3.4 and 8.3, and the SCAN home page at http://tgsv5.nws.noaa.gov/tdl/scan /scan2.html). NWS SCAN team members include personnel from the Office of Systems Development (OSD), the Office of Meteorology (OM), the Operational Support Facility (OSF) of the Office of Systems Operations (OSO), the Office of Hydrology (OH), the Storm Prediction Center (SPC) of NCEP, the Sterling, VA NWSFO (LWX) of the Eastern Region, and the Modernization Systems Management (MSM) Office.

Improved quantitative precipitation estimation, integrating WSR-88D, rain gage and satellite data, is the basis for enhanced use of QPEs at all levels of the NWS for a broad spectrum of applications. These applications include:

- the initialization, calibration, and verification of atmospheric, hydrologic, and statistical models,

- the calibration of observing systems,

- flood and fire weather forecasting, and

- a national verification program which includes NCEP, RFC, and WFO value-added QPFs.

The Hydrologic Research Lab (HRL) of OH, the EMC of NCEP, and the OSF of OSO, have developed and continue to conduct applied research to improve radar-based operational rainfall estimation techniques and their utilization (Shedd and Smith, 1991; Smith and Krajewski, 1991; NWS, 1993a,b; Lin et al., 1994; Fread et al., 1995; Baldwin and Mitchell, 1996a; Baldwin and Mitchell, 1996b; Lin et al., 1996a; Lin et al., 1996b; Seo, 1998a; Seo, 1998b; Seo, 1998c; Baldwin and Mitchell, 1997; Kuligowski, 1997; Lin et al., 1997; Breidenbach et al., 1998; Fulton et al., 1998; Miller et al., 1998; O'Bannon, 1998; Seo et al., 1998). QPEs, and their level of processing and data integration, are a function of the platform and users involved. The precipitation processing levels called "Stages" of precipitation processing, are delineated with Roman numerals and are briefly described in Table 2. For further details, see "Hydrometeorological Service Operations for the 1990's" (Office of Hydrology, 1996) and Seo et al. (1998). The NWS is currently collaborating with NESDIS to develop and validate improved satellite-derived rainfall estimates for inclusion in the multi-sensor Stage II-IV analyses.

1.7. Status of the NWS Modernization

In an additional but distinct reference, the MAR process has embraced the concept of 'Stages', which are delineated with Arabic numerals. Stage 1 was characterized by changes in operations and services related to new observing technology, specifically NEXRAD (WSR-88D) and ASOS. Weather Service Forecast Offices (WSFOs) or Weather Service Offices (WSOs) that accepted WSR-88Ds are termed NEXRAD WSFOs (NWSFOs) or NEXRAD WSOs (NWSOs). During Stage 1, County Warning Areas (CWAs) and Hydrologic Service Areas (HSAs) were realigned, and some limited reassignments of forecast responsibility from NWSFOs to NWSOs were made. Stage 1 is complete and MAR Stage 2 has commenced with the incremental deployment of AWIPS. NWSFOs and NWSOs are beginning to incorporate AWIPS into their operations. MAR Stage 2 will be complete when AWIPS, and end state staffing profiles are implemented at all field offices. Full implementation of the products and enhanced services outlined in this QPI Operations Concept document -- particularly the production of probabilistic QPF and flood forecast products -- require full MAR Stage 2 capabilities, the routine provision of expanded NCEP and TDL guidance, and the national implementation of AHPS.

Table 2. Current and planned capabilities and products associated with Stages I - IV of precipitation estimation processing (Office of Hydrology, 1996; Breidenbach et al., 1998; Fulton et al., 1998; Seo et al., 1998). Full operational implementation of these capabilities requires the national implementation of AWIPS.

Stage I	Precipitation estimation and processing are performed automatically on the WSR-88D Radar Product Generator (RPG) by the Precipitation Processing Subsystem (PPS). Stage I PPS products include: 1) the Hourly Digital Precipitation (HDP) product, in 256 levels (i.e., 8-bit) available every WSR-88D volume scan on the 4 km Hydrologic Rainfall Analysis Project (HRAP) grid (Schaake, 1989); 2) graphical one-hour, three-hour, storm total, and user-selectable (between 2 and 30 hours) total precipitation accumulation products, available every WSR-88D volume scan in 16 display levels (i.e., 4-bit) on a 2 km x 1 degree polar grid; 3) the alphanumeric Supplemental Precipitation Data (SPD) product containing a listing of PPS adaptable parameter settings and radar-gage pairs; and 4) the Digital Hybrid-Scan Reflectivity (DHR) Product (which can be converted to precipitation amount), available every volume scan on a 1 km x 1 degree polar grid. In the future, and contingent upon the operational implementation of the Open RPG (ORPG), rain gage data will be used to reduce the bias of the local WSR-88D-based precipitation estimates. These products are disseminated to all WSR-88D users.
Stage II	Precipitation estimation is performed either automatically or manually at WFOs and RFCs on the AWIPS platform. Stage II is referred to as Multi-sensor Precipitation Analysis and utilizes both the Stage I-produced HDP product and gage data. Stage II products represent 1 hour precipitation accumulations, valid on the hour, and include: 1) a gage-only, HRAP-gridded precipitation analysis; 2) a mean-field, bias-adjusted, HRAP-gridded HDP product; and 3) a multi-sensor, radar-gage HRAP-gridded precipitation analysis based upon the mean-field, bias-adjusted HDP product and gage data. In the future, the multi-sensor Stage II precipitation analysis will utilize GOES Infrared (IR) satellite data, in conjunction with NWP model temperature analyses, to help identify rain/no rain areas and mitigate the adverse impact of ground return anomalous propagation. The Stage II products are available locally and to other designated users.
Stage III	Stage III precipitation analysis is performed at the RFC, and Stage III products are RFC-wide mosaics of the aforementioned hourly Stage II products. WSR-88D data in regions of "overlapping" coverage are composited utilizing rules coded into the Stage III algorithm. HAS forecasters at the RFC provide interactive quality control (see section 5.3.1). The Stage III mosaic is used to compute mean areal precipitation (MAP) amounts for hydrologic basins, and these data are available for input into the NWSRFS. Stage III products are available in both gridded and graphical formats. Pending the national implementation of AWIPS, Stage III products will be routinely disseminated by RFCs to other NWS users such as the WFOs, and the HPC and EMC of NCEP.
Stage IV	The EMC of NCEP will mosaic the hourly Stage III products from all of the RFCs into a national precipitation analysis (NPA) (see http://nic.fb4.noaa.gov:8000/research/gcp/hdpprec.html for the pre-AWIPS experimental Stage IV product). The Stage IV mosaic, or NPA, will be used at NCEP for NWP model initialization and verification, and will disseminated via AWIPS back to WFOs, RFCs, and other designated users.

2.0. Establishing Requirements

2.1. The End-to-End Forecast Process

The ETE Forecast Process defines the steps in the forecast process, beginning with observations and culminating with the delivery of forecast and warning products to the end user. It should be noted that forecast products and guidance, generated at many of the steps in the Forecast Process, are an end in themselves (see figure 5).

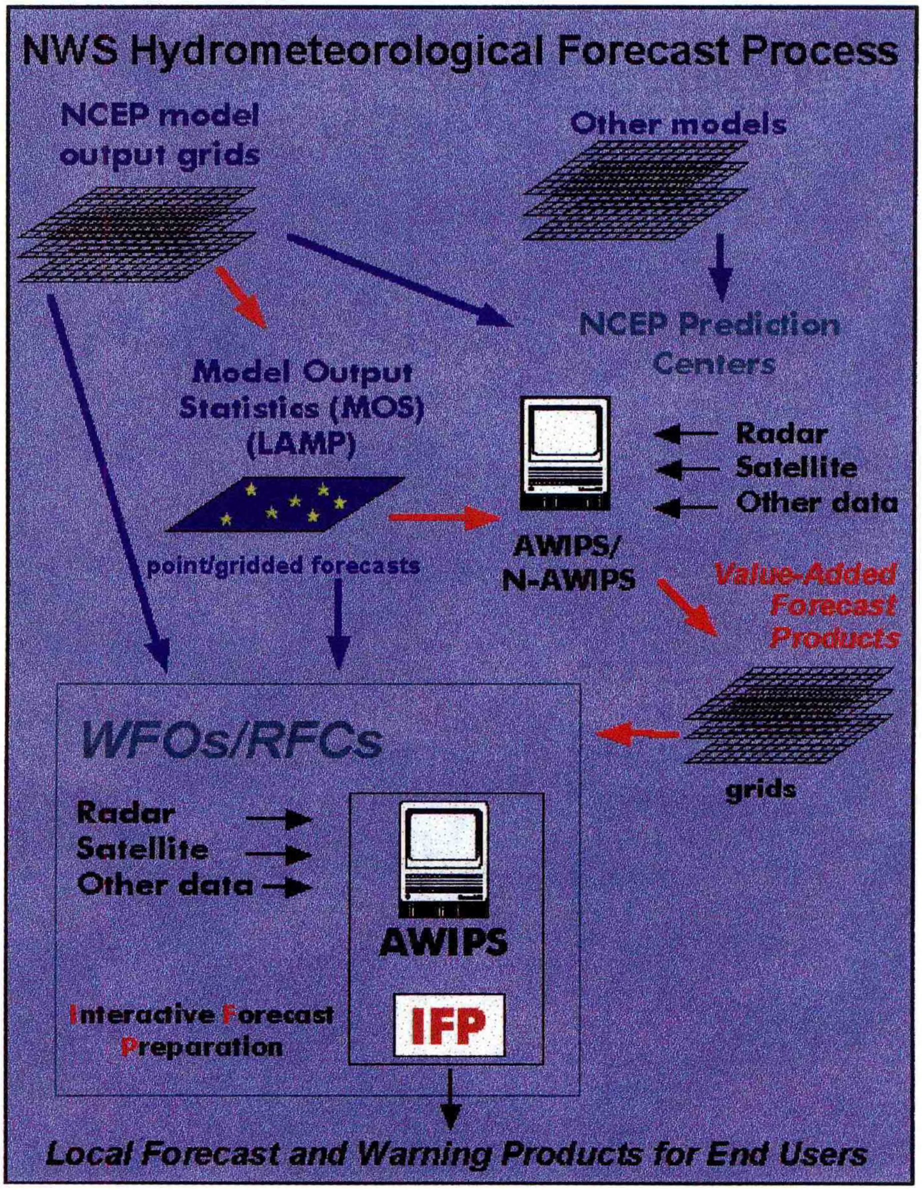

Figure 5: Graphical representation of the data and product flow required to support the modernized NWS ETE Forecast Process (from Uccellini, 1996a).

The fundamental steps or components of the NWS ETE Forecast Process are (Uccellini et al., 1995; Uccellini, 1996a; Wernly and Uccellini, 1998):

- 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 improved NCEP model-based data assimilation systems;
- The application of NCEP global, regional, mesoscale atmospheric models and ensemble prediction systems;
- The generation, dissemination, and use of model output statistics;
- The generation and dissemination of national forecast and guidance products from the NCEP service centers;
- The production and dissemination of local meteorologic and hydrologic forecasts, watches, and warnings at WFOs that are applied to public, aviation, marine, and fire-weather services;
- The production and provision of hydrologic and flood guidance to the WFOs by the RFCs; and
- The WFO coordination of all life-threatening forecast and warning products with emergency managers and other end users.

Recognizing that service requirements are defined by a diverse NWS user community, a requirements concept is applied by inverting the ETE Forecast Process and systematically working in reverse order from the user through the forecast components to observations. This requirements concept can be utilized to:

- evaluate and define operational requirements and a service concept for all forecast components;
- identify key science, technology, and product development issues and focus resources toward their effective resolution; and
- define and establish collaborative applied research efforts within the NOAA and with the meteorological community that focus on specific, high priority service issues.

2.2. Requirements from a Diverse User Community

Increasingly, users such as emergency managers (EMs), and other state and local officials are recognizing and articulating a need for hydrometeorological guidance products which quantify forecast uncertainty. The Urban Drainage and Flood Control District (UDFCD) of Denver/Boulder, CO has used QPFs since the early 1980's to predict flood potentials and provide watch/warning notifications for the local metropolitan area (Stewart, 1995). Beginning in 1990, with input from the local EMs, the UDFCD incorporated the use of more detailed PQPFs which are now routinely anticipated by decision-makers. Using the UDFCD program as a model, the Flood Control District of Maricopa County, serving the Phoenix, AZ metro area, now uses PQPFs to support daily operations. Many cities and counties in California have been using NWS QPF products for some time. More recently, a number of CA local governments like Ventura, Santa Barbara, Orange County, Los Angeles County, and others have contracted with private meteorological services to provide PQPFs. Obtaining PQPFs and other hydrometeorological products from the private sector is gaining popularity (Henz, 1997), particularly among entities who have already made a substantial investment by installing automated local flood detection and early warning systems (e.g., Dallas, Houston and Austin, TX; the Lower Colorado River Authority [LCRA]; Tulsa, OK; Las Vegas, NV) (Kevin Stewart, personal communication, 1997). PQPFs and PRSFs 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 (Zevin, 1994).

Recommendations and findings published in the Natural Disaster Survey Reports for The Great Flood of 1993 (NOAA, 1994) (see figures 6 and 7), The Northeast Flood of 1996 (NOAA, 1998a), and The Northwest Flood of 1996 (NOAA, 1998b), and Service Assessments of The Ohio River Valley Flood of March 1997 (NOAA, 1998c) and The Red River of the North 1997 Floods (NOAA, 1998d), highlight the need to provide and/or explore the utility of probabilistic hydrometeorological forecast products. Measured in terms of economic and human impact, these floods are recognized as some of the most devastating floods in modern U.S. history. 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.

At a NWS Emergency Management Forum, held March 1-3, 1995 in Arlington, VA, a broad national spectrum of user groups from the emergency management, transportation, public works, law enforcement, public safety, flood plain management, and fire service communities engaged in discussions with NWS managers and formulated recommendations designed to maximize the benefits of the NWS MAR. For warning coordination and decision making, these recommendations included the following (Adams, 1995):

- Critical information must be presented in a probabilistic manner to help emergency managers make a more accurate analysis of the risk associated with each event;

- QPFs and PQPFs should be issued nationwide; and

- Forecasts should include the full range of possible severity as well as the level of certainty associated with each forecast.

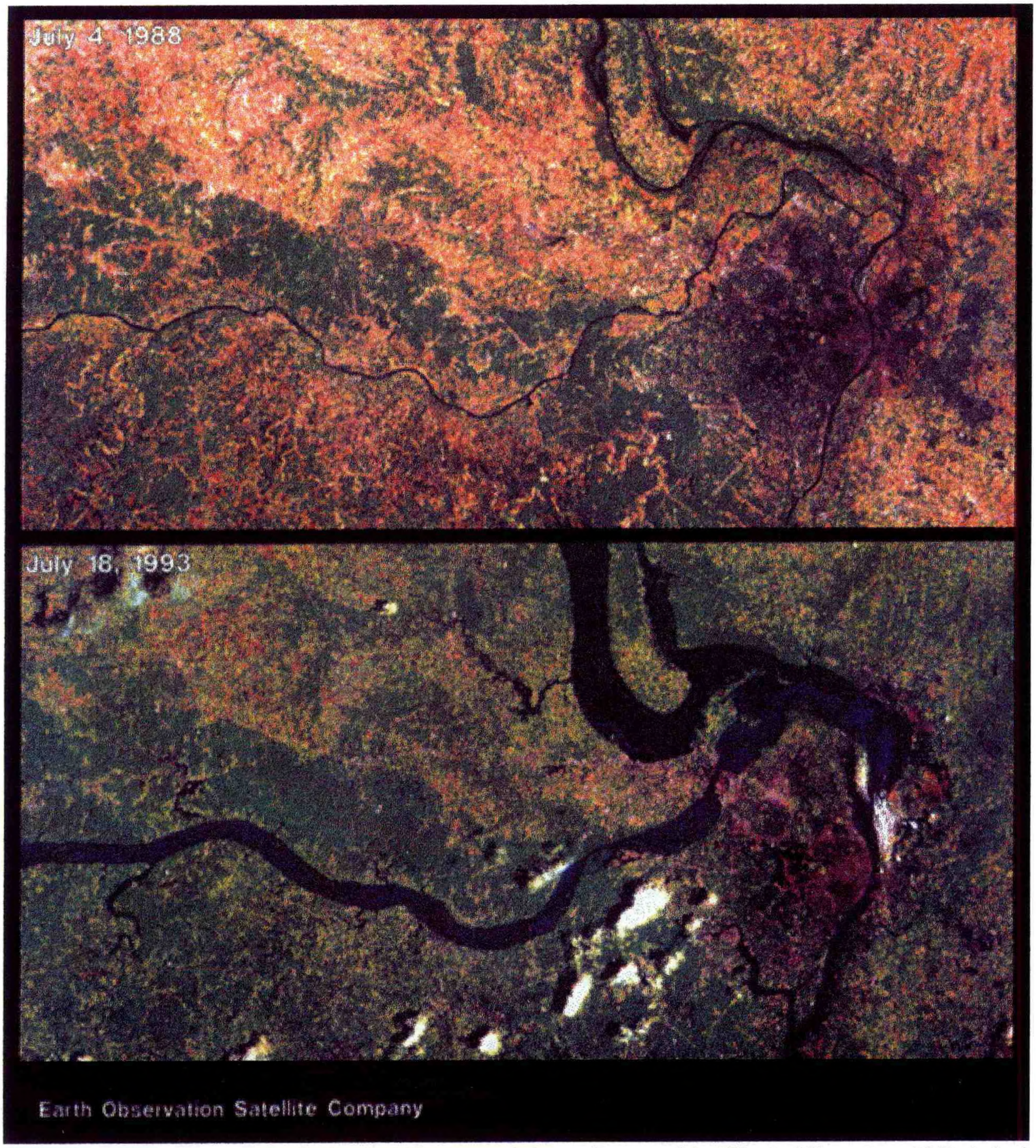

Figure 6: Landsat image of the St. Louis, MO, area and the confluence of the Illinois, Missouri, and Mississippi Rivers. The top image was created from data collected on July 4, 1988, during a severe drought at near peak conditions. In contrast, bottom image depicts the same area during near peak flood conditions on July 18, 1993, during the Great Flood of 1993 (photo courtesy of Space Imaging and Earth Observation Satellite Company, Lanham, MD).

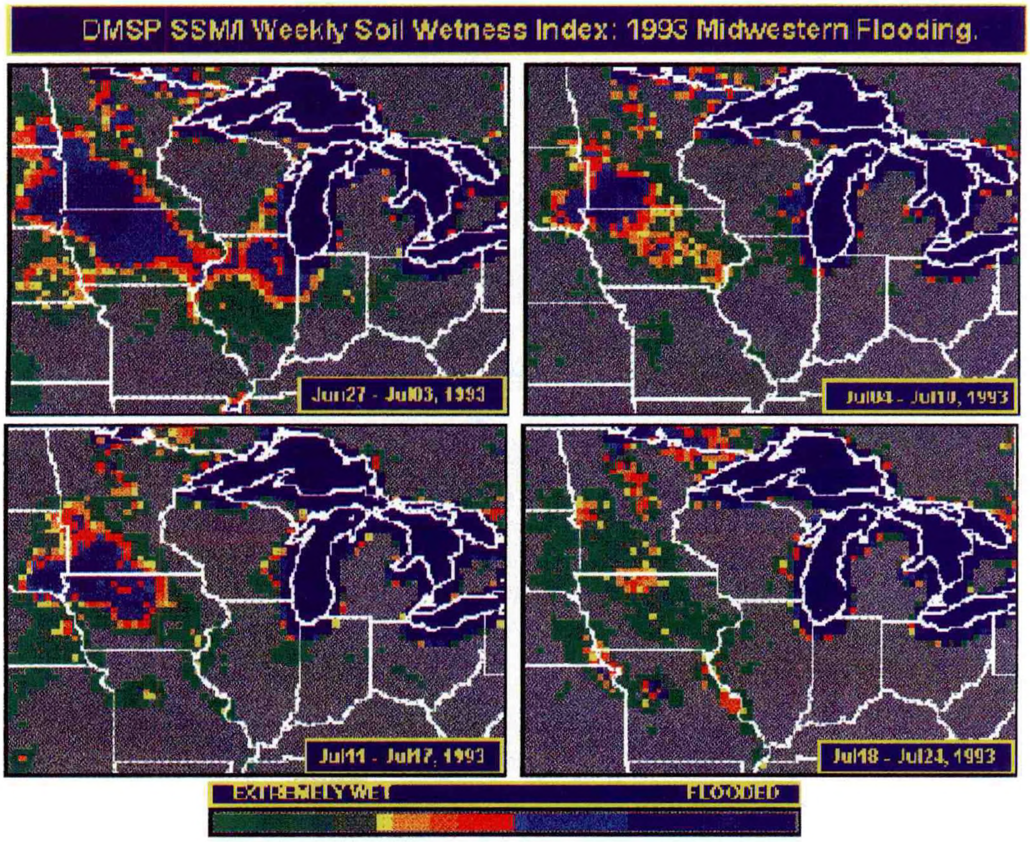

Figure 7: Weekly composite time-series of the Soil Wetness Index (SWI) over the Midwest U.S. during June/July 1993. Large areas of the Midwest experienced the worst flooding on record due to excessive precipitation during the late spring and summer of 1993. The NOAA Experimental SWI was used to monitor the areal extent of the flooding. Progressively wet ground conditions are depicted in shades of green, red, and blue, respectively. Flooded or puddled land surfaces and large water bodies are depicted in shades of blue. The SWI uses data from the Special Sensor Microwave/Imager (SSM/I) on board the Defense Meteorological Satellite Program (DMSP) F-10 and F-13 series of polar orbiting satellites (image courtesy of Rao Achutuni, NESDIS).

At the Arlington NWS Emergency Management Forum, Dr. Elbert W. Friday, Jr., the former NOAA Assistant Administrator for Weather Services, delivered a speech entitled "Modernization of Weather and Flood Warnings." In support of these and other recommendations, Dr. Friday reaffirmed that "The goal of the NWS Modernization and Associated Restructuring is to enhance our ability to protect life and property from hazardous weather and flooding." Dr. Friday further stated that "The Hurricane Program provides an example as a leader in providing critical information in concert with established user decision methodologies including forecasts, quantification of forecast uncertainty, and community action plans. Our goal is to replicate this systematic methodology across the Nation for all hazards." This QPI Concept document directly supports this important NWS goal.

The requirement for probabilistic hydrometeorological forecast products and guidance was stated again by users at several other national forums. A diverse group of users at the June 8-9, 1995, Baltimore, MD, meeting of the National Hydrologic Warning Council (NHWC) (C. R. Adams, 1996, personal communication) and the NWS-sponsored Fifth National Heavy Precipitation Workshop (HPW) held in State College, PA, during September 9-13, 1996, communicated their requirements for probabilistic hydrometeorological forecast information. At the Fifth National HPW, representatives from the NHWC, the Tennessee Valley Authority (TVA), the Connecticut Department of Environmental Protection, the Bureau of Reclamation (BOR), Weather Services International (WSI) Corporation, and the United States Army Corps of Engineers (USACE) discussed their requirements for QPI and river and flood guidance in support of emergency management, transportation, and water use. During presentations and panel discussions, emergency management representatives stated their concerns and needs with regard to public safety and property loss due to river flooding and small stream flash flooding as well as to dam safety. Transportation officials voiced concerns over the impact of flooding on both waterway travel and surface auto/truck and train travel, while water resource managers enumerated their responsibilities -- requiring NWS hydrometeorological guidance -- which include the generation of hydroelectric power, public recreation, and domestic agricultural, industrial, and household water consumption. The TVA has conducted projects wherein PQPFs have been utilized for hydroelectric power generation (Arnwine and Whitlock, 1995; Bulluck, 1995). This diverse group of users collectively articulated a need for PQPFs and probabilistic river and flood forecasts to assist them in their respective decision-making processes. Furthermore, representatives of the water resource management community articulated their need for short- through long-range probabilistic river forecasts at the Workshop on Climate Variability and Water Resource Management in the Southeastern U.S., held in Nashville TN from June 25-27, 1997. This workshop was one of many regional workshops initiated by the U.S. Global Change Research Program (USGCRP), and was sponsored by NASA, the United States Geological Survey (USGS), and NOAA (USGCRP, 1997; http://wwwghcc.msfc.nasa.gov/regional/assessment_national.html). Water resource managers stated that risk-based forecasts, which account for the uncertainty in future atmospheric and land surface events, will enable them to determine the most effective means of utilizing water resources and operating water systems. The provision of this short- through long-range information is particularly important given that the demand for water for domestic hydropower, industrial, and agricultural applications is beginning to exceed its available supply in some regions of the country. The requirement for probabilistic hydrometeorological forecast products and guidance was most recently stated by a spectrum of users at the 1997 Second National Conference and Exposition of the National Hydrologic Warning Council incorporating the Tenth Annual Conference of the Southwestern Association of ALERT Systems (SAAS) held in St. Louis, MO, from October 29-31, the 1998 American Meteorological Society (AMS)-sponsored Special Symposium on Hydrology held in Phoenix, AZ from January 11-16 (Koellner, 1998), and the 1998 NWS Modernized Product Development Workshop held in Boulder, CO from September 1-3.

In the spring of 1995, NOAA contracted the NWS Modernization Committee (NWSMC) of the Commission on Engineering and Technical Systems of the National Research Council (NRC) to perform a comprehensive evaluation of the plans, progress, and needs for change or improvement in the hydrologic and hydrometeorological products and services of the modernized NWS (NRC, 1996). In the summer of 1995, the NRC authorized the NWSMC to conduct this analysis and produce a report. Specific NWSMC recommendations regarding the production and use of QPFs included (NRC, 1996):

- "Incorporation of improved QPFs and associated uncertainties into the hydrologic models for short-range and long-term streamflow forecast is essential and requires collaborative scientific investigation by the NWS and the academic community" (p.21), and

- "The NWS should accelerate its fledgling efforts to redesign, develop, evaluate, and verify QPFs and PQPFs and assess their use in hydrologic forecast models across a range of geographic and seasonal conditions" (p.22).

Recent events have clarified and clearly illuminated an emerging need of the user community -- future NWS hydrometeorological guidance products should quantify the forecast uncertainty and convey risk.

The NWS is planning to satisfy the nationwide user requirement for hydrologic forecast products which quantify the degree of forecast uncertainty based on a transition to the routine generation of PQPFs and PRSFs. With the exception of the Pacific Region (PR) of the NWS, all NWSFOs routinely generate QPFs and provide them to their servicing RFCs to generate site-specific main-stem river forecasts (Note: Although NWSFO Honolulu, HI routinely generates QPFs, they do not provide them to the Alaska River Forecast Center [AKRFC] since NWSFO Honolulu does not require nor issue main-stem river forecasts).

2.3. The Hydrometeorological Information Working Group

The Hydrometeorological Information Working Group (HIWG), with NOAA intra-agency representation, was established by the NWS in 1990 with the specific charge to:

- establish and update operational requirements for QPE, QPF, and observational data in support of river and flash flood forecasting; and

- define the roles, responsibilities, and relationships of the components of the End-to-End Forecast Process for QPI.

The HIWG is chaired by OM and membership includes representatives from the NWS Regions, OSD, OH, NCEP, and NESDIS. Past meetings of the HIWG, and subsequent contributions from team members, have yielded considerable insight into the QPI problem. This input was used to construct the original version of this document in 1992 which was later revised in 1994. This QPI concept document was largely constructed from the input of current HIWG members during and subsequent to their July 1996 meeting (see section 2.3.1). Additional input was derived from follow-on meetings attended by HIWG members and other key personnel. These follow-on meetings, described in forthcoming sections, were necessary to clarify and expand upon critical hydrometeorological service-science issues.

2.3.1. The July 1996 HIWG Meeting

In response to the aforementioned user requirements, and to further define and update the ETE Forecast Process for QPI, the HIWG was reassembled for a three and one-half day meeting in July 1996 in the Office of Meteorology at NWS Headquarters. Key initiatives for which requirements were specified during the OM-sponsored July 1996 HIWG meeting include:

- Improve the accuracy, reliability, resolution, and availability of gridded numerical model and value-added QPFs/PQPFs;
- Utilize AWIPS point and grid editing and display capabilities for the preparation, coordination, and verification of QPFs/PQPFs;
- Effect a nationwide transition from the current generation of deterministic QPFs to the routine generation of QPFs/PQPFs for probabilistic river stage and flood forecasting;
- Extend the range of HPC and WFO value-added QPFs/PQPFs through Day 3 nationwide using available guidance as an initial forecast, particularly beyond Day 1;
- Assess the number and increase the availability of hourly, real-time, all-season, rain gage observations;
- Improve the accuracy, reliability, geographic scope, temporal resolution, and accessibility of satellite-derived QPEs;
- Develop techniques to verify and optimally merge radar, rain gauge, and satellite-derived QPEs, and provide for the real-time accessibility of an integrated ground validation analysis throughout all local (WFO), regional (RFC), and national (NCEP) service centers; and
- Establish a National Verification Program to assess the value-added by each component of the ETE Forecast Process for QPF and PQPF.

Key service-science issues which arose in support of these initiatives include:

- What is the most efficient, prudent, and scientifically sound means of achieving the transition from pre-modernized, deterministic QPF operations at all NWS field offices to a probabilistic framework?

- What is the most effective and expedient means of developing and implementing QPF/PQPF software for use in NWS field offices?

- What are the explicit PQPF and PRSF methodologies (and associated product formats) to be implemented nationally?

- Given that current estimates indicate that WFOs are staffed to support the generation of value-added 24-hour QPFs/PQPFs, how will the requirement for 0- to 72-hour value-added QPFs/PQPFs be satisfied?

- What will be the role of NCEP central guidance in the support of WFO/RFC 72-hour QPFs/PQPFs?

- When and by what means will probabilistic QPF guidance be generated for most, if not all, operational NCEP models (ensembles and MOS)?

- What is the optimal combination of single high resolution regional NWP model with a regional ensemble given limited computing resources?

- How will the NWS satisfy the operational requirement for high temporal and spatial resolution, observational- and model-based, short-range probabilistic QPF guidance for flash flood forecasting?

Beginning with the previously established user requirements for QPFs, PQPFs, and probabilistic river and flood guidance, and utilizing the ETE Forecast Process concept as a template, the HIWG specified and updated QPI requirements for each of the NWS forecast components. A comprehensive list of requirements for the ETE Forecast Process was established for QPE/QPF, which support a transition to probabilistic forecasting. HIWG discussions yielded a number of recommendations and a strategy which specifically support these initiatives and address these operational issues. These QPI requirements, and the collective input and recommendations provided by current and previous HIWG members, serve as the framework for this QPI Concept document. Implementation time lines were constructed, in coordination with the appropriate NWS and NESDIS components, which specify how and when many of these HIWG requirements will be satisfied. These time lines will be presented in the forthcoming companion QPI Implementation Plan.

2.3.2. The September 1996 Fifth National Heavy Precipitation Workshop

To further clarify and expand upon requirements and critical service-science issues associated with the ETE forecast process for QPI, the Office of Systems Development and the Office of Meteorology organized and conducted the NWS-sponsored Fifth National Heavy Precipitation Workshop. The workshop was held in State College, PA from September 9-13, 1996. More than 150 participants, including representatives of the end user community (see section 2.2), NWS, NESDIS, OAR, and academia engaged in discussions designed to address the following issues:

- What is the mission of the NWS Hydrologic Services Program and the future role of quantitative precipitation forecasts?
- What is the ETE Forecast process for hydrometeorological forecast products and services, and how must it be modernized to support the requirements of the diverse user community?
- What is the mission of the U.S. Weather Research Program, what are its research foci, and what role can it play in defining and resolving critical QPF science issues?
- What are the end user requirements and applications of hydrometeorological forecast products?
- What are the socioeconomic impacts and benefits of NWS products and services?
- What are the plans of the NWS Regions for implementing improved and expanded QPF products?
- What are the operational requirements for centrally- and locally-produced QPE and QPF guidance products?
- What are the training requirements for modernized QPI operations?
- How can QPF coordination and verification be improved?
- How can flash and river flood forecast and warning services be improved?
- What is the role and function of the HAS forecaster in modernized NWS operations?
- How has the analysis of recent floods improved our scientific understanding and forecasts of heavy rain events?

Presentations and substantial discussion among participants on these issues were used to validate and further define the requirements and roles of the NWS components of the ETE Forecast Process for QPI, and this valuable input was integrated into this plan.

2.3.3. The September 1997 HIWG AWIPS QPF Meeting

The NWS Office of Meteorology sponsored a two and one-half day meeting at the NWS Western Region Colorado Basin River Forecast Center (CBRFC) in Salt Lake City, Utah from 3-5 September to specify prioritized requirements for point and grid editing and display capabilities in support of the preparation, coordination, and verification of QPFs within AWIPS. These requirements:

- define capabilities which can be used on a spectrum of geographic scales (i.e., national through local);

- collectively satisfy the needs of operational forecasters at all steps of the NWS ETE Forecast Process for QPF; and,

- provide definition to requirements outlined in sections 3.1.4.2.2.4.1 (Prepare Digital Forecast Data) and 3.1.4.2.2.4.2 (Prepare Gridded QPF Data Set) of the NWS AWIPS System/Segment Specification (Type-A) Document, Number SSS-001-1994, dated December 16, 1994.

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., RFC HAS forecasters, and WFO and NCEP forecasters could utilize the same AWIPS application). Many of the requirements are not specific to the QPF and support the preparation of forecasts of other meteorological parameters. These capabilities support a nationwide transition to stochastic QPF forecasting, and will be updated based upon the results of the aforementioned Probabilistic ETE Risk Reduction Exercise which began in September 1998, and similar risk reduction exercises planned for other NWS Regions.

The meeting summary and prioritized AWIPS requirements for the preparation, coordination, and verification of QPFs is provided in appendix A. These requirements are being mapped into future builds of AWIPS.

2.3.4. The November 1997 First National QPE Workshop

To further clarify and validate QPE requirements and critical service-science issues which must be addressed to modernize the ETE Forecast Process for QPI, the Office of Meteorology organized and conducted the NWS-sponsored First National Quantitative Precipitation Estimation Workshop. The workshop was held at the COMET facility in Boulder, CO from November 18 through 20. QPE requirements, applications, and supporting applied research were reviewed and discussed by forty participants including representatives from the following organizations:

- NWS [OM, OH, OSD, NCEP, OSO, Eastern Region, Central Region, Southern Region, Western Region, Alaska Region, and Pacific Region];

- OAR [NSSL and FSL];

- NCAR [RAP];

- NESDIS [Office of Research and Applications (ORA), Office of Satellite Data Processing and Distribution (OSDPD)];
- NASA, and
- COMET.

The goals of the workshop were:

- Review, validate, and update the HIWG QPE requirements for hydrologic forecasting, flood warning, issuance of quantitative precipitation analyses and forecasts, numerical modeling, statistical guidance, verification, and climate applications;
- Review current applied research and product development activities for satisfying QPE requirements; and
- Develop group recommendations for collaboration among scientists for meeting future QPE requirements.

During the individual session and final workshop summaries participants generated the following preliminary recommendations:

- Unbiased satellite, radar, and multi-sensor QPEs are *critical* for operations at NCEP Service Centers, RFCs and WFOs.
- The deficiencies of current radar (e.g., range limitations, anomalous propagation, beam blockage, hail contamination and varying Z-R relationships) and satellite-based (Infrared only) algorithms must be mitigated.
- Resources should be focused to accelerate the development, testing, and implementation of improved satellite- and radar-based algorithms for precipitation (rain and snow) estimation.
- Satellite-derived precipitation estimates should be automated.
- Future applied research should focus on the integration of satellite, radar and rain gage data.
- Planning must continue to determine the most effective means of accessing, disseminating, and quality-controlling all sources of rainfall data and estimates within AWIPS.

The application of high resolution rainfall estimates for flash flood operations was the focus of considerable discussion. The provision of high resolution rainfall estimates and forecasts, coupled high resolution watershed definitions and software applications to assess and predict flash flood conditions, was identified as a top priority by representatives from the NWS Regions. This discussion stemmed primarily from three presentations:

- The Areal Mean Basin Estimated Rainfall (AMBER) Program

AMBER is a software application developed by Mr. Robert Davis at NWSFO Pittsburgh, PA which utilizes the 1 km x 1 degree Digital Hybrid-Scan Reflectivity (DHR) product from the WSR-88D to compute radar rainfall estimates in flash flood watersheds every volume scan (Davis, 1993; Davis and Jendrowski, 1996). A single rainfall estimate is computed for each 1 km x 1 degree range bin. All range bins, whose center point falls in a stream watershed, are averaged to compute the Average Basin Rainfall (ABR) for that watershed. The computed ABR values represent an area average accumulation of all radar rainfall estimates in a watershed, including zero accumulations. The 5-6 minute ABR values are summed to create rainfall accumulations for 0.5, 1, 2, 3 and 6 hours. The likelihood of flooding is determined by comparing the temporally aggregated ABR and rate of precipitation accumulation with RFC FFG; i.e., the ABR needed to bring a stream to bankfull. The high resolution DHR rainfall grid enables AMBER to compute ABR in watersheds as small as one square mile in area. AMBER is currently utilized to compute ABR for more than 2,400 streams every radar volume scan for the NWSFO Pittsburgh HSA. AMBER has evolved significantly from over a decade of development at NWSFO Pittsburgh, and on numerous occasions has proven itself as a very effective operational tool. A full description of the history, functionality, and operational utility of the AMBER program can be found at http://www.nws.noaa.gov/er/pit/tamber.htm.

- The WFO Hydrologic Forecast System (WHFS)

WHFS is an integrated system comprised of many OH Hydrologic Research Lab (HRL)-developed applications that support the hydrology program at a WFO (Office of Hydrology, 1996; Roe et al., 1998). Current and planned WHFS capabilities include applications for data collection and management, data display, hydrometeorologic modeling, and product formatting and management functions. The hydrometeorologic modeling component of WHFS includes: 1) the Area Wide Hydrologic Prediction System (AWHPS) which provides for the analysis, display, and comparison of observed and forecast precipitation with FFG to equip WFO forecasters with a means of assessing the areal flash flood potential, and 2) the Site Specific Hydrologic Prediction System (SSHPS) which is a local hydrologic model that will provide the WFO forecaster a means of evaluating, and subsequently generating hydrologic forecasts for fast-response and headwater stream basins. A more complete description of WHFS can be found in section 6.1 and at http://hsp.nws.noaa.gov/oh/hrl/.

- The System for Convection Analysis and Nowcasting (SCAN)

As introduced in section 1.6, and elaborated upon later in section 8.3, SCAN is a collaborative effort involving the NWS, NSSL, NCAR/RAP, FSL, NESDIS, and COMET. The primary motivation for SCAN is to improve the accuracy and timeliness of warnings (e.g., flash flood, severe thunderstorm, tornado) issued by NWS forecasters, through the development of automated warning guidance. The goals of SCAN are: 1) to detect, analyze, and monitor convection and generate short-term probabilistic forecasts and warning guidance automatically within AWIPS, and 2) to couple previous research and development efforts into one integrated approach to forecasting convection and related hazardous phenomena. These research and development efforts include the NSSL Warning Decision Support System (WDSS), the NCAR Thunderstorm Auto-nowcaster, the NWS' AWIPS Thunderstorm Product, and WHFS. A more detailed description of SCAN can be found in Smith et al., 1998 and at http://www.nws.noaa.gov/tdl/scan/scan2.html.

NWS regional Scientific Services Division (SSD) chiefs and other participants were impressed by the AMBER flash flood application and expressed a desire to see similar functionality included in the hydrometeorologic modeling component of WHFS. Although the flash flood modeling component represents only one of a broad spectrum of WHFS applications, this component was recognized as critical given the significant economic and human impact of flash flooding (see table 1, section 1.3). Furthermore, workshop participants were very interested in SCAN, its relationship to WHFS, and its potential to 1) improve the watch/warning capability at the WFO, and 2) serve as a vehicle for the implementation of future nationally- and locally-developed applications within AWIPS.

The results of the workshop discussion sessions validated and expanded upon previous HIWG-specified requirements and were integrated into this QPI document. A summary of the First National Quantitative Precipitation Estimation Workshop was developed by the Office of Meteorology in FY98 and a companion QPE implementation plan will be developed during FY99.

2.3.5. The February 1998 National Workshop on WHFS, AMBER, and SCAN

In response to flash flood issues raised at the First National QPE Workshop, the NWS OM convened a one-day workshop to discuss the current status and the future design and integration of hydrologic software applications to improve operational flash flood assessment, prediction, and warning within AWIPS. These software applications include WHFS, AMBER, and SCAN. National managers, developers, and regional representatives assembled for the workshop on February 11, 1998 at NWS Headquarters in Silver Spring, MD. Attendees included representatives from the following organizations:

- NWS [OM, OH, OSD, Eastern Region, Central Region, Southern Region, Western Region, Alaska Region, Pacific Region, OSO, and MSM],

- OAR [NSSL], and

- The University of Oklahoma (OU).

The primary objectives of the workshop were:

- Identify key operational AWIPS requirements and capabilities necessary to improve NWS flash flood operations,

- Define data, software, hardware, and human resource requirements to implement and test AMBER outside the NWSFO in Pittsburgh, PA,

- Define a future operational relationship between WHFS and SCAN in AWIPS which optimizes resources for the assessment, prediction, and warning of flash flooding, and

- Discuss NSSL and cooperative NSSL/OU efforts to develop hydrometeorological applications and the potential for collaboration with the NWS.

The results of the workshop discussion sessions were integrated into this QPI document.

Primary issues raised and recommendations made at the National Workshop on WHFS, AMBER, and SCAN include:

Issue 1: What AWIPS capabilities are necessary to improve NWS flash flood operations?

- General Recommendation:

    - The NWS should support a *sustained and aggressive effort* to develop and implement applications which enhance our operational flash flood capability within AWIPS.

- Specific Recommendations:

    - Provide field offices the high resolution DHR product to compute rainfall estimates within AWIPS.

    - Include AMBER capabilities in future versions of the AWHPS of WHFS (i.e., map DHR-based rainfall estimates in locally-defined high resolution basins and use ABR to compute flash flood threat).

    - Provide WFOs the procedures, software, and training necessary to specify and/or modify local basin definitions using the OH Integrated Hydrologic Automated Basin Boundary System (IHABBS), ArcView, or other nationally-supported Commercial Off-The-Shelf (COTS) Geographic Information System (GIS) application.

    - Provide the capability to create, edit, and display spatial reference data such as parent and sub-basins, stream locations and names, reservoir and dam locations, counties (including the name, state, code, zone, etc.), transportation routes (e.g., streets, highways, railways, etc.), and important landmarks (e.g., towns, schools, hospitals, etc.) to assist forecasters in the issuance of flash flood watches and warnings.

- Provide the capability to display AWHPS flash flood guidance products within the AWIPS Display 2-Dimensions (D2D) and store these products in the AWIPS data structure so that these products are accessible to SCAN algorithms.

- Provide modernized RFC-generated, high resolution, GIS-based threshold-runoff FFG to WFOs in AWIPS.

- Provide WFOs gridded, high resolution (i.e., 1 km, 8-bit, every volume scan) regional radar mosaics (e.g., DHR) in near real-time to mitigate the impact of range degradation and other known radar deficiencies.

- Store the high temporal and spatial resolution QPF/PQPF output of SCAN algorithms (e.g., TDL's extrapolative-statistical precipitation algorithm within the AWIPS Thunderstorm Product and NCAR's Thunderstorm Auto-nowcaster) in the AWIPS data structure so that these products are accessible to WHFS for use in the:

    - AWHPS to compute the forecast ABR and predict flash flood threat, and

    - SSHPS to produce site-specific forecast time series for selected points in small, fast-responding (headwater) stream basins [While being able to identify flash flood potential, and possibly specifying the stream(s) most vulnerable to flooding is essential, being able to provide a forecast crest or categorical forecast of the magnitude of the event is equally critical. The SSHPS will incorporate the Soil Conservation Service (SCS) curve numbers as a method for computing stage forecasts. This method should be ideal for flash flood forecasting since it uses basin soil-type as a parameter for runoff calculations. This calculation of average basin soil-type is consistent with the GIS-based enhancement planned for WHFS].

Issue 2: What must be accomplished to implement and test AMBER outside the NWSFO Pittsburgh?

- General Recommendation:

    - Facilitate OSF, NSSL, and NWS Region near-term, limited, interim testing of AMBER.

- Specific Recommendations:

    - Provide field offices immediate access to the WSR-88D DHR product (AWIPS sites fitted with an A/B switch on the 56 Kbs line from the RPG, and WDSS sites, currently have access to the DHR product; availability at limited number of other sites may require the submission of a NEXRAD Change Request by OM).

- Utilize ArcView or IHABBS for local basin delineation. WFOs opting to use IHABBS should contact their RFC focal point for assistance.

- Collaborate with NSSL to develop and field test a Graphical User Interface (GUI) for AMBER.

- Conduct concurrent testing of AMBER and AWHPS at the Washington D.C.-Baltimore forecast office in Sterling, Virginia during 1998 SCAN field test.

A complete summary, including a synopsis of all workshop presentations, is provided in appendix B.

3.0. Historical Perspective and Current Status

In this section, a brief summary of the history and current status of QPF in the NWS Regions is presented. A similar summary for HPC, TDL and EMC is provided in sections 7.0, 8.0, and 9.0, respectively. This QPI document is clearly focused on supporting the future production of probabilistic QPFs and the provision of user-required hydrometeorological and hydrologic forecasts which quantify uncertainty and convey risk. However, over the past several years, substantial and noteworthy contributions to the QPI effort have been made by the NWS Regions, NCEP, and TDL. To put the forthcoming transition to improved QPI and hydrologic services into perspective, and to provide the baseline upon which we will expand and improve our products and services, it is important to describe the current status of QPF activities and recognize the tremendous regional and national efforts which support QPI and flood operations.

3.1. Eastern Region

QPFs were first issued on an operational basis in the Eastern Region (ER) in 1977 to support the Critical Flood Support Office (CFSO) concept. The CFSO concept was established in response to the growing need to include future forecasts of precipitation in river forecasts during flood events, and was based on the operational requirements of the RFC and WSFO. Any WSFO within the RFC service area could declare a "Critical Flood Day" which then would require the assigned CFSO to provide QPFs for the RFC's entire service area. The CFSO prepared these QPFs utilizing input and guidance from the NCEP. The CFSO concept continued through the late 1980s in the Eastern Region. During that time a number of field offices, including the NWSFOs located in Charleston, WV and Pittsburgh, PA, began to routinely prepare QPFs on a daily basis for the OHRFC.

As the preparation and use of QPFs expanded, the need to automate the processing and integration of QPFs into field operations increased. In response to this increasing need, a number of the tasks required to prepare and process QPFs were automated. The Northeast RFC (NERFC) developed an automated QPF plotting program in 1989, and the NWSFO in Cleveland, Ohio developed an interactive QPF program for the personal computer (PC) in 1990 which allowed the NWSFO to explicitly define both the spatial and temporal distribution of forecaster-prepared, value-added QPFs (Peroutka and Partain, 1990).

During the late 1980's, ER participated in a risk reduction exercise that established the HAS function at the OHRFC (Eastern Region, 1990). This risk reduction exercise superseded the CFSO concept with the HAS function at the RFCs. The primary purpose of the risk reduction exercise was to define the responsibilities of the HAS forecaster and implement the function in an operational RFC setting. Based upon this risk reduction exercise, the role and responsibilities of the HAS function were defined to include the:

- hours of operation,

- necessary staff resources,
- methods of, and criteria for, interaction with weather forecast offices and national centers,
- necessary hardware and software, and
- training requirements.

One of the primary functions of the HAS unit at the RFC is to consolidate (mosaic), and reconcile differences among, forecasts of hydrometeorological variables provided by supporting NWSFOs (e.g., six hour QPFs and temperatures) over the RFC service area for use in the operational hydrologic forecasts.

Once the operational functions of the HAS were defined, it became clear that improved software tools were needed to:

- assist NWSFO forecasters in the preparation of QPFs, and
- assist HAS forecasters at the RFC with the integration/mosaicking of NWSFO-prepared QPFs for input to NWSRFS.

Consequently, an objective of the OHRFC HAS Risk Reduction Exercise was to develop these software tools. To satisfy these needs, software applications were developed by Mr. Mark Fenbers of the OHRFC. The first application developed was entitled HASQPF, which was designed to facilitate the efficient execution of the HAS responsibility to mosaic NWSFO-prepared QPFs (Fenbers, 1993). HASQPF is currently used operationally by all RFCs in ER and a number of RFCs in other CONUS Regions. An additional and companion software application entitled WinQPF was also developed to support the preparation of QPFs at NWSFOs (Fenbers, 1995). The primary impetus for developing WinQPF was to improve upon previous PC-based QPF programs and provide for the processing of precipitation and temperature forecasts in a gridded format for use by RFCs. WinQPF also provided other capabilities previously unavailable in PC-based QPF software applications such as multiple map overlays and displays of aggregate gridded and basin average QPFs. WinQPF emulates AWIPS era grid processors and allows users the capability to implement customization. Mr. Mark Fenbers still provides critical operational support for both the HASQPF and WinQPF software applications.

The OHRFC HAS Risk Reduction Exercise began to come to a close as the other ER RFCs started staffing and implementing the HAS function during 1992 and 1993. By the close of 1993, all ER NWSFOs were routinely preparing 6-hour QPFs through a range of 24 hours on a daily basis for their servicing RFCs. The RFCs were mosaicking the QPFs and using them as input to NWSRFS for daily river and flood forecasting. During flooding situations, RFCs often request WFO-prepared QPF updates at 6-hour intervals for ranges exceeding 24 hours.

During the NWSO spin-up period in ER (1994-1997), the NWSFOs continued to provide QPFs for NWSO forecast areas. As the new NWSOs started to spin-up, they integrated QPF into their operations. By the start of FY 97, all ER NWSOs and NWSFOs were routinely producing 24-hour gridded, deterministic QPFs, with a temporal resolution of six hours, for their respective HSAs.

In addition to implementing deterministic QPF operations and applications at all ER NWSFOs and NWSOs, ER pioneered the NWS probabilistic QPF effort at NWSFO Pittsburgh in the early 1990s. Section 4.1 provides a description and brief history of ER's efforts to implement probabilistic QPF. By coupling hydrometeorological concepts with the operational application of probabilistic theory, ER examined the feasibility of developing and implementing a complete probabilistic hydrometeorological system through a COMET project between the OHRFC and the UVA. This COMET Outreach Project which began in 1994, and previous COMET and NSF-supported research on PQPF (Krzysztofowicz et al., 1993), provided the foundation for the ongoing ER probabilistic risk reduction exercise. ER's commitment to improve QPF operations and expand the implementation of probabilistic forecasting remains strong, as evidenced by their current efforts in the planning and execution of this important risk reduction exercise.

3.2. Southern Region

Other than to mention precipitation in somewhat qualitative terms as part of the agricultural forecast package, QPFs have not been routinely issued by Southern Region (SR) offices until recent years. In the late 1970s, spurred by an increased emphasis on mitigating the impacts of flash floods and land falling tropical systems, a handful of SR forecasters became involved in forecasting QPF with a focus on forecasting heavy rain. Members of this initial cadre of SR personnel committed to promoting the science and the operational generation and application of QPFs included Alan Johnson, Gary Grice, Jimmy Don Ward, Edward Mortimer, and Jim Belville. This group began publishing papers, Technical Memoranda, and SR technical attachments on the subject which led to a heightened awareness and an increased interest in QPF throughout the SR. Among these was the 1978 NOAA Technical Memorandum entitled, "A Flash Flood Aid-The Limited Area QPF," written by Jim Belville, Alan Johnson and Jim Ward.

By the early 1980s, annual SR QPF workshops were being held. SR Technical Memoranda were published in 1985 and 1986 containing papers presented at the workshops. With an increased national emphasis on heavy precipitation and flood forecasting, these early regional workshops evolved and expanded to become the NWS National Heavy Precipitation Workshops which are now held every other year or as frequently as resources permit.

Meanwhile, a few SR offices experimented with preparing and issuing QPFs. The Lubbock, TX NWSFO began issuing maximum, point QPFs for the International Boundary and Water Commission (IB&WC) during the middle 1970s. In the middle 1980s, the IB&WC requested that a new approach be used. This required that the NWSFO in Lubbock prepare and provide QPFs depicting areas in the Rio Grande Basin having a twenty per cent chance of receiving an inch or more of rain in a 24-hour forecast period. In light of this support for the IB&WC, the Lubbock NWSFO holds the distinction of being the first SR office to routinely issue QPF.

After the disastrous Pearl River Flood of 1979, the WSFO in Jackson, MS began to prepare QPF for inclusion in NWSRFS to improve operational forecasts of river floods. The process involved the WSFO telephoning the Lower Mississippi River Forecast Center (LMRFC) to provide a "most-likely" QPF and a worst-case-scenario QPF. The LMRFC would then run their models with these values and either telephone or transmit the results using Automation of Field Operations and Services (AFOS) communications. The provision of these "as-needed" QPFs to the LMRFC continued for about fifteen years. However, in October of 1994 the NWSFO in Jackson, MS began the routine issuance of gridded QPFs utilizing the PC-based WinQPF software application (Fenbers, 1995).

During the middle 1990s, the Tulsa Risk Reduction Exercise was conducted as a part of the NWS MAR. This effort involved the Arkansas-Red Basin River Forecast Center (ABRFC) in Tulsa, OK and the SR offices they serviced. This provided valuable lessons on how to implement QPF in the field forecast environment. In light of the successful use of WinQPF at SR field offices, and the parallel emergence of WinQPF as the standard QPF application for much of the CONUS, Southern Region Headquarters (SRH) chose to implement it at NWSFO/NWSOs throughout the region. Based upon the favorable results of this risk reduction exercise, SRH decided that the implementation date for region wide, routine QPF issuance would be July 1, 1996. Prior to this implementation date, operational procedures and applications necessary for the preparation and verification of QPFs were refined and solidified at the NWSFOs in Lubbock, TX and Jackson, MS.

As the SR implementation date approached, HSD supported the NWSFOs/NWSOs by providing a substantial amount of QPF information, education, and training. In April and again in July of 1996, SR HSD distributed a list of references and several technical papers focused on QPF, heavy rain forecasting, heavy rain climatologies, and forecast decision tree applications. These materials were designed to help NWSFO/NWSO training focal points educate their staffs on the preparation and use of QPF, and included reference material on more difficult concepts such as basin average precipitation.

Additionally, during the Summer of 1996, four QPF workshops were organized by HSD and members of the four collocated SR NWSFOs and RFCs. These workshops, held at each of the four collocated NWSFOs and RFCs, were attended by forecast staff from every forecast office in SR, as well as forecasters from the Central Region forecast offices which support the ABRFC. The workshops were designed to provide field forecasters training and education focused on QPF and its implementation across SR. This training included "hands on" instruction at the RFCs, wherein forecasters were provided the opportunity to observe HAS forecasters as they mosaicked NWSFO/NWSO-produced QPF, and RFC hydrologists as they utilized QPF to generate main-stem river forecasts.

Presently, all SR NWSFOs/NWSOs produce QPF at least twice a day with issuances at 1200 and

0000 UTC. These regular issuances include four 6-hour forecasts comprising a 24 hour time frame. Updates and inconsistencies between adjacent offices are coordinated with the help of HAS forecasters at the appropriate SR RFCs. Updates to QPF are issued if and when valid NWSFO/NWSO-produced QPFs become unrepresentative of the current hydrometeorological situation.

SR RFCs have begun utilizing the Internet to facilitate coordination and information exchange with NWSFO/NWSO forecasters. ABRFC and WGRFC presently post their mosaicked QPF products on their home pages. Additionally, they each include tutorials explaining the concept of MAP, and ABRFC posts flash flood risk graphics on its home page. These flash flood risk graphics are derived by quantitatively comparing NWSFO/NWSO-produced QPFs with flash flood guidance.

Since the SR QPF implementation began, significant strides have been made. While the problems of over forecasting small rain events and under forecasting extremely heavy rain events still exist, a study by staff members of the ABRFC (NOAA Technical Memorandum NWS SR-187) has shown a twenty percent increase in overall river forecast accuracy with the use of QPF, as compared to not using QPF for the same forecast run. ABRFC is also routinely issuing river forecast (RVF) products with and without QPF. However, the "without QPF" forecasts are for informational purposes only. This practice has been deemed an unqualified success by the offices they support.

Although SR has successfully implemented QPF throughout the region, continued improvements in river forecast and QPF accuracy and the provision of improved products and services, to include products which quantify uncertainty and convey risk, remain an operational priority.

3.3. Western Region

QPFs have been an integral part of the hydrologic services program in Western Region (WR) for many years. In fact, the California-Nevada RFC (CNRFC) in Sacramento, CA and the Northwest RFC (NWRFC) in Portland, OR have been using QPF for the preparation of river forecasts for more than 20 years. This QPF is prepared by several NWS forecast offices which include those located in San Francisco and Monterey, CA, Reno, NV, Portland and Seattle, WA, and Boise, ID. Additionally, the CBRFC in Salt Lake City, UT has routinely used daily QPF from the NWSFO located in Phoenix, AZ for main-stem river forecasting during the past several years. The CBRFC also uses QPF provided by the co-located NWSFO in Salt Lake City during snowmelt situations. These WR offices use various techniques, including "rainy day ratios," to produce point QPFs for their servicing RFCs (Greg Rishel, personal communication, 1997). One of the primary reasons for the addition of QPF to the operational river forecast process was to provide improved estimates of inflows to flood control projects. The agencies managing these flood control projects have, in turn, used this NWS guidance to establish water release schedules.

QPFs are routinely generated in the WR of the NWS during the "wet season", which typically extends from October through April. During the remainder of the year, there is climatologically less precipitation which is largely convective in nature, and the localized nature of these convective events makes them more difficult to predict utilizing currently available operational QPF guidance and techniques. Hence, QPF efforts in WR have been focused on the "wet season", when increased precipitation occurs and QPF guidance and techniques enable a higher degree of forecast success.

During the 1996-1997 "wet season," the QPF program at the CNRFC included the generation of QPFs at least once per day by the NWSFOs in Monterey, CA and Reno, NV for input to the RFC models. The primary method used to generate these QPFs were "rainy day normals" (Greg Rishel, personal communication, 1997). Forecasters utilized guidance from NCEP to facilitate the preparation of their QPFs. A local orographic model (Rhea, 1998) was also used to generate operational QPF guidance. Additionally, NWSFO San Francisco used the recently developed Mountain Mapper (Henkel and Peterson; 1996) (see section 4.2) software application in a test mode to generate and verify QPFs. Point QPFs were generated by the NWSFOs and transmitted to the CNRFC in Standard Hydrometeorological Exchange Format (SHEF) code, where they were converted to forecast MAPs (FMAPs) for inclusion in the operational river models. QPFs were issued more frequently for heavy precipitation events. In fact, as many as four issuances were made daily during precipitation events to support CNRFC river forecast model runs.

In the NWRFC's area of responsibility during the 1996-1997 "wet season," QPFs were generated by the NWSFOs located in Portland, OR, Seattle, WA, and Boise, ID. This effort encompassed more than just forecasts of precipitation amounts. Forecasts of maximum and minimum temperatures and freezing levels were included in every QPF generation. These forecasts were routinely issued once daily, with updates as often as four times daily during precipitation events. As with the CNRFC's area, the forecasts were made for point locations, the QPF information was transmitted in SHEF code, and the RFC generated FMAPs and forecast mean areal temperatures (FMATs) from this information. Forecasters used a variety of guidance in preparing QPFs, including NCEP guidance and output from the Pennsylvania State University (PSU)-NCAR Mesoscale Model version 5 (MM5).

The CBRFC received daily QPF from NWSFO Phoenix for the state of Arizona during the 1996-1997 "wet season." NWSFO Phoenix routinely generated QPFs utilizing NCEP guidance and the Mountain Mapper software application. The SHEF encoded QPFs were converted to FMAPs at the CBRFC. The NWSFO in Salt Lake City also provided QPFs to the co-located CBRFC during the snowmelt season.

The Western Region ambitiously expanded their QPF program during the 1997-1998 "wet season" to include the routine preparation of QPFs at all NWSFOs and NWSOs. The three WR forecast offices in Montana east of the continental divide, which support the Missouri Basin RFC (MBRFC) in the Central Region, utilized the WinQPF software application for preparing QPF, while all other WR offices used Mountain Mapper for this task.

Mountain Mapper has been adopted as the WR standard for generating and verifying QPFs due to its functionality of incorporating climatology and high resolution terrain into the process. These functions are vital to the generation of areal QPFs in the WR due to the complex terrain. Mountain Mapper provides forecasters the versatility to prepare QPFs at predetermined and/or user-specified point locations, along a "backbone" (or axis), and as an areal average. Individual NWSFOs and NWSOs coordinate the format, time of issuance, and frequency of their QPFs with neighboring offices and their servicing RFC. QPFs are updated at least once daily by all WR offices from October through April.

The River Forecast Centers utilize Mountain Mapper to verify NWSFO/NWSO-prepared QPFs and provide each forecast office their respective HSA verification statistics in a timely manner to enable forecasters to assess, calibrate, and improve their skill. Additionally, the RFCs provide operational support and training for the versatile Mountain Mapper application. Through their ingenuity and commitment to improving the operational generation and use of QPFs, the WR has advanced the science and developed QPF applications and techniques which will continue to benefit operations into the AWIPS era.

3.4. Central Region

In 1991, the Louisville, KY office became the first Central Region (CR) site to routinely issue QPFs. These QPFs were generated and provided to the OHRFC in support of river and flood forecast operations. Prior to this time, RFCs requested QPF on an event driven basis from WSFOs that were Critical Flood Support Offices. Immediately following the initial provision of QPFs at Louisville, CR conducted two QPF risk reduction exercises in support of the gradual implementation of QPF throughout the region. With the July 1998 commencement of routine QPF generation at the spin-up weather forecast office in Northern, IN (which began operating in early FY 98), the implementation of a region-wide QPF program in CR is complete. The necessary initial training was provided to representatives of all CR field offices via several QPF workshops held during the period 1994 - 1996.

In 1992, the first CR QPF risk reduction exercise, involving the Milwaukee, WI forecast office and the North Central River Forecast Center (NCRFC), was conducted. The primary objectives of the risk reduction were to identify the steps necessary to implement QPF operationally and quantitatively determine whether QPF was beneficial to river forecasting. This exercise ran from April 1 through November 15 and required that the Milwaukee office generate spatially-averaged QPFs to a range of 24 hours in 6-hour intervals. These QPFs were issued once per day when the maximum forecast 24-hour QPF, anywhere in the forecast domain of the Milwaukee office, was at least 0.50 inches. The provision of QPFs to the NCRFC during this risk reduction was limited, due to a protracted dry period and the minimum precipitation ($\geq$0.50 inches) requirement. The NCRFC determined that the river forecasts with QPF were improved in the first 12 hours, but that the accuracy decreased significantly from 12 to 24 hours. The impact of QPFs on the river forecast was found to cause overforecasting of river stages (i.e. river forecasts for near or above flood stage verified 41 percent of the time for river forecasts with QPF compared to 89 percent verifying without QPF [Schwein, 1996]).

The second CR QPF risk reduction exercise, which was conducted from April 15 through October 3, 1993, involved the Minneapolis, MN office in addition to the Milwaukee forecast office and the NCRFC. This risk reduction was based upon the results and recommendations of the earlier 1992 exercise. Spatially-averaged 6-hour QPFs were issued daily, regardless of amount, to a range of 12 hours instead of 24 hours. In contrast to the earlier risk reduction, substantial precipitation was observed during the 1993 warm season and river forecasts including QPF were markedly better. In fact, river forecasts for near or above flood stage verified 82 percent of the time for river forecasts with QPF compared to 80 percent verifying without QPF [Schwein, 1996]).

After the Great Midwest flood of 1993, Central Region Headquarters (CRH) and the NCRFC made a concerted effort to expand the use and generation of QPF in routine river forecast and flood operations. As of June 6, 1994 the NCRFC was utilizing QPFs prepared by the six CR NWSFOs located in Milwaukee, WI, Minneapolis, MN, Chicago, IL, Indianapolis, IN, Des Moines, IA, and St. Louis, MO in their daily river forecasts. These QPFs, issued once per day around 1200 UTC, represented spatially-averaged precipitation, were provided in 6-hour intervals to a range of 24 hours. In contrast to the risk reductions in 1992 and 1993, the routine preparation of QPFs was continued through the winter months (of 1994-1995) since it was difficult to determine the cutoff date for the occurrence of liquid precipitation (i.e., January thaws are not unusual). Furthermore, CRH felt that issuing a daily QPF year round as a part of the routine forecast process would enable forecasters to better calibrate and improve their skill. Beginning July 12, 1994, the aforementioned six CR forecast offices began to issue two 6-hour updates at 0000 UTC on a daily basis.

Between 1994 and 1996, most of the remaining CR NWSFOs and NWSOs integrated the preparation of QPFs into their routine forecast operations. Additionally, in June of 1995, NWSFO/NWSO verification of QPF began. On July 9, 1996, the Missouri Basin RFC (MBRFC) began to use QPFs issued around 1200 UTC operationally in their river forecasts. On May 1, 1997, all NWSFOs and NWSOs supporting the NCRFC began issuing four 6-hour forecasts at 0000 UTC as opposed to two. This expanded support for the 24 hour forecast period beginning at 0000 UTC was the result of an internal review of NCRFC river forecasts. River forecasts initialized at 0000 UTC commonly "stair-stepped" after the first 12 hours due to a lack of QPF information (i.e., RFC river forecasts for time periods which are not supported by NWSFO/NWSO-prepared QPFs use a QPF of zero as input). In light of this review, the NCRFC recommended that QPFs should also be included through 24 hours for the forecast period beginning at 0000 UTC, to mitigate the significant negative impact of zero QPFs on the river forecasts initialized at 0000 UTC.

All CR weather forecast offices currently issue QPFs for use in daily NWSRFS operations. Excepting the two CR forecast offices which support the CBRFC in the WR, operational QPFs are prepared using the WinQPF software application (Fenbers, 1995). The CR offices which support only the OHRFC, issue one routine forecast per day, while those offices which support the NCRFC, MBRFC, and/or ABRFC issue QPFs twice per day. The two CR offices located in Riverton, WY and Grand Junction, CO, which support WR RFC operations, issue daily QPFs during the spring snowmelt season as required by CBRFC. These offices utilize the Mountain Mapper software application to generate and verify QPF. Although QPF has successfully been implemented throughout the region, CR remains committed to identifying and resolving the QPF issues necessary to improve the reliability and accuracy of operational QPFs and expanding their use at the RFC to improve hydrometeorological services.

3.5. Alaska Region

Until recently, the generation of QPFs in Alaska Region (AR) was limited to those requested by the Alaska RFC (AKRFC) prior to or during potential flood events. The NWSFO with forecast responsibility for the area of concern provided the AKRFC with the required QPFs.

The three AR NWSFOs located in Anchorage, Fairbanks, and Juneau began issuing QPFs on a routine basis during the Fall of 1996, and as of May 1998 were generating point QPFs once a day for three to seven locations within their respective forecast domains. These QPFs are issued at 18 UTC with 6-hour temporal resolution through a range of 24 hours. QPF verification is performed by the AKRFC utilizing precipitation reports from gages in close proximity to the forecast points, and the results are provided to the NWSFOs.

QPFs prepared by AR NWSFOs are issued in text format and transmitted to the AKRFC. The AKRFC has supported the preparation of QPFs at the NWSFOs by providing climatic guidance for each of the required forecast locations. This climatic guidance specifies the probability of occurrence of the following ten categories of precipitation as a function of low-level wind direction:

- Category 0 = 0.00 inches,
- 0.10 inches ≥ Category 1 > 0.00 inches,
- 0.25 inches ≥ Category 2 > 0.10 inches,
- 0.50 inches ≥ Category 3 > 0.25 inches,
- 0.75 inches ≥ Category 4 > 0.50 inches,
- 1.00 inches ≥ Category 5 > 0.75 inches,
- 1.50 inches ≥ Category 6 > 1.00 inches,
- 2.00 inches ≥ Category 7 > 1.50 inches,
- 3.00 inches ≥ Category 8 > 2.00 inches, and
- Category 9 > 3.00 inches.

NWSFO forecasters prepare operational QPFs by reviewing and integrating observed data, gridded NWP model data, MOS guidance, and the influence of local terrain.

3.6. Pacific Region

Pacific Region (PR) forecasters at the NWSFO located in Honolulu, HI routinely issue site-specific (point) QPFs twice a day during the early and late morning hours. Point QPFs have been prepared in PR for over 35 years and were originally generated to help sugar cane farmers develop irrigation schedules, and determine when to burn their fields in preparation for harvesting. Current QPFs support flash flood operations, and the beneficiaries of these forecasts have expanded to include internal NWS forecasters at PR WSOs, civil defense personnel, and water resource managers.

NWSFO Honolulu issues QPFs for twenty-four locations of which twenty-two have verification data available via either automated tipping bucket rain gages or Cooperative Observers. The automated rain gages provide rainfall observations as frequently as every fifteen minutes while the Cooperative Observer reports are 24 hour precipitation totals. The influence of orography in Hawaii yields a significant spatial variability in precipitation amount which can exceed 200 inches per year between forecast locations. QPFs are issued in a text format utilizing 12 h and 24 h precipitation categories of:

- less than .10 inches,
- less than .25 inches,
- .25 to .50 inches,
- .50 to .75 inches,
- .50 to 1.00 inches,
- .75 to 1.00 inches,
- 1.00 to 2.00 inches,
- 2.00 to 3.00 inches, and
- greater than 3.00 inches.

A brief forecast discussion accompanies each QPF issuance.

The early morning QPFs are valid for the 12 hour forecast period beginning at 6 AM local time on the day of issuance, and are issued with a two to four hour lead time. The late morning forecast (issued between 10 and 11 AM local time) is a 24 hour forecast valid from 6 PM the day of issuance to 6 PM following the day, and is roughly a 12 to 36 hour forecast. Planned enhancements to the forecaster-prepared QPFs include increasing their temporal resolution to better support flash flood operations.

Flash flooding in HI is frequently associated with land slides. The time elapsed from peak rainfall to peak flow is frequently within the range of 15 to 45 minutes. Most flash flooding events occur when the rainfall rates, associated with heavy rainfall producing phenomena, significantly exceed the rate of infiltration. The topography serves to focus the location and enhance the intensity of precipitation. Given this, and the fact that much of the mountainous landscape is impervious to rainfall, HI is particularly susceptible to the threat of flash flooding. When flash flooding does occur, most streams with very few exceptions return to a nonhazardous "base flow" state within thirty minutes to three hours after the cessation of rainfall.

4.0. Future Direction of Operational QPF and its Projected Use in River Forecasting

4.1. Pioneering Efforts in Probabilistic QPF

Initial NWS efforts to develop an operational, probabilistic hydrometeorological forecasting system began in earnest in 1990, under the direction of ER Headquarters (ERH). A comprehensive, scientifically-based systems approach, integrating theory and operations was utilized to design this prototype system (Zevin, 1994). The system couples probabilistic quantitative precipitation and hydrologic forecasts with a flood warning decision system (Krzysztofowicz, 1993; Krzysztofowicz et al., 1993; Zevin, 1994). The impetus for the risk reduction project was twofold:

- quantify the forecast uncertainty for end users; and
- increase the lead time of NWS hydrometeorological watch and warning products.

Comparing the high cost of flood-related damage with that associated with response preparation, ERH personnel recognized that users would be better served by probabilistic hydrometeorological forecast products. Users provided with a precipitation probability distribution for a specified area and time interval, a probability distribution for a river stage/flow at a specific river forecast point, and a probabilistic innundation map for a specified time interval will be better equipped to make optimal decisions. Risks can be explicitly accounted for in decision making, enabling users to determine the most prudent and efficient course of action with regard to the pre-positioning of resources and the mobilization of personnel (Krzysztofowicz et al., 1993; Zevin, 1994).

The production of unbiased, spatially-averaged or point QPFs for hydrologic modeling represents a significant challenge facing operational forecasters. The broad spectrum of space and time scales on which precipitation organizes and occurs makes precipitation amount one of the most -- *if not the most* -- difficult predictands and a major source of uncertainty in hydrologic forecasting (Krzysztofowicz, 1993; NRC, 1996). The inherent complexity of the precipitation forecast problem is directly attributable to the fact that:

- 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 non-linear.

Krzysztofowicz and Drake (1992), Krzysztofowicz (1993), and Zevin (1994) have shown that a probabilistic format for QPFs enables forecasters to quantify the uncertainty associated with the predictand, yielding three fundamental benefits:

- facilitates the generation of unbiased rainfall predictions,
- provides information about future precipitation necessary to generate PRSFs, and
- enables users to make decisions that optimize their socioeconomic benefits (i.e, provides for an assessment of forecast probability and lead time vs. potential flood severity).

This approach is particularly valuable given the inherent uncertainty about the predictand. Sources of forecaster uncertainty are manifold and include:

- experience/familiarity with given forecast problem,
- the accuracy of operational NCEP models and statistical and value-added guidance and their relative consistency -- and forecaster ability to identify and reconcile differences,
- the availability of remote and in-situ observations which adequately capture characteristic features and physical processes responsible for organizing and maintaining precipitation elements, and
- the ability of a forecaster to integrate observations and guidance to conceptualize and accurately predict storm evolution.

Krzysztofowicz et al. (1993) conducted a comprehensive verification of deterministic QPFs prepared by forecasters at the NWSFO located in Pittsburgh, PA from 1988 through 1990, which underscored the need to implement a probabilistic format for QPFs. Results of the verification study revealed a bias toward over-forecasting[1]. Discussions with forecasters led Krzysztofowicz et al. (1993) to suggest that the degree to which rainfall was over-forecast was a direct manifestation of an increasing level of uncertainty about the forecast, given the underlying limitation that only a *single* value be used to express forecaster judgement. Furthermore, Krzysztofowicz (1983) and Alexandridis and Krzysztofowicz (1985) have shown that the (economic) value of probabilistic forecasts is always at least as large as that of their deterministic counterparts and the potential economic gain from probabilistic forecasts (relative to deterministic forecasts) is directly correlated with the degree of uncertainty about the predictand. In light of these results and the inherent complexities and associated forecaster uncertainty in quantitatively forecasting rainfall amount, the benefits of adopting and implementing a probabilistic format for QPFs could be very large.

Utilizing the PQPF component of this probabilistic hydrometeorological forecasting system, forecasters at the NWSFO in Pittsburgh, PA (PBZ) routinely generated and verified 24-hour PQPFs twice daily for two basins of the upper Ohio River from August 1990 through August 1998. The basins are the Lower Monongahela River basin above Connellsville, which covers 3429 square

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[1] Schwein (1996) has shown, through verification of QPFs in the NWS Central Region, that forecaster bias is to over-forecast low amounts of precipitation and under-forecast high amounts.

kilometers (1324 square miles) in Pennsylvania and Maryland and the Upper Allegheny River basin above the Kinzua Dam, which covers 5853 square kilometers (2260 square miles) in Pennsylvania and New York. The methodology utilized at PBZ to define the precipitation probability distribution is a theoretically sound means of satisfying the minimum hydrologic requirements for future precipitation in support of probabilistic (and current deterministic) river stage forecasting. Significant input from, and iteration with, operational forecasters yielded an approach which effectively couples the meteorologic forecast process with probabilistic reasoning (Bayesian inference) to quantify forecast uncertainty (Krzysztofowicz et al., 1993; Zevin, 1994). The methodology decomposes the forecast problem into two independent tasks (Krzysztofowicz, 1993):

(1) forecast the basin-average precipitation (W) expected for a specified (24-hour) period, and

(2) disaggregate the expected precipitation into subperiods of equal duration (6-hour periods).

To perform task (1), NWSFO Pittsburgh forecasters specified three unconditional exceedance fractiles (x_{75}, x_{50}, and x_{25}) of the 24-hour basin-average rainfall (W). Treating W as a continuous random variable, these exceedance fractiles were used to define an exceedance function, or probability distribution, for each basin for a specified time interval. Given a probability p, where $0 < p < 1$, the 100p% exceedance fractile of W, written $x_{100p\%}$, is defined as a rainfall estimate with an associated probability of exceedance of $P(W > x_{100p\%}) = p$ (Krzysztofowicz, 1993; Krzysztofowicz et al., 1993). For example, the 50 percent exceedance fractile, denoted x_{50}, represents a forecast rainfall amount (which in the case of PBZ represents a basin average amount) that has an equally likely chance of being exceeded or not exceeded (i.e, the median). Similarly, the 25 percent exceedance fractile represents a quantitative rainfall forecast which has a 25 percent chance of being exceeded and a 75 percent of not being exceeded.

Accomplishing task (2) required that forecasters specify the expected fraction of the precipitation for each of the four 6-hour subperiods. The expected fraction, z_i, satisfying the conditions (Krzysztofowicz, 1993):

- $0 \leq z_i \leq 1$;
- $I = 1, 2, 3, 4$; and
- $z_1 + z_2 + z_3 + z_4 = 1$,

is the fraction of the 24-hour basin average precipitation W that a forecaster expects to occur during the *i*th 6-hour subperiod (i.e., $z_i = W_i / W$), conditional on the hypothesis that $W > 0$. For a complete description of the first generation PQPF methodology and judgmental process formerly employed at PBZ, the reader is referred to Krzysztofowicz (1993) and Krzysztofowicz et al. (1993).

An important component of the human decision process that culminates with the specification of exceedance fractiles and expected fractions is the evaluation and integration of direct model and value-added guidance. During the course of the risk reduction exercise at PBZ, forecasters evaluated the current sources of QPF guidance -- direct model output, HPC value-added QPFs, and MOS. PBZ forecasters found centrally-produced value-added guidance produced by the NPPU of HPC most beneficial, but noted that no guidance could be used directly to generate local, areal average QPFs/PQPFs. This lack of direct application was due to many factors which include incompatible product format (i.e, no spatially-averaged NWP model or value-added PQPF guidance), issuance times, and valid periods, as well as the perceived accuracy of the guidance (Krzysztofowicz and Drake, 1993). To eliminate this problem, efforts are underway to ensure that value-added QPFs/PQPFs generated in support of probabilistic river and flood forecasting -- at all steps of the modernized ETE Forecast Process -- will be generated and disseminated using consistent product formats, issuance times and valid periods. This consistency will facilitate a more efficient use of guidance by enabling gridded (and point) value-added products to be used directly for the generation of QPFs/PQPFs.

It is interesting to note that PBZ forecasters were initially reluctant to generate PQPFs. However, with the appropriate training, and through experience and timely verification feedback, they generated basin average PQPFs as a matter of routine procedure. PBZ forecasters continue to routinely generate gridded PQPFs utilizing a second generation methodology (see section 4.2.1). The increased potential for service benefits provided by producing user-requested probabilistic hydrologic forecasts merit pursuing a NWS-wide transition to probabilistic quantitative precipitation forecasting, as noted heretofore.

4.2. Experimental Probabilistic End-to-End Hydrometeorological Forecasting System in Support of Modernized NWS Operations

In an effort to develop and test an AWIPS-compatible (second generation) version of the aforementioned probabilistic forecast methodology and specify a probabilistic ETE framework for national implementation, the NWS commenced a two-year risk reduction exercise in September 1998. The original concept for this Probabilistic ETE Risk Reduction Exercise was discussed and supported by the HIWG during the July 1996 meeting (see section 2.3.1). This risk reduction exercise is a collaborative CSTAR effort with Dr. Roman Krzysztofowicz of UVA (Krzysztofowicz, 1996; Adams et al., 1999) which builds upon previous collaborative development efforts between the NWS ER and UVA. NWS Eastern Region Headquarters (ERH), OH , OM, the HPC of NCEP, the TDL of OSD, the OHRFC, ER NWSFOs, and end users are actively engaged in this important activity. Users who receive and evaluate NWS probabilistic hydrologic products include:

- the Randolph County Emergency Management Association in WV, and
- the Waterways Association and the Tucker County Emergency Management Association in PA.

Similar risk reduction exercises are necessary and being planned for the other NWS regions to ensure that an ETE probabilistic framework for national implementation, addresses and accommodates diverse regional and user needs. These risk reduction exercises are currently scheduled to begin in FY 01-02 pending the availability of resources through the normal budget initiative process associated with the Advance Short Term Warning and Forecast Process.

*4.2.1. Generation of Probabilistic QPF*s

ER NWSFOs located in Pittsburgh, PA and Charleston, WV (RLX) are routinely generating gridded 24-hour PQPFs twice per day covering the Monongahela River Basin above Grays Landing, PA. The second generation PQPF methodology employed is an extension of the approach developed and previously utilized at PBZ. Centrally-produced, gridded QPF/PQPF guidance from TDL and HPC is available and can be edited by forecasters utilizing the grid editing software of the Interactive Computer Worded Forecast (ICWF) System. Under a Cooperative Agreement with the NWS, and in collaboration with the risk reduction participants, Dr. Roman Krzysztofowicz of UVA has developed enhancements to this grid editing software to help forecasters integrate and edit central guidance to generate statistically coherent, physically realistic, value-added QPFs/PQPFs (Mills and Krzysztofowicz, 1998). Substantial input from experienced HPC and ER forecasters via an initial workshop in February 1997 and several subsequent meetings have yielded a straightforward AWIPS-compatible, prototype PQPF methodology. This prototype methodology satisfies *both* the current (deterministic) requirements for QPF and the projected future (probabilistic) requirements for QPF/PQPF in support of river and flood forecasting, although its application outside of the NWS Eastern Region has not yet been tested. Modifications to the PQPF methodology employed by PBZ forecasters since August of 1990 include the specification of:

- gridded, spatial-average (versus basin-average) precipitation amounts,
- gridded, spatial-average Probability of (measurable) Precipitation (PoP) values,
- conditional (rather than unconditional) 24-hour exceedance fractiles; and,
- two (versus three) 24-hour exceedance fractiles.

The sequence of events which culminated in these modifications includes:

- A recognition by HIWG members, field forecasters, AWIPS developers, and Dr. Roman Krzysztofowicz of UVA that to extend the operational preparation of PQPFs from two basins to the entire forecast domain of a WFO (or the CONUS in the case of HPC), forecasters must generate gridded, spatial-average (versus basin-average) precipitation forecasts. The probabilistic characteristics of the QPF are scale-dependant in that they are different for different sized basins. Therefore, specifying PQPFs individually for the numerous basins which comprise the domain of a WFO would be an overwhelmingly complex and time consuming task.

- A recommendation by Dr. John Schaake, the Chief Scientist of the Office of Hydrology, that the PoP be explicitly specified to ensure that the RFCs are provided adequate information to specify the probability distribution for precipitation when the PoP is low (e.g., if the PoP is less than 25 percent, the unconditional exceedance fractiles x_{75}, x_{50}, and x_{25} are all zero -- as a result of this, it becomes necessary to consider explicitly the conditional distribution for precipitation). With the adoption of this recommendation, the exceedance fractiles become conditional on measurable precipitation occurrence. When a two-parameter model for the exceedance function (i.e., probability distribution) is employed, such as the Weibull model (Johnson and Kotz, 1970), only two exceedance fractiles need to be assessed (Krzysztofowicz, 1998a). As a result of discussions with HPC and PBZ forecasters, it was determined that the conditional exceedance fractiles x_{50}, and x_{25} would be assessed during the Probabilistic ETE Risk Reduction Exercise in the Eastern Region (other exceedance fractiles, such as x_{75}, can be inferred from the probability distribution).

- A presentation by Dr. Roman Krzysztofowicz of the results of a comparative verification of 24-hour basin-averaged QPFs prepared by HPC and PBZ during the period December, 1992 to October, 1996 for the Lower Monongahela River basin above Connellsville, in Pennsylvania and Maryland, and the Upper Allegheny River basin above the Kinzua Dam, in Pennsylvania and New York (Krzysztofowicz and Sigrest, 1999b). As a part of this study, Dr. Krzysztofowicz conducted an assessment of the calibration of HPC QPFs as 1) an exceedance fractile of the 24-hour basin-average precipitation amount W, and 2) an exceedance fractile of W, conditional on the occurrence of precipitation during the 24 hour forecast period. This assessment revealed that the HPC forecasts of W, conditional on the occurrence of precipitation during the 24-hour forecast period, were considerably better calibrated than unconditional forecasts. During the course of a February, 1997 workshop, Dr. Krzysztofowicz learned from HPC forecasters that they employ a judgmental process wherein the specification of QPFs is conditioned on the occurrence of rainfall. In light of this, and input from other field forecasters, an objective of the Probabilistic ETE Risk Reduction Exercise in the Eastern Region is to explicitly test this conditional forecast methodology in a probabilistic context.

Given the aforementioned modifications, forecasters are utilizing AWIPS hardware and prototype software, to specify the 24-hour probability distribution of rainfall amount by editing and/or specifying three 24-hour, value-added grids which include 1) the 50 percent and 25 percent *conditional* exceedance fractiles, x_{50C} and x_{25C} (i.e., rainfall estimates with an associated probability of exceedance of 50 percent and 25 percent, respectively, *conditional on the occurrence of rainfall*); and 2) the PoP. Forecasters additionally edit and/or specify gridded, 6- and/or 12-hour expected value QPFs (or expected fractions) to disaggregate the 24-hour total (conditional) expected precipitation into subperiods of equal duration. Specifically, forecasters are provided the option of 1) utilizing a hierarchical approach (i.e., subdividing the 24-hour total into two 12-hour forecasts, and further subdividing each of the two 12-hour forecasts into two 6-hour QPFs), or 2) editing and/or specifying expected values (or fractions) for each of the four 6-hour forecast periods directly.

Disaggregation of the mean (expected value) of the conditional distribution is performed assuming disaggregative invariance, i.e., the expected fractions:

$$(\frac{W_1}{W},\frac{W_2}{W},\frac{W_3}{W},\frac{W_4}{W})$$

conditional on W > 0 at a given grid point, are stochastically independent of the 24-hour conditional mean (Krzysztofowicz and Pomroy, 1997; Krzysztofowicz and Sigrest, 1997). When a forecaster opts to edit and/or specify expected values when performing the temporal disaggregation, gridded fields of expected fractions are computed from the edited expected value QPFs.

These gridded QPFs/PQPFs and PoPs are generated twice per day and provided to the OHRFC in Wilmington, OH, where they are non-interactively mosaicked by HAS forecasters. These edited, forecast grids are utilized as input to the OH Ensemble Precipitation Processor (EPP) to produce an ensemble of Mean Areal Precipitation (MAP) time series for RFC sub-basins (Schaake and Larson, 1997; Schaake and Larson, 1998). This information serves as input to the OH Ensemble Streamflow Prediction (ESP) Model to generate short-range PRSFs (Office of Hydrology, 1996; Schaake and Larson, 1997; Schaake and Larson, 1998; Seo et al. 1999; Schaake et al., 1999). In parallel, the edited grids are utilized as input to the UVA Bayesian Precipitation Processor (BPP) which will interface with the UVA Analytic Model for short-range PRSF (Kelly and Krzysztofowicz, 1996; Krzysztofowicz, 1997; Krzysztofowicz et al., 1997, Krzysztofowicz, 1998b; Krzysztofowicz, 1999; Herr and Krzysztofowicz , 1999). A comparison of the PRSFs generated via these two approaches is being made at four river forecast points in the Upper Monongahela River Basin.

The majority of NWS field offices routinely generate gridded 6-hour expected value (deterministic) QPFs through a range of 24 hours utilizing the PC-based WinQPF application (Fenbers, 1995) developed at the OHRFC. Notable exceptions are WR and PR, where point rather than gridded QPFs have been the standard for many years. AR also issues QPFs in a point format, and has been doing so on a routine basis since the Fall of 1996. WR forecast offices routinely issue 6-hour QPFs through a range of 72 hours in a point format, 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. A recently developed QPE/QPF application, Mountain Mapper (Henkel and Peterson; 1996) (also see section 11.2.3), utilizes WR-developed grid editing tools and NWSRFS precipitation pre-processing software (and high resolution gridded climatic precipitation analyses) to remap gage measurements of rainfall and point QPFs as grids and compute MAP and FMAP values for hydrologic basins. Specifically, Mountain Mapper utilizes 4 km monthly climatological Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation analyses from the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Water and Climate Center (WCC) at Oregon State University (http://www.ocs.orst.edu/prism/prism_new.html) to interpolate point precipitation estimates and forecasts to the Hydrologic Rainfall Analysis Project (HRAP) grid. In the near term, an approach similar to that employed by Mountain Mapper could be utilized within AWIPS to remap point PQPFs as grids.

Provided high resolution gridded guidance which accurately accounts for the complex orography, WR forecasters could prepare QPFs by editing grids rather than issue point forecasts (Andy Edman, 1997, personal communication). It is envisioned that the operational implementation of advanced atmospheric data assimilation techniques and higher resolution, physically representative, numerical and statistical models and ensemble prediction systems will provide gridded forecast guidance with sufficient spatial detail and accuracy to enable all field forecasters to directly edit and generate gridded QPFs/PQPFs and PoPs using AWIPS. During September 1997, a broad spectrum of operational forecasters and software developers were assembled at the Colorado Basin RFC (CBRFC) in Salt Lake City, UT to specify AWIPS requirements in support of the preparation, coordination, and verification of QPFs/PQPFs for all components of the forecast process (see section 2.3.3). A meeting summary and a list of prioritized requirements, which are being mapped into future AWIPS builds, is provided in appendix A.

The additional forecast responsibility imposed upon forecasters to generate PQPFs (vs. current deterministic QPFs) is anticipated to be small relative to the potential service benefits, although this assumption remains to be proven via the ER risk reduction and additional probabilistic risk reduction exercises projected for other NWS Regions. The PQPF methodology to be tested in the forthcoming ER risk reduction requires a maximum of two additional grids, per 24 hour forecast period, beyond the current responsibilities of most field offices.

4.2.2. Generation of Probabilistic River Stage Forecasts

The OH has presented their plans for utilizing PQPFs in ESP to generate short-range PRSFs at several forums to include:

- the July 1996 HIWG meeting,
- the Fifth National Heavy Precipitation Workshop at State College, PA, in September, 1996 (Schaake, 1996),
- the 13th Conference on Hydrology at Long Beach, CA, in February 1997 (Schaake and Larson, 1997),
- the Special Symposium on Hydrology at Phoenix, AZ, during January 1998 (Schaake and Larson, 1998), and
- the 14^{th} Conference on Hydrology at Dallas, TX, during January 1999 (Adams et al., 1999; Perica et al., 1999).

The OH short-range ESP methodology builds upon recently completed collaborative COMET sponsored research between the OHRFC and the UVA (Krzysztofowicz, 1998b) and benefits from current collaborative work between the OH and UVA. The OH short-range ESP methodology is a computationally intensive approach, and an assessment of the computer and staffing resources necessary to implement this methodology operationally will be conducted as a part of the ongoing probabilistic risk reduction in the ER. A similar assessment to determine the resources required to implement the UVA Bayesian forecasting system, will also be conducted. The OH ESP approach will utilize PQPF information in the following manner to generate PRSFs (Schaake, 1996; Schaake and Larson, 1997; Schaake and Larson, 1998; Seo and Finnerty, 1998; Perica et al., 1999a; Perica et al., 1999b; Schaake et al., 1999; Seo et al., 1999):

- Interpolate PQPFs (gridded 24 hour conditional exceedance fractile values X_{25C} and X_{50C}) and gridded 24-hour PoPs to the 4-km HRAP grid;

- Interpolate 6- and 24-hour expected value QPFs (conditional on the occurrence of rainfall during 24-hour forecast period) to the 4 km HRAP grid;

- Utilize the OH Ensemble Precipitation Processor (EPP) -- a statistical model recently developed by HRL -- to generate an ensemble of precipitation time series at each HRAP grid point. An ensemble member is a set of gridded 6-hour precipitation patterns. EPP will re-scale the PQPFs and PoPs by adding spatial variability at the HRAP-scale (see figure 8) -- this added variability is needed since hydrologic models are sensitive to spatial variability. The amount of spatial variability added by the EPP will be adjusted so that the climatology of the ensemble members matches the climatology of the observed precipitation. The effective scale of the PQPF product is the area over which observed precipitation must be averaged so that the distribution of forecast exceedance probabilities of the observations is most nearly a uniform distribution. For the purpose of the probabilistic risk reduction exercise in ER, the effective scale of the value-added HPC/WFO/RFC HAS PQPF products is assumed to be approximately 5,000 square kilometers, and this scale will be modified if necessary as verification data become available;

- Compute MAPs for each 6-hour period for each ensemble member to produce an ensemble of basin MAP time series;

- Input the ensemble of basin MAP time series into NWSRFS. Each ensemble member is processed independently for all RFC hydrologic forecast areas to produce an ensemble of equally likely flow hydrographs for each river forecast point;

- Utilize an error model to adjust flow hydrographs to account for the uncertainty in the hydrologic model and the initial conditions (Perica et al., 1999b) [Prior to implementation, OH will 1) develop and fully test this model to ensure it accurately quantifies the multiple sources of hydrologic uncertainty, and 2) provide error model documentation and training];

and,

- Generate probabilistic river guidance products from the adjusted ensemble of streamflow hydrographs.

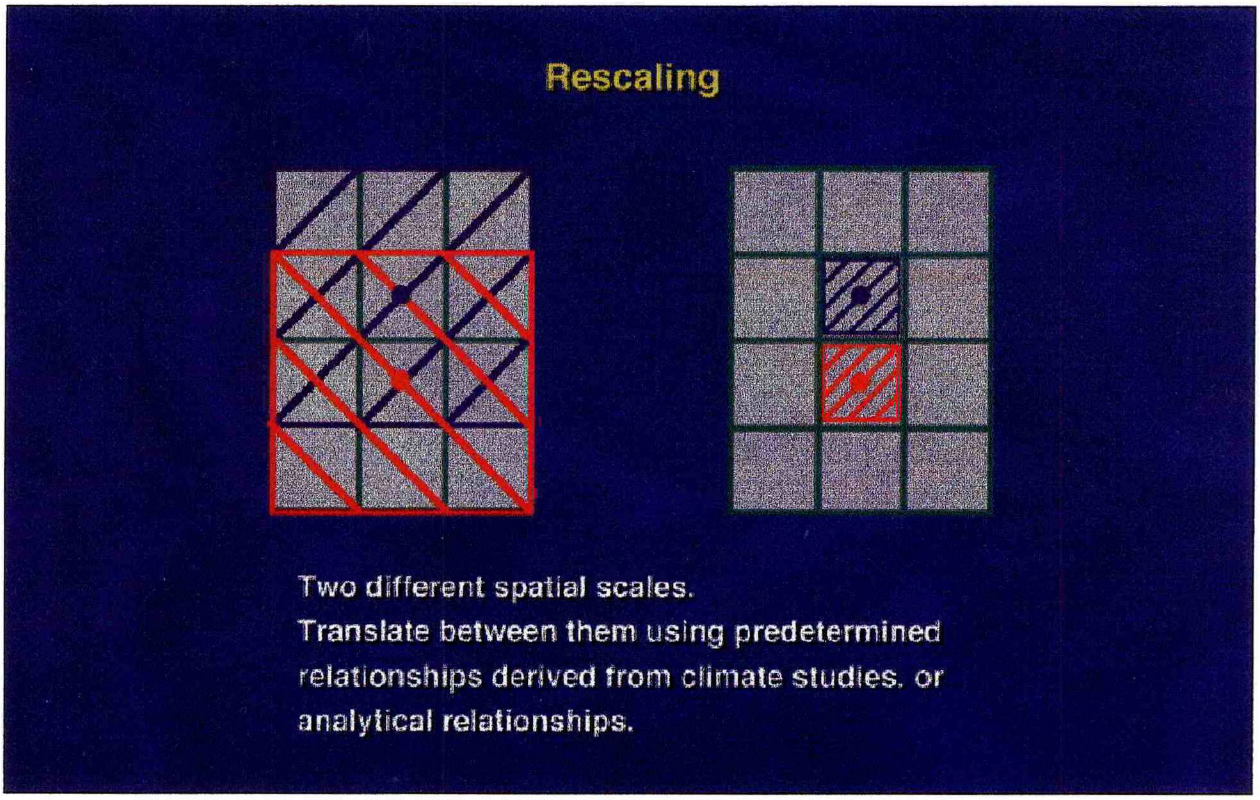

Figure 8: Schematic depicting how the Office of Hydrology Ensemble Precipitation Processor will re-scale forecaster-prepared probabilistic QPFs and PoPs. Figure on left depicts information with effective resolution of 9X displayed on a grid with resolution X. The figure on the right depicts the information after re-scaling with an effective resolution equal to that of the grid on which it is displayed (courtesy of Edwin Welles, Office of Hydrology).

4.2.3. Prototype PRSF Products and Decision Assistance Tools

An additional risk reduction exercise, utilizing ESP within AHPS to generate long-range PRSFs, was conducted in the Des Moines River Basin during March 1997 (Office of Hydrology, 1997). The primary goals of the Des Moines Risk Reduction Exercise were to:

- Use climate coupling and ESP techniques in long-range hydrologic forecasts,

- Provide probability information in hydrologic products, and
- Demonstrate a flood inundation mapping capability.

The Des Moines River Basin was selected because of the devastating impacts of the Great Flood of 1993, and the exercise successfully demonstrated that AHPS is ready for national implementation. The risk reduction exercise was a collaborative effort involving the North Central RFC (NCRFC) in Minneapolis, MN, NWS Central Region Headquarters in Kansas City, MO, the NWSFO located in Des Moines, IA (DSM), and the Office of Hydrology in Silver Spring, MD. Participants from the user community included the USGS, the Rock Island U.S. Army Corps of Engineers, the City of Des Moines, the City of Des Moines Water Works, the State of Iowa, and Iowa State Emergency Managers. User-requested, long-range probabilistic hydrologic products, utilizing short-term deterministic QPF and climate coupling (see figures 9, 10, and 11), included a:

- 60-day ESP probability time series for flow, volume, and stage,
- 60-day exceedance probability plot for flow and stage, and
- Flood inundation map depicting 25, 50, and 75 percent probabilities of flooding at 60 days.

In support of the ongoing probabilistic risk reduction in the NWS Eastern Region, and in coordination with the NWS, the UVA has developed a prototype River Forecast Interface (RFI) for use by WFO forecasters and end users. Forecasters and users will use the RFI to display routinely generated short-term (i.e., through Day 3) PRSF guidance output from 1) the OH ensemble streamflow prediction system and 2) the UVA Bayesian forecasting system (see figure 12). Both of these PRSF systems utilize 24-hour forecaster value-added PQPFs as input. The RFI was designed to serve four primary purposes (Gunderson and Krzysztofowicz, 1999):

- to display the PRSF for a specific forecast point;
- to serve as a forecaster decision aid for issuing routine and flood watch/warning products;
- to communicate information to end users, and
- to aid end users in making decisions.

The RFI is a critical forecaster tool which will be thoroughly tested and enhanced during the current ER risk reduction, and future risk reductions being planned for other regions.

The results and collective assessment of the Des Moines, ER, and future probabilistic risk reductions will be utilized to specify a probabilistic hydrometeorological system for national implementation.

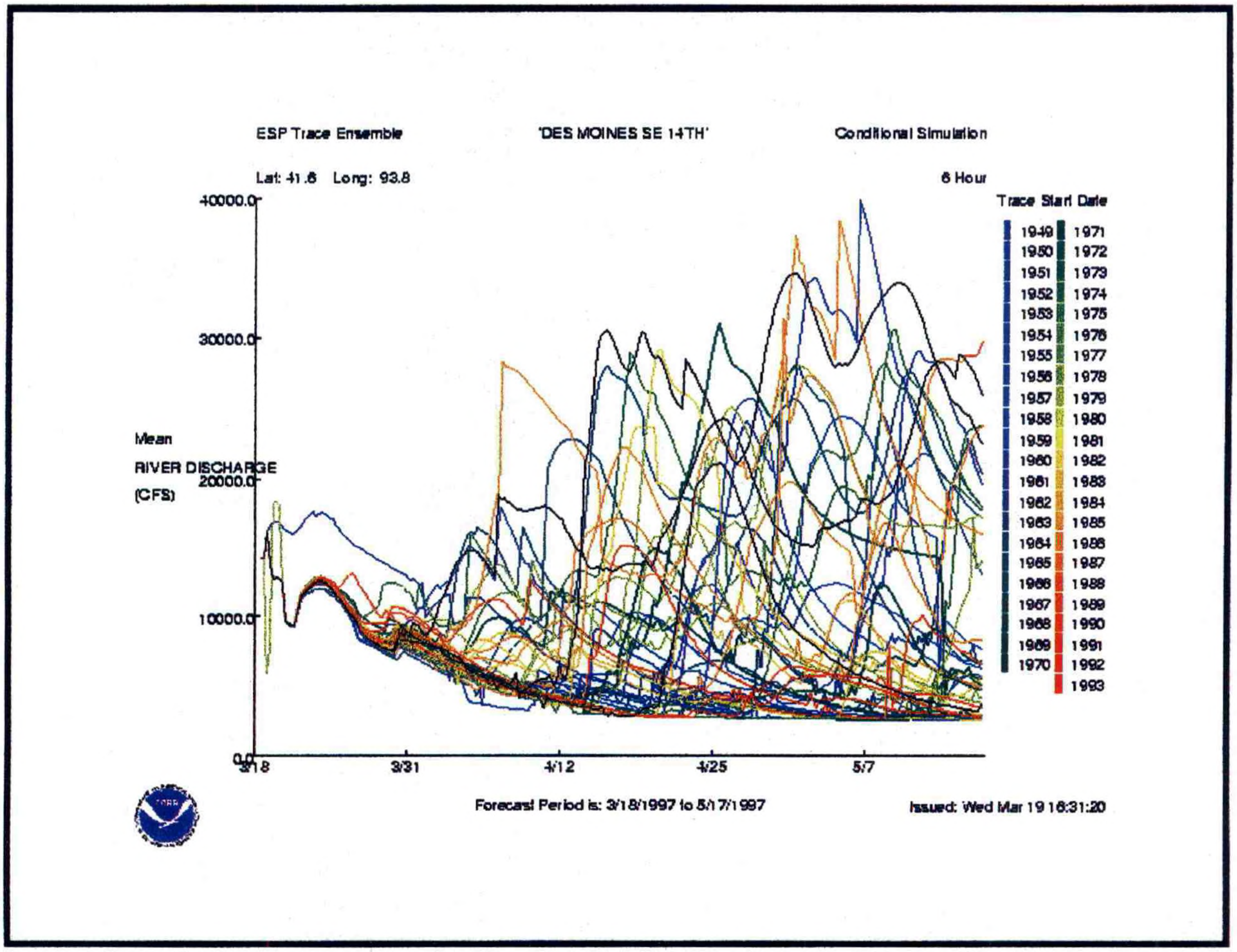

Figure 9: AHPS-based long-range (60 day) "spaghetti" plot of river discharge utilizing ESP and climate coupling (courtesy of Lee Larson and Edwin Welles, Office of Hydrology).

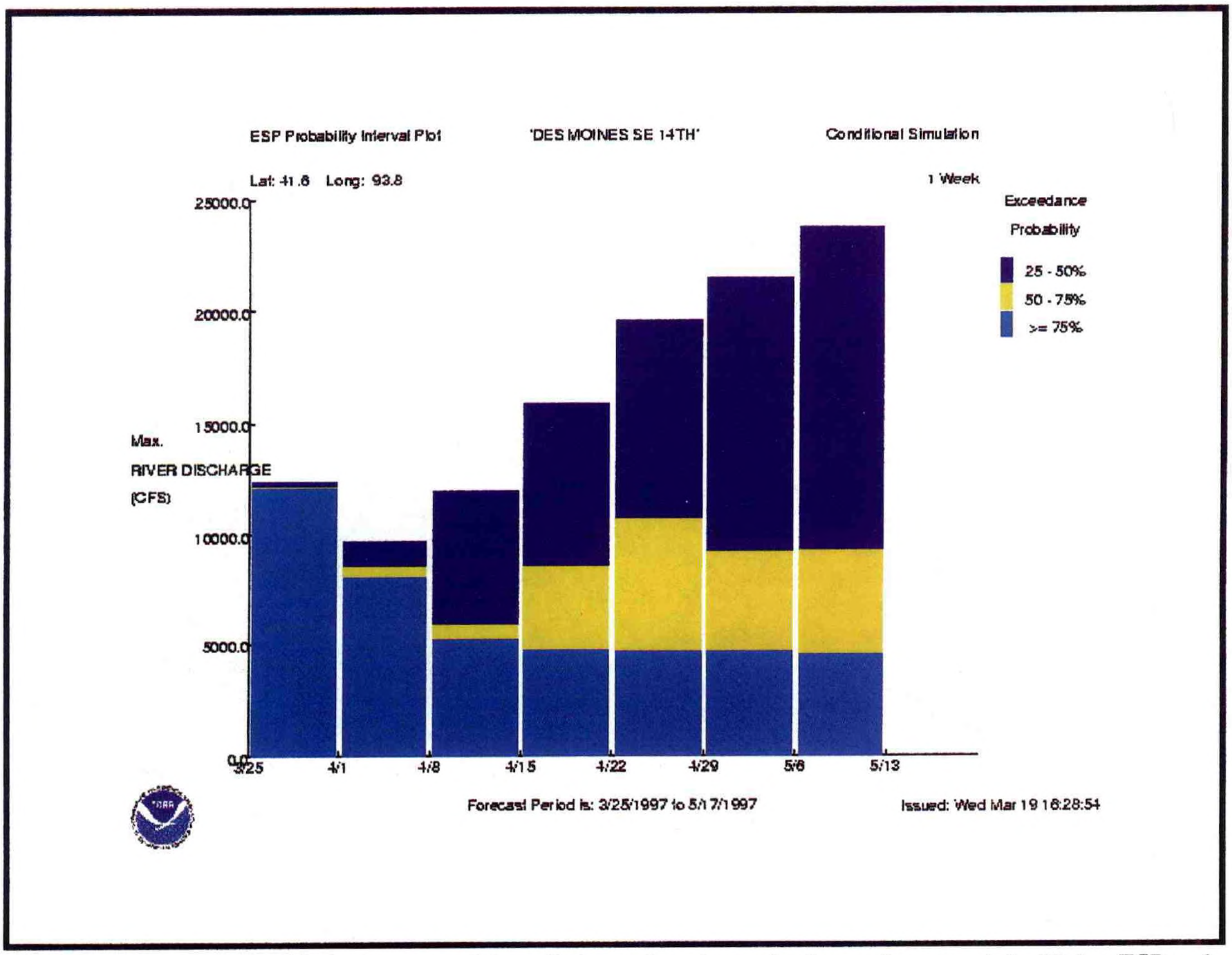

Figure 10: Weekly probabilistic forecasts of river discharge based upon hydrographs generated utilizing ESP and climate coupling (see figure 9) (courtesy of Lee Larson and Edwin Welles, Office of Hydrology).

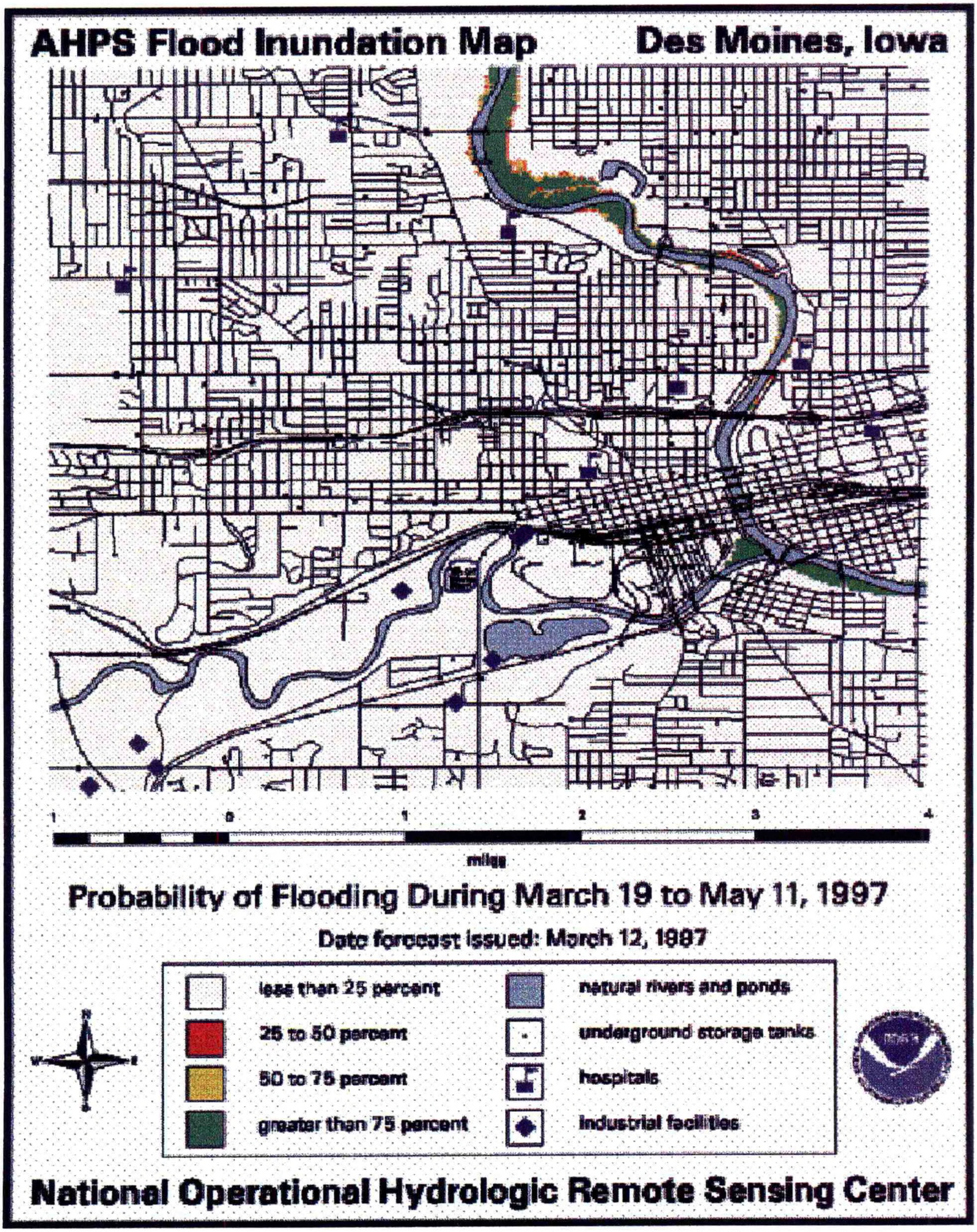

Figure 11: AHPS flood inundation map for Des Moines, IA, depicting percent probabilities of flooding (courtesy of Lee Larson and Edwin Welles, Office of Hydrology).

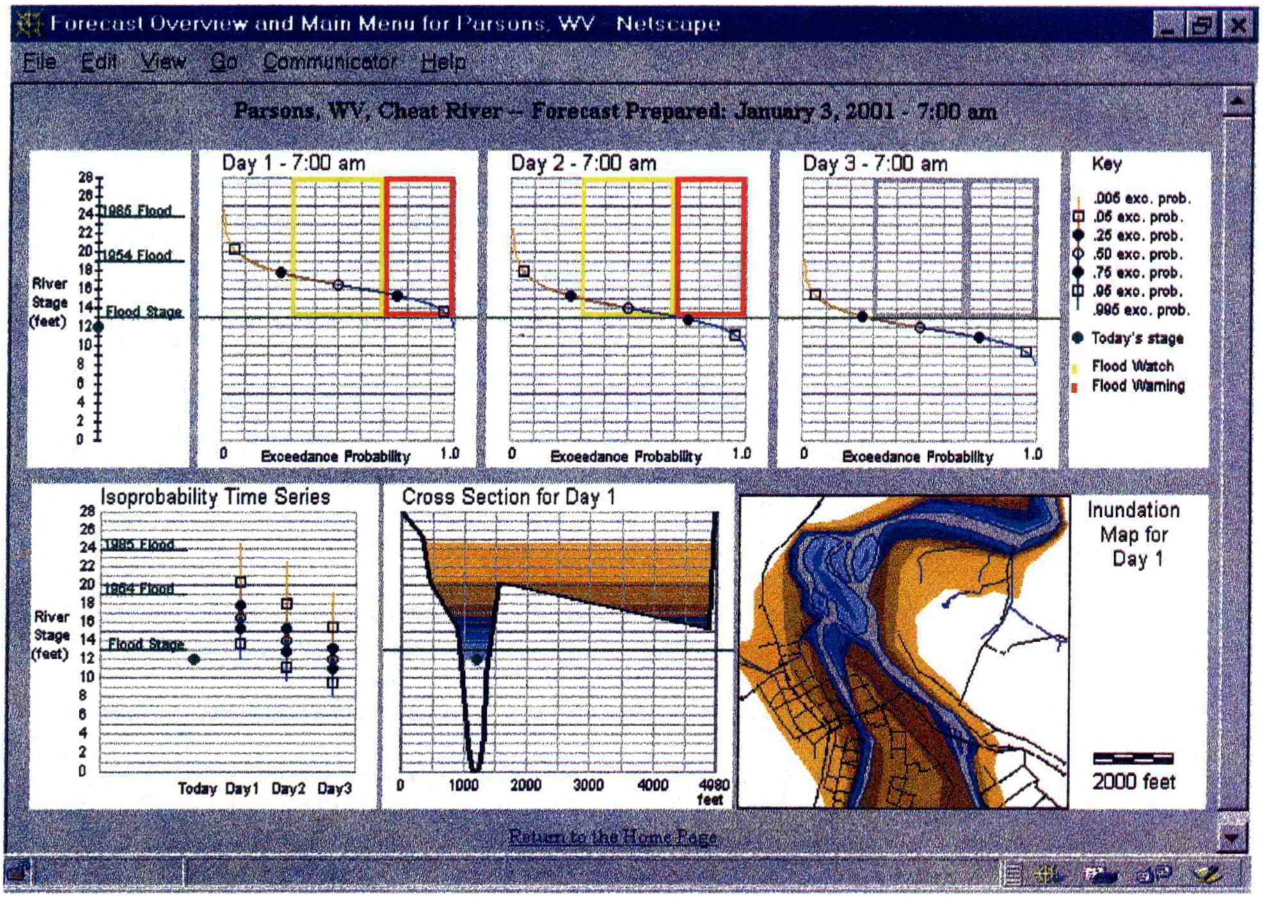

Figure 12: RFI main menu page with probabilistic river forecast overview depicting 1) river stage exceedance functions for Day 1, Day 2, and Day 3 (three top center panels) with watch (yellow) and warning (red) alarm boxes, 2) isoprobability times series for Day 1, Day 2, and Day 3 (lower left panel), 3) the river cross section with color-coded exceedance fractiles, and 4) a probability of innundation map. Due to resource constraints, a high resolution topographic map is being used in lieu of the innundation map for the ER probabilistic risk reduction exercise. Image courtesy of Louise Gunderson and Roman Krzysztofowicz of UVA.

5.0. River Forecast Center Products and Requirements

Recognizing the increased societal and economic benefits of risk-based hydrologic forecasts, and responding to end user requests, RFCs plan to effect a transition from short-range deterministic to short- through long-range probabilistic river stage forecasting. This transition is contingent upon 1) the implementation of AHPS, 2) the development, successful testing, documentation, and implementation of methodologies which produce short-range PRSFs and accurately quantify and account for hydrologic uncertainties, and 3) regional risk reductions wherein a quantitative assessment of associated resource requirements is conducted to ensure enhanced services can be provided with projected staffing and computational capabilities.

5.1. River Forecast Center Operations

RFCs integrate numerous river stage/flow, temperature, and precipitation observations and forecasts, and input this information into hydrologic models to generate streamflow stage forecasts for hundreds of river forecast points within the forecast domain of each RFC. RFC forecasts are vital for the preparation and issuance of timely and accurate watches and site-specific river flood warnings at WFOs and are applied to a broad spectrum of hydrologic problems by diverse users. Observed and predicted precipitation, or the lack thereof, has a significant influence on the future variation of river stage with time. Consequently, QPEs and QPFs can greatly enhance the value of river-stage forecasts. RFCs are beginning to assimilate Stage III-based, hourly, gridded precipitation time series for use in operational hydrologic forecast models. Additionally, RFCs currently utilize deterministic QPFs as input into NWSRFS and will require PQPFs to generate probabilistic river stage and flow forecasts. The format of probabilistic QPFs will be based upon the results of the forthcoming HIWG-supported ER risk reduction exercise (see section 4.2), and similar risk reduction exercises planned for other NWS regions. Advanced Hydrologic Prediction System (AHPS)-based forecasts, spanning the temporal range from hours to months, will benefit from improved QPEs and QPFs/PQPFs (see figure 13). AHPS will utilize as input a continuous spectrum of future precipitation information to include HPC-WFO-RFC/HAS forecaster value-added PQPFs, statistically post-processed global ensemble-based PQPFs, and RFC-modified climatological PQPFs, for the short-, medium-, and long-ranges, respectively (Fread et al., 1999; Perica et al., 1999a). RFCs will use NCEP/Climate Prediction Center (CPC) forecasts to adjust climatological PQPF information so the statistical properties of the adjusted climatological data agree with the CPC forecast. The use of CPC forecasts to adjust climatological PQPFs was successfully demonstrated by OH and the North Central RFC (NCRFC) during the March 1997 risk reduction exercise in the Des Moines River Basin. The primary applications of the AHPS-based short- through long-range river forecasts (which incorporate the impact of snowmelt when necessary) include:

- flood forecasting,
- hydroelectric power generation,
- municipal water supply management,

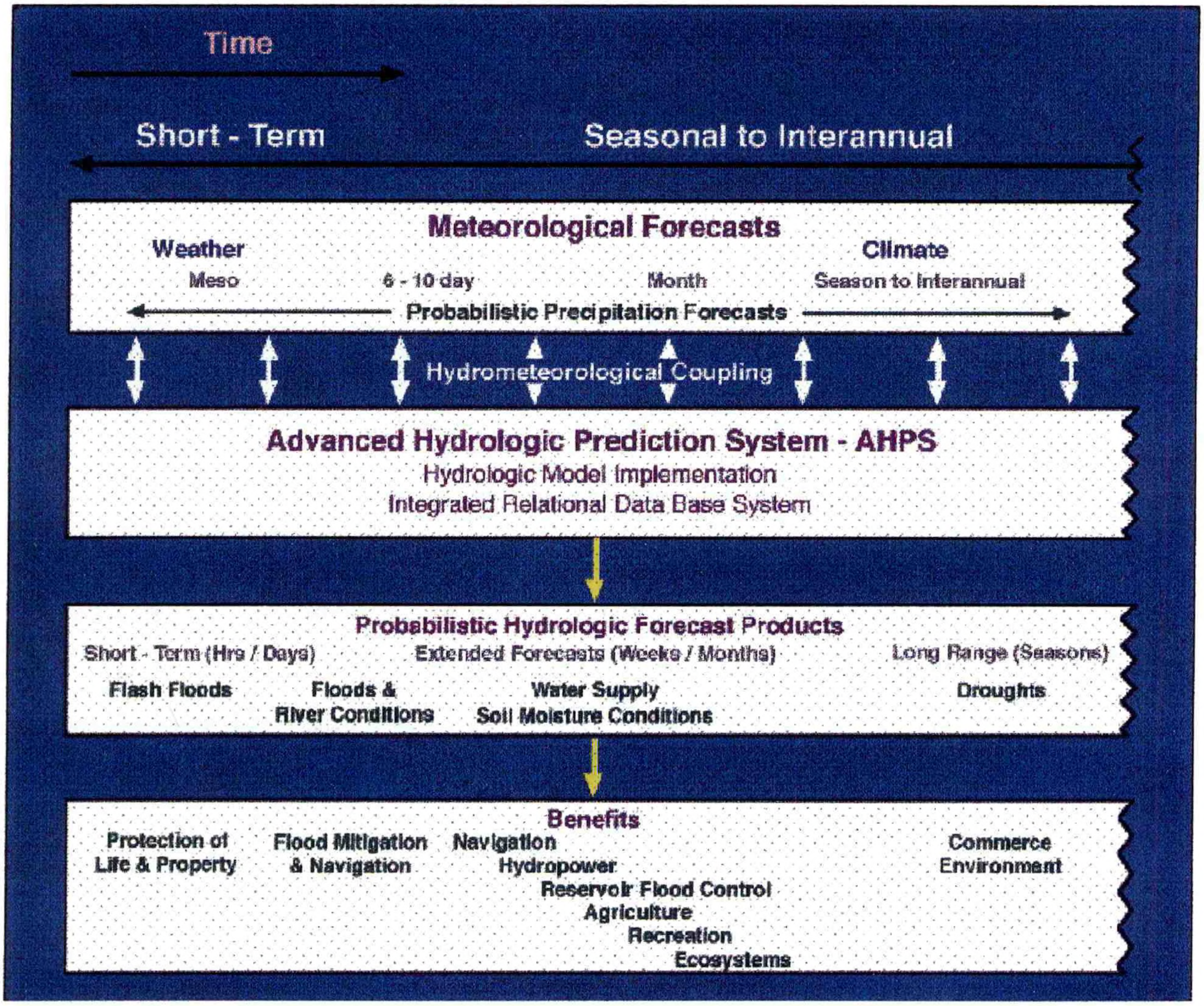

Figure 13: Illustration of the coupling between atmospheric and hydrologic models, and the applications and benefits of AHPS-based, short- through long-range probabilistic forecast and warning products (courtesy of John Ingram, Office of Hydrology).

- navigation,
- recreation,
- transportation,
- irrigation, and
- reservoir operation.

Additionally, RFCs provide FFG to WFOs for use in determining the areal potential for flash flooding and the issuance of flash flood watches and warnings. A more detailed explanation of the present and future operational capabilities of an RFC is contained in Zevin (1994), Fread et al. (1995), Chapter 2 of "Hydrometeorological Service Operations for the 1990's" (Office of Hydrology, 1996), Fread (1998), and Schaake and Larson (1998). The methodologies used to generate and issue PRSFs and flood watches and warnings, and the format of these products, will be based upon results of the recently completed risk reduction exercise in the Des Moines River Basin, the ongoing probabilistic risk reduction exercise in the NWS Eastern Region, forthcoming risk reductions being planned for other NWS Regions, and coordination with external users.

5.2. The Production of Quantitative Precipitation Information at the River Forecast Center

As a matter of routine operations, RFCs will produce precipitation analyses and forecast products on the Hydrologic Rainfall Analysis Project (HRAP) (Schaake, 1989) grid for their area of forecast responsibility. The HRAP grid is a superset of the Limited-area Fine Mesh (LFM) model, polar stereographic grid, with a 1/40 LFM meshlength.

5.2.1. Analyses

RFCs will generate the following HRAP-gridded analyses (Office of Hydrology, 1996):

- *Stage III Multi-Sensor Precipitation Analyses*

  The hourly, 4-km, Stage III product is a composite (or mosaic) of all the Stage II multi-sensor precipitation analyses produced at WFOs whose WSR-88D coverage intersects an RFC's area of responsibility (see table 2 section 1.6). The HAS forecaster performs an interactive analysis and quality control check on the mosaicked data. This analysis and quality control consists of activities such as substituting gage-only precipitation fields for multi-sensor fields and editing areas affected by anomalous propagation. The Stage III analyses are utilized in the RFC hydrologic models and will also be provided to contributing WFOs and to NCEP.

- *Post Analyses of Precipitation Accumulation*

  Post analyses will incorporate additional ground-validation information into the hourly Stage III products. Temporal aggregates of the hourly Stage III analyses will be generated utilizing additional gage reports not available in near real-time or on an hourly basis (i.e., COOP rainfall reports, additional GOES DCP reports, etc.). A 24-hour post analysis will be conducted (for the 24-hour periods 1200-1200 UTC and 0000-0000 UTC) to provide a Stage III precipitation product which contains all possible data sources. This post analysis product will be utilized to perform an optimal update of soil moisture variables in RFC models, and will be provided to contributing WFOs and NCEP to verify PoPs and QPFs/PQPFs.

- *Flash Flood Guidance*

In support of areal flash flood warning and forecast operations, RFCs will typically produce 1-, 3-, 6-, 12-, and 24-hour HRAP-gridded FFG twice per day. The frequency at which the FFG is updated may vary by RFC as a function of season in accordance with the needs of their associated WFOs. This guidance will be provided to WFOs and the NCEP and will be utilized to determine the areal potential for flash flooding. Areal gridded FFG, which will be calculated using new nationally-supported, OH-developed algorithms (Sweeney, 1992; Office of Hydrology, 1996; http://hsp.nws.noaa.gov/oh/hrl/ffg/ffgplan.htm) is based upon:

- GIS-based, gridded threshold runoff values,
- current soil moisture variable states in the RFC hydrologic model;
- the latest observed precipitation (e.g., Stage III) since the last update of the soil moisture model; and
- a hydrologic model which calculates the rainfall necessary to cause bankfull flows within the specified time intervals along the stream network grid.

Gridded threshold runoff values represent the estimated discharge necessary to cause bankfull conditions in each HRAP-grid area and will be pre-calculated (and updated as necessary) for each RFC grid element using a GIS and a simple hydrologic model.

5.2.2. Forecasts

A primary duty of the forecaster performing the HAS function will be to assimilate a spatially and temporally consistent representation of QPFs/PQPFs and PoPs (and temperatures where required) over the RFC's area of responsibility for input to NWSRFS. The primary input to this process will be the QPFs/PQPFs and PoPs (through Day 3) provided by all supporting WFOs. The HAS forecaster will use AWIPS software applications to mosaic and edit WFO QPFs/PQPFs and PoPs. Where inconsistencies exist in these forecast products across WFO boundaries, the HAS forecaster is responsible for coordinating with their partner WFO (and HPC) forecasters to reconcile these differences. The development (in coordination with UVA) and implementation of sophisticated statistical-human software tools within AWIPS will facilitate the mosaicking of PoPs and QPFs/PQPFs. These AWIPS tools are necessary to ensure that the task of mosaicking Day 1, 2, and 3 grids is feasible and that HAS forecasters can add value through their expert judgement. AWIPS must enable RFC HAS and WFO forecasters to view both mosaicked unedited and HAS-edited WFO QPFs/PQPFs and PoPs and thereby facilitate the coordination process. The RFC HAS (and WFO) forecasters will also have gridded NCEP and TDL guidance products and climatological QPFs/PQPFs and PoPs at their disposal to facilitate the preparation/assimilation of forecasts. It is expected that prior coordination among the WFOs involved will minimize the amount of additional reconciliation required by the HAS forecasters. When necessary, every effort will be made by the HAS forecaster to reconcile substantial differences between WFO QPFs. If substantial differences across WFO borders remain after WFO and HAS coordination efforts, the HAS forecaster will alter QPF/PQPF and PoP products provided by one or more of the WFOs in accordance with regional policy. This approach will ensure that temporally and spatially consistent mosaics are input to NWSRFS. In potential flood situations, it is recommended that the HAS forecaster coordinate any substantial modifications with the affected MICs and/or HICs. The final mosaicked products will be ingested into RFC hydrologic modeling systems to produce deterministic and risk-based hydrologic forecast information as described in section 5.1.

5.3. River Forecast Center Quantitative Precipitation Information Requirements

Operational RFC hydrologic models require observed hydrometeorological variables (e.g., precipitation, temperature, potential evaporation, etc.) and river stage and predicted precipitation amounts as input to simulate soil moisture and streamflow. Stages corresponding to these simulated streamflow rates are obtained from stage-discharge relationships before the information is disseminated to the public as river and flood forecasts.

RFC models are currently calibrated to individual sub-basins which average ~2000 square kilometers in size. Eventually, the modeling of these sub-basins will involve further subdivision of areas as advanced distributed modeling procedures are implemented. With the availability of the quality-controlled, multi-sensor Stage III precipitation analyses, gridded high resolution observed rainfall amounts will be available in near real-time. AHPS-based modeling procedures are evolving to take full advantage of these fine-scale precipitation analyses, as well as high resolution QPFs/PQPFs.

It is imperative that the observed and forecast precipitation amounts assimilated into the operational RFC hydrologic models be as unbiased as possible. The multi-sensor Stage II-III rainfall analyses, integrating WSR-88D, ASOS, and other gage rainfall accumulations (e.g., ALERT, IFLOWS, GOES DCP, state Mesonets, etc.) provide high temporal (hourly) and spatial (4 km) resolution QPEs. The Stage II-III products are designed to optimally integrate these data and maximize the accuracy of the rainfall estimates (Shedd and Smith, 1991; Smith and Krajewski, 1991; NWS, 1993a,b; Fread et al., 1995; Breidenbach et al., 1998; Seo, 1998a; Seo, 1998b; Seo, 1998c; Seo et al., 1998). Current efforts to increase the number and availability of gage rainfall data, critical for the real-time bias correction of radar rainfall estimates, will be outlined in section 10.0. For a specified spatial scale, QPFs/PQPFs should be unbiased in the sense that over many forecasts, the average areal amount forecast (and its frequency of occurrence for PQPFs) should be the same as that observed within a reasonable sampling error. If precipitation is overestimated or overforecast, the corresponding forecast streamflow volumes will be too large and the stages too high. Similarly, if precipitation is underestimated or under forecast, the converse is true. The problem is compounded in large, complex basins. Excessive (or insufficient) simulated runoff from upstream basins is routed into downstream basins, thereby rendering stage forecasts for downstream points even less reliable than those for upstream points when significant QPF/PQPF biases are introduced upstream.

In the near future, the multi-sensor Stage II-IV precipitation analyses will utilize GOES Infrared (IR) satellite data in conjunction with NWP model temperature analyses to help identify rain/no rain areas and mitigate the adverse impact of ground return anomalous propagation (Breidenbach et al., 1998). Efforts are underway to expand the use of satellite data for rainfall estimation. These efforts are vital to the development of a high resolution multi-sensor QPE covering the NWS's entire area of forecast responsibility which takes advantage of the strengths and avoids the weaknesses of each observation platform. Satellite-derived QPEs will provide offshore rainfall estimates and have the potential to mitigate the impact of radar-rainfall estimation problems which include:

- beam blockage;
- precipitation development, growth and/or evaporation below the radar beam (e.g., mountain valleys and shallow bands);
- incomplete coverage;
- bright banding;
- range degradation (e.g., beam broadening, attenuation, etc.); and
- universally unrepresentative reflectivity (Z) vs. precipitation rate relations for rain, snow, and ice.

The NESDIS Office of Research and Applications (ORA), in cooperation with OM and OH, is developing and testing an automated, multi-channel, GOES-based algorithm to generate QPEs. The "Auto-Estimator" algorithm estimates instantaneous rainfall rate from satellite radiance measurements with adjustments for storm and environmental characteristics which have a direct bearing on rainfall rate (Zhang and Scofield, 1994; Achutuni et al., 1996a; Achutuni et al., 1996b; Vicente, 1996; Vicente and Scofield, 1996; Vicente and Scofield, 1997; Vicente et al., 1998; Vicente and Scofield, 1998a; Vicente and Scofield, 1998b). The Auto-Estimator is planned to evolve to a multi-sensor technique through the integration of SSM/I-based rainfall estimates (Paul Menzel and Rod Scofield, personal communication, 1998). Recently developed and planned algorithm enhancements include parameters which account for the impacts of:

- the rate of cloud top growth;
- the cloud top temperature gradient (to differentiate updraft cores from anvil cirrus);
- the atmospheric water vapor content (Eta model precipitable water [PW] x mean relative humidity [RH]);

- cloud location errors (parallax correction);
- sub-cloud evaporation/sublimation;
- overestimation of precipitation in areas of cirrus cloud (the delineation of areas of active precipitation will be accomplished through the use of SSM/I, gage, and radar data);
- the height of the equilibrium level; and
- orography.

HPC, in concert with OH, EMC, OM, and NESDIS, is testing and validating this algorithm to determine its utility and formulate a methodology to integrate satellite-derived QPEs with gage and radar rainfall estimates. Results of this validation study are currently available via the Internet at the Web address http://www.ncep.noaa.gov/hpc/roz/verify/.

The current version of the Auto-Estimator algorithm estimates instantaneous rainfall rates for the continental U.S. and adjacent coastal areas every 15 minutes, and utilizes these estimates to compute 1) the hourly average rainfall rate, 2) the accumulated rainfall every hour, 3) the 6-hour accumulated rainfall at 06, 12, 18 and 00 UTC, and 4) the daily accumulation at 12 UTC. The results are available in real time both to the NESDIS Satellite Analysis Branch (SAB) and to Internet users at the Web address http://orbit-net.nesdis.noaa.gov/ora/ht/ff. Users have access to the latest 24 hours of data, zoom and animation capability, and can overlay state and county maps.

Given the great importance of precipitation analysis products for operational hydrologic and atmospheric modeling and QPF, the HRL of OH continues to validate and assess the quality of the Stage II-IV multi-sensor rainfall analyses for a spectrum of space-time scales to fully understand and maximize their operational utility. Further, additional applied research is necessary to fully assess the significance of gage network density on these multi-sensor QPEs, and to quantify and account for the uncertainty in NWS operational QPE products.

An additional RFC requirement, pertaining to the HAS function, is the capability to view and animate national mosaics of radar reflectivity and vertically integrated liquid (VIL) water. RFCs have the capability to produce, view, and animate hourly Stage III precipitation mosaics for their own forecast areas, but they cannot do the same for radar reflectivity and VIL water. Also, HAS do not have the capability to generate and/or loop any type of regional/national composite radar products which cover their entire forecast domain. To obtain radar reflectivity or VIL water data in near real-time, HAS forecasters must dial-up radars individually and routinely encounter transmission problems, busy signals, and premature termination of data inquiry by the remote WSR-88D Principal User Processor (PUP) being accessed. Further, the process is time consuming and data are limited to those WSR-88Ds whose surveillance area intersects the RFC's umbrella of responsibility. With the exception of Stage III precipitation mosaics, HAS forecasters have access to limited WSR-88D data and are relegated to generating a mental composite of available data. The ability to directly access and loop composite WSR-88D data (in near real-time) within and beyond their forecast area is crucial to monitoring the development and evolution of precipitation systems, forecasting their timing and intensity, and generating a mosaicked QPF/PQPF. Further, the AWIPS GUI utilized to display the composite images must enable HAS forecasters to:

- animate (or loop) the images,
- control the animation rate and number of images,
- automatically update the loop with the latest available image,
- zoom in on image features or specific geographic locations, and
- overlay GIS-based spatial reference data (see section 6.3) to include state, county, city, and hydrologic basin boundaries as well as streams, rivers, roads, railway systems and other significant user-specified landmarks such as hospitals and schools.

The implementation of AWIPS Build 4.2 will provide expanded functionality which will facilitate the dialing of multiple radars and the generation of regional mosaics. Furthermore, the planned delivery of basic radar products over the AWIPS Wide Area Network (WAN) to the national site for rebroadcast over the Satellite Broadcast Network (SBN), will further increase the availability of these data for the construction of mosaics.

5.3.1. RFC Requirements for Observations, QPE, Related Products, and Systems Capabilities

In support of the HAS function, current hydrologic operations, and advanced AHPS-based forecasting RFCs require:

In Situ Observations

- A *minimum* of 30 and a target of 50 real-time, spatially-distributed, all-season rain-gage observations per WSR-88D umbrella. This spatial density is required to adequately perform real-time Stage I radar rainfall bias corrections[1] and generate the Stage II-III multi-sensor products (Anagnostou et al., 1997).

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[1] *Rainfall bias corrections are planned to be performed in the future and are contingent upon the operational implementation of the ORPG.*

Radar

- Near real-time, WSR-88D, national, 15-minute a) 2-km, 1 dBZ (8-bit, 256 level) DHR and b) 4-km (4 bit, 16 level) VIL mosaics. The provision of these composite products requires implementation of the Open Systems architecture for the WSR-88D (Uccellini, 1996b). These national mosaics are required within 10 minutes of the mosaic valid time, will be comprised of the most recent data available, and will not include any radar data with a valid time more than 15 minutes previous to the valid time of the mosaic.

Multi-Sensor Analyses

- Near real-time, 4-km, hourly, valid on-the-hour, Stage II-III (for the forecast domain of the RFC) and Stage IV (national) quality controlled multi-sensor rainfall analyses integrating WSR-88D, ASOS, other gage rainfall data (e.g., ALERT, AHOS-T, IFLOWS, GOES DCP, state Mesonets, etc.) and satellite-derived rainfall estimates (Auto-Estimator-based satellite-derived precipitation estimates will be generated by the SAB of NESDIS -- see section 6.3.1 for specific product formats).

Systems Capabilities

- The AWIPS capability to display and interrogate precipitation and radar reflectivity and VIL mosaics and overlay GIS-based spatial reference data.

- The AWIPS capability to archive river stage observations, precipitation observations and analyses, and quantitative precipitation forecasts, especially for forecast verification.

5.3.2. RFC Requirements for QPF/PQPF, Related Hydrometeorological Guidance Products, and Systems Capabilities

In support of the HAS function, current hydrologic operations, and a national transition to AHPS-based, short- through long-range probabilistic river stage forecasting, RFCs require:

WFO Guidance

- Unbiased, value-added QPFs/PQPFs which represent areal average precipitation (the projected format of the PQPFs is specified in section 4.2; QPFs are expected values [or expected fractions] conditional on the occurrence of rainfall during the 24-hour period).

- QPFs/PQPFs and PoPs with the highest possible information content.

- WFO 0-72-hour, value-added, HRAP-gridded, QPFs/PQPFs and PoPs issued *twice* per day for the forecast periods beginning at 0000 and 1200 UTC, with a *minimum* temporal resolution of:

- Day 1: 6-hour QPFs (or expected fractions) and 24 hour PQPFs and PoP
- Day 2: 12-hour QPFs (or expected fractions) and 24 hour PQPFs and PoP
- Day 3: 24-hour PQPFs and PoP

[Note: 1) The frequency requirement (i.e., twice per day) for this information may vary by NWS Region as a function of season and/or current hydrometeorological events; 2) Current hydrologic models input QPF information for six hour periods. In light of this, and pending the results of the ER probabilistic risk reduction and similar risk reductions in other NWS regions, the Day 2 and Day 3 requirement will likely be increased to a temporal resolution of six hours prior to a national implementation of probabilistic forecasting; 3) Companion temperature forecasts will also be provided by WFOs as required by their servicing RFC.]

Local Guidance

- Gridded climatological PoP and conditional and unconditional QPF/PQPF guidance provided in a format consistent with the above RFC requirements.

Central Guidance

- The full suite of centrally-produced EMC model output, HPC value-added products, and TDL/EMC statistical guidance products required and utilized by WFOs to generate QPFs/PQPFs and PoPs for the RFC (see section 6.3.2 for a description of the WFO requirements).

- NCEP/EMC and OSD/TDL Day 4 through 14 (96 - 336-hour), statistically value-added, medium-range gridded PQPFs and PoPs *once* per day for the forecast period beginning at 1200 UTC, with a *minimum* temporal resolution of 24-hours (EMC global ensemble runs will serve as the basis for these PQPF products).

- NCEP/CPC long-range gridded precipitation probability anomaly forecasts issued on the 15th day of the month for:

  - the ensuing month, and

  - thirteen 3-month climate outlooks, successively lagged by one month each.

  The outlooks are probability estimates of total precipitation falling within the lower (below-normal), middle (near-normal), and upper (above normal) third of the climatological distribution (the required format and information content of these products may change pending forthcoming discussions between OH and CPC).

- The point/grid editing and display capabilities listed in Appendix A which support the preparation, coordination, and verification of QPFs/PQPFs within AWIPS.

5.4. Verification of QPI and Related Products

Verification of QPFs/PQPFs, PoPs, and (probabilistic) river forecasts will be routinely performed in parallel at the RFC. Locally computed measures of QPF/PQPF skill will be consistent with those specified in section 11.3 for the proposed National ETE verification program. QPFs/PQPFs and PoPs assimilated by the HAS forecaster for input into the hydrologic models will be verified against the RFC-produced aggregate Stage III post-analyses of precipitation accumulation or their equivalent. The timely computation of these verification scores and their provision to the HAS forecaster is critical. HAS forecasters will utilize this information to assess their performance, explore opportunities for improving assimilation techniques, and ensure their mosaicked QPFs/PQPFs are well calibrated and add value to the hydrologic forecasting process.

6.0. Weather Forecast Office Products and Requirements

In direct response to RFC and end user requirements, WFOs plan to incrementally expand hydrometeorological services to include the generation and issuance of 0-72 hour QPFs/PQPFs and AHPS-based probabilistic river forecast and warning products. Furthermore, the implementation within AWIPS of advanced decision assistance tools such as SCAN and WHFS will enable WFOs to issue more timely and accurate flash flood watches and warnings.

6.1. Weather Forecast Office Operations

The NWS MAR will enable field offices to improve and expand their provision of hydrometeorological services. Hydrometeorological products are currently disseminated to the public through Hydrologic Service Area (HSA) Offices, of which there are approximately 121 for the entire country. HSA responsibilities have been assigned to WFOs as a part of the NWS MAR. To enable WFOs to manage these hydrometeorological responsibilities and accomplish their operational mission, sophisticated decision assistance, product generation, and coordination capabilities will be implemented within AWIPS. These capabilities, which will include WHFS, SCAN, and the functionality of WinQPF and Mountain Mapper (see section 2.3.3. and appendix A), will facilitate the preparation of improved forecast and warning products. WHFS is an integrated system consisting of many applications which support the hydrology program at a WFO. WHFS capabilities include applications for data collection and management, data display, hydrometeorologic modeling, and product formatting and management functions. SCAN will integrate and enhance WHFS flash flood functionality within the AWIPS D2D to facilitate the watch/warning decision process. Furthermore, the QPF/PQPF output of SCAN algorithms and other QPF guidance will be used to compute the forecast average basin precipitation and predict the flash flood threat. Forecasters often face the difficult challenge of forecasting, monitoring, and issuing warning products for concurrent hazards. It is anticipated that the full implementation and coupling of SCAN and WHFS will reduce the likelihood of unwarned hazards, and promote the issuance of more timely and accurate flash flood watches and warnings.

WFO hydrometeorological responsibilities will include:

- *Preparation and Public Dissemination of River Forecasts and Flood Warnings*

Using stage, volume, discharge and other types of RFC forecast guidance, WFOs will be responsible for issuing public hydrologic products for what are often referred to as "main-stem" rivers. A river product formatter (RiverPro), resident in WHFS, will facilitate the efficient execution of this responsibility [for details of WHFS, the reader is referred to Chapter 3 of "Hydrometeorological Service Operations for the 1990's" (Office of Hydrology, 1996), Roe et al. (1998), and the Internet at the following address: http://hsp.nws.noaa.gov/oh/hrl/]. RiverPro ingests locally and RFC-developed site-specific forecasts and automatically composes hydrologic forecast and river flood warning products for review, modification (if necessary), and issuance by the WFO forecaster. However, RFC river stage forecasts are normally only modified by a WFO forecaster after consultation with the RFC. In the process of generating hydrologic products, RiverPro accesses site-specific information from the hydrologic database which contains static E-19 data. E-19 data define the physical and historical characteristics of each river forecast point to include impact statements describing the historical consequences of different river stages and crests. Since WFO-produced QPFs/PQPFs are a primary input to the RFC hydrologic models, WFOs play an important role in ensuring that the highest quality product is issued to the public in a timely manner.

- *Preparation and Public Dissemination of Flash Flood Watches and Warnings*

WFO forecasters will assess the potential for flash flooding and determine whether to prepare and issue public products using the hydrometeorologic modeling component of WHFS, and SCAN. The hydrometeorologic modeling component of WHFS includes the Site-Specific and Area-Wide Hydrologic Prediction Systems (SSHPS and AWHPS, respectively). These WHFS applications will allow the forecaster to access, integrate, and display observational data and analyses which include gridded FFG from the RFC, observations of precipitation and river stages, and WSR-88D data and derived precipitation products. SCAN will integrate and enhance the WHFS AWHPS flash flood functionality and enable forecasters to directly integrate and display flash flood threat products with companion high resolution observational and forecast data sets, analyses, and guidance within the AWIPS D2D. *These flash flood threat products will be generated automatically within SCAN every WSR-88D volume scan.* Furthermore, the high temporal and spatial resolution QPF/PQPF output of SCAN algorithms, EMC and TDL numerical and statistical model QPFs/PQPFs, and HPC and WFO value-added QPFs/PQPFs will be used within SCAN to generate automated flash flood threat products.

The WHFS SSHPS is a local hydrologic model which will enable the WFO forecaster to supplement RFC-provided main-stem river forecast guidance with site-specific, locally-generated forecast time series for selected points in small, fast-responding (headwater) stream basins. The WHFS AWHPS provides for the analysis, display, and comparison of observed and forecast precipitation with flash flood guidance. Introductory AWHPS capabilities include the ingest and on-demand comparison of WSR-88D-based precipitation estimates and forecaster prepared QPFs to FFG. These WSR-88D-based precipitation estimates include HRAP-gridded (4 km) Stage I and Stage II analyses (see table 2, section 1.6). These gridded precipitation estimates can be spatially aggregated over counties, zones, and RFC-defined MAP areas (basins), and temporally aggregated for 1, 3, 6, 12, and 24 hour durations. The comparison of forecaster prepared QPFs and FFG will initially be performed on the MAP scale.

Within AWIPS beyond Build 4.2, it is projected that SCAN will automatically generate AWHPS-like (i.e, HRAP-gridded) flash flood threat products. These threat products include the comparison of 1, 3, 6, 12, and 24 hour FFG with Stage I analyses every volume scan and Stage II multi-sensor and gage-only analyses once per hour. Additionally, comparisons will be made between FFG and statistical, numerical, and forecaster-prepared QPFs on a frequency consistent with the availability of these respective guidance products. It is important to note that OM, OH, OSD, and NSSL are also actively engaged in a coordinated effort to provide a small stream basin flash flood monitoring and forecasting capability (i.e., AMBER functionality) within SCAN. Utilization of this AMBER functionality operationally, however, would require WFOs to assume responsibility for defining small watersheds, on the order of ten square miles or less, over their respective forecast domains. SCAN will afford forecasters the capability to display flash flood threat products with high resolution companion data and products which include but are not limited to 1) lightning, radar, satellite, ASOS, high resolution terrain, and spatial reference data, 2) spotter reports, 3) radar and satellite-derived precipitation estimates, 4) Local Analysis and Prediction System (LAPS) analyses, and 5) all centrally- and locally-produced direct model and value-added forecasts and guidance. Locally-produced QPF products include short-term probabilistic precipitation forecasts generated via the Local AWIPS MOS Program (LAMP) QPF System, the AWIPS Thunderstorm Product, and the Thunderstorm Auto-nowcaster. Centrally-produced guidance products which will be accessible via SCAN for display within the AWIPS D2D, to assist WFO forecasters in assessing the threat for flash flooding include HPC QPFs, the HPC Rainfall Potential for Exceeding Flash Flood Guidance Product (see table 5, section 7.2), the SPC Heavy Rain Mesoscale Discussion (MD), and high resolution EMC NWP mesoscale model guidance. The SPC Heavy Rain MD is a new (FY 98) event driven product focused on describing 1) where heavy rain is likely to occur over small localized areas (generally not to exceed the size of four Midwestern or eight Eastern U.S. counties), 2) what type of phenomenon will generate the precipitation, 3) when the rain will begin and how long it will persist, and 4) the conditions and processes favoring the impending development of meso- and microscale phenomena capable of producing significant rainfall within the following 0-3 hour period. Specifically, SPC Heavy Rain MDs are issued when 1) rainfall rates up to 3 inches per hour are expected with slow moving convection (e.g., storms moving at 10 knots or less), 2) rainfall amounts of at least 2 inches expected at any one location within one hour, 3) rainfall rates of at least 1 inch/hour are expected to last at least 3 hours with a total rainfall of at least 4.5 inches, or 4) the forecast of an end to a heavy rain event. For more information on the SPC Heavy Rain MD the reader is referred to http://www.nssl.noaa.gov/~spc/products/meso/mesoform.htm. An accompanying Internet graphic depicting the affected CWAs will also be available via the SPC home page at: www.nssl.noaa.gov/~spc. Utilizing automatically generated flash flood threat products and the aforementioned companion data and products, SCAN will enable forecasters to assess the flash flood threat in conjunction with the threat of other hazardous phenomena such as severe thunderstorms and tornadoes. This is especially important given that the occurrence of these threats are not mutually exclusive (e.g., high precipitation [HP] supercells, mesoscale convective complexes [MCCs], etc., can and do produce severe weather and flash flooding).

The aforementioned HPC and SPC products, along with flash flood threat products generated within SCAN, will be used to assess and continually monitor the potential for flash flooding. To enhance forecaster situational awareness, SCAN will compute a SCAN CWA Threat Index (SCTI) for both flash floods and severe weather. Centrally- and locally- produced forecast and guidance products will be integrated to compute these indices, thereby applying the ETE Forecast Process more effectively to these threats. The SCTI will be updated automatically and displayed in the D2D of AWIPS as two small color-coded buttons (one each to depict the flash flood and severe weather threats) (see http://tgsv5.nws.noaa.gov/tdl/scan/scti.html for a more detailed description of the SCTI). A prototype of the SCAN CWA threat indices for flash floods and severe weather is presented in figure 14.

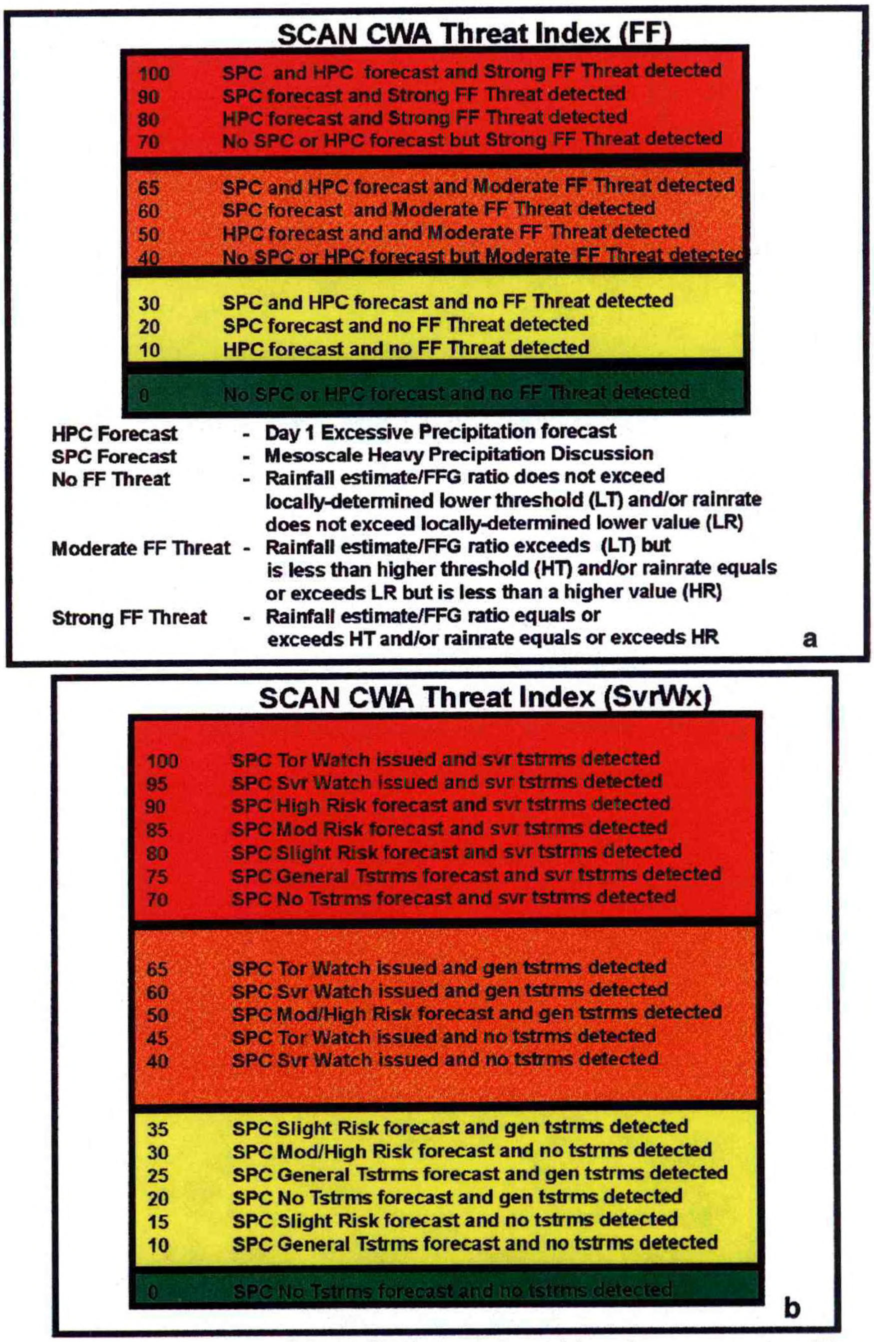

Figure 14: Prototype SCAN CWA flash flood (a) and severe weather (b) threat indices incorporating HPC and SPC centrally-produced guidance, and flash flood threat products generated locally on AWIPS within SCAN. In figure a, HPC Day 1 refers to the graphical HPC Rainfall Exceeding FFG Product. (Figure courtesy of Stephan Smith, Office of Systems Development)

The AWIPS Interactive Forecast Preparation System (IFPS) will automatically ingest the guidance and products produced by SCAN to prepare flash flood watches and warnings for review, modification (if necessary), and issuance by the WFO forecaster. Because of the fast response of small streams to precipitation, WFOs depend on quality observations and high resolution forecasts of rain events over these stream basins to provide flash flood watches and warnings. Therefore, accurate and timely precipitation observations, forecasts, and derived products will be a vital and integral part of the WFO hydrometeorological services.

- *Quantitative Precipitation and Temperature Forecasts*

The WFO has the responsibility to produce and disseminate QPFs/PQPFs to fulfill the RFC hydrologic forecast functions and its own flash flood services, and satisfy the operational needs of diverse users. Gridded, areal-average QPFs/PQPFs and PoPs (see section 5.3.2) will be generated routinely using specialized AWIPS software applications. These software applications will include the salient characteristics and capabilities of WinQPF and Mountain Mapper (see appendix A). The implementation of AWIPS will facilitate the generation of gridded QPFs/PQPFs, and improve inter-office coordination by enabling WFOs to view mosaicked, unedited WFO and edited HAS QPFs/PQPFs. Further, WFO forecasters will have the capability within AWIPS to directly initialize points and/or grid editors with locally- and centrally-produced QPF/PQPF guidance (or climatological guidance), which will expedite the generation of value-added forecast products. The WFO's primary sources of initial QPF/PQPF guidance will be HPC value-added products, TDL Model Output Statistics (MOS), and EMC single model and ensemble-based products. In addition to the QPFs/PQPFs and PoPs, the WFO will also produce, in the appropriate seasons and as requested by their servicing RFC, gridded temperature forecasts for those areas affected by snowmelt flooding.

The use of hydrometeorological forecasts varies markedly across the United States. Consequently, NWS policy and WFO services must reflect and account for this diversity. These variations are primarily due to 1) regional differences in terrain, watershed configuration, and associated flooding problems, 2) unique user requirements derived through interactions with federal, state, and local agencies, 3) local community use of the river systems and local river management practices, and 4) climatological regimes which may limit or favor the accuracy of longer term forecasts. In light of these marked differences, NWS operational policy must provide sufficient flexibility to allow WFOs to most effectively accommodate the needs of local users.

6.2. The Production of Quantitative Precipitation Information at the Weather Forecast Office

6.2.1. Analyses

WSR-88D-based, HRAP-gridded, Stage I and II hourly precipitation analyses will be produced locally on the WFO AWIPS (see table 2 section 1.6 and sections 5.2 and 5.3 for more details on the Stage analyses). Stage I analyses will be generated every WSR-88D volume scan (every 5-10 minutes depending upon the local scan strategy of the WSR-88D) and used for the areal assessment of flash flooding within the Area-Wide Hydrologic Prediction System of WHFS (see section 6.1), while Stage II analyses will be produced hourly and provided to the servicing RFC.

6.2.2. Forecasts

In support of a national transition to probabilistic hydrologic forecasting, the WFO's will transition over the next several years from issuing point or gridded QPFs and public text products (wherein little QPF/PQPF information is provided) to detailed gridded QPFs/PQPFs through Day 3 at the highest possible resolution. These gridded products will be used by *both* the servicing RFCs as input to the NWSRFS and by the public through official forecasts (see RFC requirement section 5.3.2 - note: PR is serviced by the AKRFC, but does not provide them QPFs since PR does not require nor issue main stem forecasts). These QPF/PQPFs and PoPs will be issued twice per day (for forecast periods beginning at 1200 and 0000 UTC), with a minimum temporal resolution of 6 hours through the 0-24 hour forecast period, 12 hours for the 24-48 hour forecast period, and 24 hours for the 48-72 hour period. The RFC frequency requirement (i.e. twice per day) for this information may vary by NWS Region as a function of season and/or current hydrometeorological events. The QPFs/PQPFs are just one element of a complete weather forecast, and in some cases represent only one component of the forecast weather information required for input to NWSRFS. For example, air temperature and the amount of precipitation falling on a snow pack[1] are both important in determining how quickly the snow pack will melt to assess the threat of flooding. It is important that all NWS forecast service products (both public and internal products) provide a consistent and complete message to ensure that the user community responds appropriately. To ensure meteorological consistency of all service products issued by the NWS, **WFOs are responsible for the official issuance of all service products (integrated total forecast) in their area of responsibility**.

The WFO forecaster will have at their disposal a number of tools to help them prepare QPFs as part of an integrated total forecast. Briefly, they include: 1) centrally-produced NCEP numerical model guidance and HPC value-added products, 2) statistical guidance from TDL/EMC for operational EMC models including global and regional ensembles, and 3) local applications and models. These forecast tools will need to continue to evolve and improve with time. WFO forecasters will require additional training to make the most effective use of these tools. The primary system that the forecaster will use to evaluate these data sets and generate a forecast is AWIPS. It is imperative that AWIPS provide a user-friendly grid editor that will allow the WFOs to 1) retire QPF legacy software such as WinQPF and Mountain Mapper and 2) improve services by effecting a NWS-wide transition from traditional text forecasts to issuing high resolution gridded forecasts of QPF/PQPF *and* other primary sensible weather elements (i.e. surface temperature, surface winds, clouds, precipitation type, etc). These gridded data sets will form the basis for all forecasts issued

[1] *Other meteorological parameters such as wind speed and humidity are also important although they are not currently utilized in NWSRFS.*

by WFOs to the public and internal customers.

The method of dissemination of QPFs/PQPFs and PoPs provided to the RFCs will evolve with time. Initially, any gridded QPF forecast generated by the WFOs will be provided on or converted to the HRAP grid at the RFC (Appendix A). However, additional work is needed to determine the optional gridded resolution to provide the RFCs for input into the Ensemble Prediction Processor (EPP). The effective scale of the probabilistic products will be borne out by verification. The RFCs will ingest the gridded WFO QPFs/PQPFs and PoPs and mosaic the forecasts over a larger area consistent with the RFCs domain of responsibility.

6.3. Weather Forecast Office Quantitative Precipitation Information Requirements

To satisfy RFC hydrologic model input requirements for QPF/PQPF (section 5.3.2) and to support the preparation of improved river forecast and flood watch and warning products within AWIPS, WFOs will require the following QPE, QPF/PQPF, and related hydrometeorological and hydrologic guidance products and capabilities:

- *Observations of Precipitation and River Stage*

  Accurate real-time precipitation (e.g., ASOS, IFLOWS, ALERT, GOES DCP, state Mesonets, etc.) and river stage observations are critical for monitoring and forecasting flood events, and precipitation observations are crucial to the local generation of the Stage I-II analyses (see table 2 section 1.6, and sections 5.3 and 5.3.1). NWS efforts to expand the availability of real-time precipitation observations which meet NWS standards (for accuracy, siting, maintenance, etc.) will be described in section 10.0. Observations of significant precipitation are required immediately after its occurrence. The WSR-88D provides precipitation estimates every volume scan over its area of coverage, while each ASOS automatically sends a message containing measured precipitation as often as every 15 minutes when either the locally-specified 15-minute or 1-hour alert criteria are met (Office of Systems Development, 1994). In addition, the forecaster can request from ASOS precipitation information correct to the minute of the request.

- *Precipitation Analyses*

  Locally-generated QPEs, including the Stage I and II products, must be as unbiased as possible and provided in a format consistent with the spatial and temporal requirements of SCAN and WHFS. Additionally, gridded RFC (Stage III), NCEP (Stage IV) precipitation estimates must be as unbiased as possible and provided in near real-time. WFOs will also utilize satellite-derived QPEs produced by the SAB of the Office of Satellite Data Processing and Distribution (OSDPD) within NESDIS, to evaluate the intensity, duration, and areal extent of heavy precipitation events. The current Satellite Precipitation Estimate (SPE) product, which has been provided to NWS field offices since the late 1970's, continues to be a valuable source of information for the assessment of flooding conditions (Scofield, 1984; Scofield, 1987; Borneman, 1988; Kusselson, 1993; Scofield and Achutuni, 1996; Scofield and Kusselson, 1996). However, the labor-intensive Man-computer Interactive Data Access System (McIDAS)-based manual Interactive Flash Flood Analyzer (IFFA) technique utilized to prepare these SPEs, only enables a single precipitation system to be analyzed at a time. This limitation and the growing need for a near real-time, national, satellite-derived QPE product for integration with the Stage II-IV multi-sensor analyses, serves as the impetus to develop, test, and implement an automated satellite-derived rainfall (Auto-Estimator) product (see section 5.3).

- *GIS-based High Resolution Basin Definitions and Reference Data*

High resolution basin (watershed) specification on the order of ten square miles or less is required to enable the comparison within AWIPS of FFG with 1) basin average, DHR-based QPEs, and 2) basin average QPF output from SCAN algorithms and other sources. A nationally-supported GIS application and training, and digital elevation model (DEM) data, are necessary for WFOs to specify and/or modify local basin definitions. Furthermore, WFOs need the capability to create, edit, and display spatial reference data such as parent and sub-basins, stream locations and names, reservoirs and dam locations, counties (name, state, code, zone, etc.), transportation routes (e.g., streets, highways, railways, etc.), and important landmarks (towns, schools, hospitals, etc.) to assist forecasters in the issuance of flash flood watches and warnings. Initial DEM processing, quality control, and basin delineation may be done centrally, but forecast offices will need the capability to make local modifications. Given that urban areas often present unique flash flood problems, WFOs must have the capacity to locally customize and update basin boundaries to best define high threat areas. Since DEM-based stream networks may not always accurately represent actual streams and rivers, it is imperative that basin delineations be quality controlled (constrained) by high resolution geophysical stream data.

- *WSR-88D-based Mosaics*

WFO forecasters, like RFC HAS forecasters, require the capability to directly access, mosaic, and loop WSR-88D reflectivity and VIL water data in near real-time for an area larger than their own radar umbrella. An AWIPS GUI, with the same specifications outlined in section 5.3, is also required. This capability is critical for accurately identifying, monitoring, and forecasting the timing and intensity of flash flood producing convective systems and preparing QPFs/PQPFs.

- *RFC FFG and Site-Specific Main-Stem River Forecasts*

High resolution, GIS-based, RFC-produced FFG is a necessary and important input to SCAN and the AWHPS of WHFS to assess the areal potential for flash flooding. Furthermore, RFC main-stem river forecasts are vital for the preparation and issuance of timely and accurate site-specific forecasts and flood warnings at WFOs, and AHPS-based probabilistic main stem forecasts are essential for satisfying the user requirement for risk-based hydrologic forecasts (see sections 2.2 and 5.1).

- *Centrally- and Locally-Produced QPF/PQPF Guidance Products*

Centrally- and locally-generated QPFs/PQPFs must be unbiased, and provided in a format consistent with the spatial and temporal requirements of the RFC, SCAN, and the WHFS hydrometeorologic models (i.e, AWHPS and SSHPS). HPC, TDL/EMC, and EMC activities to expand and improve QPF/PQPF products and guidance will be outlined in sections 7.0, 8.0, and 9.0, respectively.

Extending the range of WFO-produced QPFs through 72-hours, and effecting a transition to the generation of PQPFs, will increase the WFOs reliance on centrally-produced forecast and guidance products. During the July 1996 HIWG meeting, regional NWS representatives voiced concerns about issuing Day 2 and 3 QPFs/PQPFs and stated that expanded EMC, HPC, and TDL guidance is critical for satisfying this important RFC requirement. Many CONUS representatives emphasized the need for HPC guidance extended through Day 3. To fulfill the expanded RFC requirement for QPFs/PQPFs, WFOs require additional NWP model runs which maximize the collective information content of:

- higher resolution, longer-range EMC mesoscale NWP model runs;
- EMC global and regional ensemble NWP model runs; and
- EMC storm-scale NWP model runs.

These model requirements directly support the development and provision of associated guidance products, in a format explicitly satisfying RFC QPF/PQPF and PoP requirements, which include:

- QPF/PQPF and PoP guidance for the operational EMC NWP models, including global and regional ensembles *(Models without probabilistic guidance will have limited utility for future [stochastic] HPC, WFO, and RFC applications);* and
- HPC value-added QPFs/PQPFs and PoPs through Day 3.

The generation and operational availability of centrally-produced, gridded, HPC and statistical PQPF guidance is *essential* to support current operations and the planned field transition to probabilistic quantitative precipitation forecasting. Future TDL/EMC NWP model-based probabilistic guidance will be provided via optimizing procedures for statistical post-processing of direct model output, including runs from the newly emerging ensemble approach.

Short-range, high resolution, observational- and model-based, QPFs/PQPFs are required for the issuance of flash flood watches and warnings and the risk-based assessment of flash flooding events within SCAN and WHFS. Flash flood responsibilities require the WFO to focus on very small areas and drainage basins. It is planned that a nationally-supported GIS application will be used to specify these high resolution basins, which can be as small as one square mile in area. Therefore, QPF/PQPF guidance products should be provided at this level of detail, wherever possible. Recently developed probabilistic products which support flash flood forecasting and provide short-range, high resolution QPFs/PQPFs include TDL's Extrapolative-Statistical WSR-88D-based product (Kitzmiller, 1996) and the LAMP QPF (Glahn et al., 1991; Charba, 1998a, b; Charba et al., 1998b). These applications will be run locally on AWIPS and are described in section 8.3. Additionally, as described in sections 2.3.4 and 6.1, SCAN, which incorporates the aforementioned TDL products and other sources of high resolution QPF/PQPF, will improve a WFO forecasters' capability to detect, analyze, and monitor convection and generate local watch and warning products. Details of the system design, specifications, and recently completed and near term field testing of SCAN will be presented in section 8.3.

- *Climatological QPF/PQPF Guidance*

  WFOs require gridded climatological PoP and conditional and unconditional QPF/PQPF guidance provided in a format consistent with the requirements of the RFC (section 5.3.2). The required effective scale of this guidance will initially be 5,000 square kilometers, although this scale will be modified as PQPF and PoP verification data become available (see section 4.2 for an explanation of effective scale). Climatological guidance in this format will directly support the generation of value-added QPFs/PQPFs and PoPs.

6.3.1. WFO Requirements for Observations, QPE, Related Hydrometeorological and Hydrologic Guidance Products, and System Capabilities

In support of the provision of improved and expanded hydrometeorological services, WFOs require:

In Situ Observations

- A *minimum* of 30 and a target of 50 real-time, spatially-distributed, all-season rain-gage observations per WSR-88D umbrella for the bias correction of Stage I radar rainfall analyses and the local generation of the Stage II multi-sensor products (Anagnostou et al., 1997).

- RFC-produced, SHEF-formatted Daily Hydrometeorological (HYD) bulletins containing all 24-hour precipitation gage observations for the 1200-1200 UTC and 0000-0000 UTC periods. [These bulletins should include *all* quality-controlled gage precipitation observations used in the 1200 and 0000 UTC NWSRFS model runs and should be transmitted by the RFC as soon as these data are input into NWSRFS. Gage reports of zero precipitation must also be included, where available.]

Radar

- Near real-time, Stage I precipitation products to include:

  - the 1 dBZ (i.e., 8-bit, 256 level) Digital Hybrid-Scan Reflectivity (DHR) Product (which can be converted to precipitation amount), available every volume scan on a 1 km x 1 degree polar grid;

  - the Hourly Digital Precipitation (HDP) product, in 256 levels (i.e., 8-bit) available every WSR-88D volume scan on the 4 km HRAP grid;

  - graphical one-hour, three-hour, storm total, and user-selectable total precipitation accumulation products, available every WSR-88D volume scan in 16 display levels (i.e., 4-bit) on a 2 km x 1 degree polar grid; and

  - the alphanumeric Supplemental Precipitation Data (SPD) product containing a listing of PPS adaptable parameter settings and radar-gage pairs.

- Near real-time, WSR-88D regional, every volume scan a) 1-km, 1 dBZ (8-bit, 256 level) DHR and b) 4-km (4-bit, 16 level) VIL mosaics whose domain is defined by the AWIPS Local Area Grid (750 km x 750 km). These regional mosaics are required within 5 minutes of mosaic valid time, will be comprised of the most recent data available from all neighboring radars, and will not include any radar data with a valid time more than 10 minutes previous to the valid time of the mosaic.

- Near real-time, WSR-88D, national, 15-minute a) 2-km, 1 dBZ (8-bit, 256 level) DHR and b) 4-km (4 bit, 16 level) VIL mosaics. These national mosaics are required within 10 minutes of the mosaic valid time, will be comprised of the most recent data available, and will not include any radar data with a valid time more than 15 minutes previous to the valid time of the mosaic.

Satellite

- NESDIS satellite-derived QPEs -- commonly referred to as satellite precipitation estimates (SPEs) -- and associated text products.

  - Near-term *minimum* requirements for manual IFFA-based products (prior to implementation of automated SPEs):

■ Product Frequency and Format

Table 3: Manual IFFA-based products and their frequency of issuance.

		Event Type		
		winter storms	***cold-top convection***	***lake effect snow***
SAB Products [1,2]	***Gridded 4-km SPE***	*1 hr*	*1 hr*	*1 hr*
	Text/SIM [3]	*3 hr*	*3 hr*	*3 hr*
	Gridded 4-km Storm Total SPE	*3 hr*	*3 hr*	*3 hr*
	Consultation	*as requested by field personnel*		

[1] An orographic correction is required for SPE products.

[2] An "End of Support Notification" will be included as part of the final message in support of a specific event.

[3] When SAB SPE gridded products cannot be generated due to inadequate satellite signatures, text products may be issued more frequently.

■ IFFA Product Issuance Criteria

Products (text and graphic/grid) will be issued when 1) conditions suggest that flash flooding is imminent/occurring or if a flash flood warning has been issued, or 2) heavy snowfall ($\geq$ 4"/12 hours) is observed and/or winter storm warnings are issued, or 3) products are requested by NWS field personnel.

■ Multiple Event Prioritization

When the above product issuance criteria are satisfied, SAB will support events of differing type in the following order 1) flash floods, 2) heavy rainfall associated with winter storms, 3) heavy snowfall (normally heavy snowfall associated with winter storms will have priority over Lake Effect Snow [LES] events, however, there may be exceptions for extreme LES events). If multiple events of the same type satisfy the product issuance criteria, the SAB forecaster in coordination with the QPF forecasters in the Forecast Operations Branch (FOB) of HPC will prioritize events/requests and provide service accordingly.

- *Minimum* Requirements for Operational Automated SPEs

  - Product Frequency and Format

Table 4: Automated satellite-based products and their frequency of issuance. See section 5.3 for more details.

		Event Type
		Full Spectrum of Precipitation Phenomena (i.e., cold-top convection, winter storms, tropical convection, lake effect storms, and stratiform/embedded warm-top convection events)
SAB Products[1,2,3]	***Gridded SPE (quality controlled, 4- km)***	*.5 hr*
	Text/SIM	*2 hr*
	Storm Total SPE	*grids will be summed locally at WFO/RFC*
	Consultation	*as requested by field personnel*

[1] SPEs will be based upon compositing instantaneous rainfall estimates derived from (1) GOES satellite imagery with a temporal resolution greater than or equal to 15 minutes and (2) POES SSM/I data when available.
[2] Since the automated satellite-based algorithm(s) will be designed to generate SPEs for the spectrum of precipitation phenomena and the SPEs will be generated on a scheduled basis, there will not be a need for Product Issuance Criteria or Multiple Event Prioritization.
[3] SPE estimates are required by all NWS Regions, including the Alaska and Pacific Regions.

Multi-Sensor Analyses

- Near real-time, 4-km, hourly, valid on the hour, Stage II, III and IV multi-sensor rainfall analyses integrating WSR-88D, ASOS, other gage rainfall data (e.g., ALERT, AHOS-T, IFLOWS, GOES DCP, state Mesonets, etc.) and satellite-derived rainfall estimates.

- RFC HRAP-gridded, quality-controlled Stage III 6-hour aggregate and 24-hour post-analyses of precipitation for the 1200-1200 UTC and 0000-0000 UTC periods.

Hydrologic Guidance Products

- RFC site-specific (probabilistic) streamflow stage forecasts for all main-stem river forecast points within the WFO HSA twice per day, with more frequent updates during flooding situations (Note: The frequency requirement [i.e., twice per day] for this information may also vary by NWS Region as a function of season).

- Modernized RFC-generated, high resolution, GIS-based, 1-, 3-, 6-, 12-, and 24-hour threshold-runoff FFG, updated twice daily, for the WFO HSA, with more frequent updates during active precipitation situations (Note: The minimum frequency requirement [i.e., twice per day] for this information may also vary by NWS Region as a function of season).

Systems Capabilities

- The incorporation of AMBER capabilities in future versions of SCAN/AWHPS (i.e., map DHR-based rainfall estimates in locally-defined high resolution stream basins and use ABR to assess the flash flood threat).

- The capability to display SCAN/AWHPS flash-flood guidance products within the AWIPS D2D.

- The procedures, software, and training necessary to specify and/or modify local basin definitions using a nationally-supported GIS application.

- The capability to create, edit, and display GIS-based spatial reference data to assist forecasters in the issuance of flash flood watches and warnings.

- The capability to display and interrogate precipitation and radar reflectivity and VIL mosaics and overlay GIS-based spatial reference data.

- The AWIPS capability to archive river stage observations, precipitation observations and analyses, and quantitative precipitation forecasts, especially for forecast verification.

6.3.2. WFO Requirements for QPF/PQPF, Related Hydrometeorological Guidance Products, and Systems Capabilities

In support of improved and expanded hydrometeorological services and the local preparation of 0-72 hour value-added QPFs/PQPFs and PoPs, WFOs in all NWS Regions require:

NWP Model Guidance

An optimum combination of:

- High resolution (horizontal spatial resolution $\leq$ 10 km) EMC mesoscale NWP model runs:
  - longer-range (0-84 hour), run twice per day for the 0000 and 1200 UTC initial times; and
  - short-range (0-3 hour), run hourly.

- EMC global ensemble NWP model runs through Day 7 (0-168 hour), once per day at a spatial resolution ≤ 105 km (T126).

- EMC 0-84 hour regional ensemble NWP model runs twice per day (for the 0000 and 1200 UTC initial times), at a horizontal spatial resolution of < 40 km (these projected minimal resolutions will be updated pending the results of the EMC regional ensemble assessment -- see section 9.3).

- EMC 0-30 hour, high resolution (horizontal spatial resolution ≤ 3 km) storm-scale NWP model runs (event driven).

Central Guidance

- HPC gridded, areal average, value-added 0-72 hour QPFs/PQPFs, PoPs (satisfying the minimum RFC requirements -- see section 5.3.2), and companion graphical and text products issued twice per day for the forecast periods beginning at 0000 and 1200 UTC.

- Gridded probabilistic guidance based on operational EMC high resolution mesoscale NWP model and/or regional ensemble simulations -- this includes:

  - QPF/PQPF and PoP guidance in the projected format specified in section 4.2, which supports an operational methodology designed to satisfy the minimum RFC requirements for probabilistic hydrologic forecasting (see section 5.3.2),

  - probabilistic precipitation type, freezing level, snow melt, and soil moisture deficit forecasts, and

  - probabilities of exceeding pre-determined rainfall amount thresholds.

Local Guidance

- Gridded 20-km LAMP QPF products with a temporal resolution of 1 hour to a range of 5 hours, 3 hour in the 4-10 hour range, and 6 hour in the 7-22 hour range, for use as guidance for the issuance of flash flood watches and warnings.

- SCAN-based, 0-3 hour, gridded, high resolution (horizontal spatial resolution ≤ 4 km) QPF/PQPF guidance to assess the areal potential for flash flooding (e.g., via the NCAR Thunderstorm Auto-nowcaster and TDL's extrapolative-statistical precipitation algorithm within the AWIPS Thunderstorm Product).

- Gridded climatological PoP and conditional and unconditional QPF/PQPF guidance provided in a format consistent with the requirements of the RFC (section 5.3.2).

- The capability to store the high temporal and spatial resolution QPF/PQPF output of SCAN algorithms (e.g., TDL's extrapolative-statistical precipitation algorithm within the AWIPS Thunderstorm Product and NCAR's Thunderstorm Auto-nowcaster) in the AWIPS data structure so that these products are accessible to WHFS for use in the:

  - AWHPS to compute the forecast ABR and predict flash flood threat, and

  - SSHPS to produce site-specific forecast time series for selected points in small, fast-responding (headwater) stream basins.

- The point/grid editing and display capabilities listed in Appendix A which support the preparation, coordination, and verification of QPFs/PQPFs within AWIPS.

6.4. Verification of QPI and Related Products

Verification of the officially issued QPFs/PQPFs and PoPs as well as the centrally and locally-produced guidance products is essential to provide forecasters with timely and objective feedback to calibrate and improve their skill. Verification of WFO-produced user products which are based in part on precipitation information--such as flash flood warnings--will be performed according to the National Verification Plan (see National Weather Service, 1991a). Each WFO will verify its forecasts for their own area of responsibility. The RFC-produced aggregate Stage III post analyses of precipitation accumulation, or their equivalent, will be utilized as the ground validation. Locally computed measures of QPF/PQPF skill will be consistent with those specified in section 11.3 for the National ETE verification program.

7.0. Hydrometeorological Prediction Center Guidance Products and Requirements

Extending the range of WFO-produced/RFC-mosaicked QPFs through Day 3, and effecting a national transition to the generation of PQPFs, will increase NWS field office reliance on HPC value-added forecast and guidance products. It will also require that HPC extend its product suite from Day 2 to Day 3 and introduce national PQPF guidance products.

7.1. Hydrometeorological Prediction Center Operations

7.1.1. Historical Perspective

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 Forecast Operations Branch (FOB) of the HPC. The title of the FOB has changed since this time, and it was formerly known (in reverse chronological order) as the Weather Forecast Branch (WFB), the Heavy Precipitation Branch (HPB), and the Quantitative Precipitation Branch (QPB). Initially, 24 hour Day 1 QPFs were issued by QPB forecasters early each morning. These forecasts were (and still are) valid from 1200 UTC to 1200 UTC the following day, and were based on the 12-36 forecast of the most current 0000 UTC NWP (in the early 1960's, barotropic) model run. In July 1964, the QPF product suite was expanded to include a Day 2 QPF and a Day 2 Update, each valid for the 24 hour forecast period beginning 1200 UTC the following day. The Day 2 QPF and Day 2 Update products were introduced as early morning and early afternoon products, respectively, and are still issued at those times today (see table 5).

In the early 1960s, with only the barotropic model and no explicit precipitation guidance, the operational production of manual QPFs was heavily reliant on empirical forecaster-developed techniques. In 1966, with the arrival of the six-layer Primitive Equation (6LPE) model, manual QPFs became more of a "value-added" product as forecasters increased their use of numerical model output. In 1971, the Limited-area Fine-Mesh (LFM) model was implemented operationally and provided precipitation forecasts to 24 hours, which were later extended to 48 hours. QPB forecasters considered the LFM's explicit prediction of precipitation amount superior to that of the 6LPE model, and these model improvements were coincident with a marked increase in forecaster skill (Olson et al., 1995). The subsequent introduction of the Regional Analysis and Forecast System (RAFS) in 1986, the Eta (and meso-Eta) in 1993, and continuing enhancements to the Aviation (AVN) model have contributed to an improvement in the skill of manual QPFs over the past decade.

In 1981, the title of the precipitation branch changed from the QPB to the HPB. Coincident with this change was the introduction of new forecast guidance designed to support ETE flash and river flood operations nationwide. Excessive Rainfall Outlooks and short-range 6 hour QPFs were introduced. The Excessive Rainfall Outlooks include a graphical Rainfall Potential Exceeding FFG Product and an accompanying Excessive Rainfall Discussion. Two 6 hour QPFs, covering consecutive 6 hour periods, were produced approximately 4-6 hours before the start of the first 6 hour period. These two 6 hour QPFs continue to be produced four times per day, while the Excessive Rainfall Outlooks continue to be produced three times per day with special issuances as required (see table 5). In 1992, an additional 6 hour QPF was introduced which, like the aforementioned 6 hour QPFs, is issued four times per day (see table 5). This product is known as the Revised/Nowcast, since it is a 6 hour forecast of precipitation for the immediate future. The Revised/Nowcast provides guidance on significant synoptic and mesoscale events which are ongoing or imminent. Continued expansion of the HPC product suite in 1997, included two additional 6 hour QPFs. These two new QPFs are issued in the early morning and the early afternoon, and cover the final twelve hours of the 24 hour 1200-1200 UTC and 0000-0000 UTC forecast periods, respectively. These products directly support the preparation of QPFs at WFOs, and the mosaicking of QPFs by HAS forecasters at RFCs for input to NWSRFS.

Heavy snow forecasts are also prepared by HPC forecasters. These forecasts cover the continental U.S. and assist WFO forecasters in the issuance of winter storm watches and warnings. A manual Heavy Snow Forecast product was first issued in 1962, and covered a 12 hour period 6-18 hours into the future. In response to user requests, HPC extended the range of their snow forecasts to 30 hours through the addition of the 12 hour Heavy Snow Outlook product in the early 1990s. The Heavy Snow Forecast and Heavy Snow Outlook products are currently issued four times per day from September fifteenth through May fifteenth, and on an as needed basis during the remainder of the year (see table 5).

7.1.2. Current and Future Operations

FOB forecasters currently monitor and assess the threat for heavy rainfall and/or snowfall through the continual examination and integration of (Corfidi and Comba, 1989; Funk, 1991; Sullivan, 1993; Olson et al., 1995; Schneider et al., 1996):

- real-time, in-situ observations and remotely-sensed data (rain gage, WSR-88D-based mosaics, satellite imagery);
- global and regional atmospheric NWP model output; and
- MOS guidance products.

FOB forecasters reconcile differences between the observational data, operational NCEP NWP models, and statistical guidance to prepare and issue the aforementioned manual (value-added), 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. Excepting the Eta model, verification scores have also been computed for atmospheric model-generated QPFs since 1987. Comparisons of HPC and model skill scores over the 7-year period ending in 1994 (Olson et al., 1995) reveals that the:

- HPC Day 1 (24 hour) QPF consistently add value to the direct atmospheric model QPFs, and

- with few exceptions, the HPC Day 2 QPF outperforms the Day 1 direct model QPF.

During the July 1996 meeting, HIWG representatives from the CONUS regions (excepting WR), clearly stated the need for the *current and expanded future HPC support* to satisfy WFO QPF/PQPF and PoP requirements. Representatives from the Pacific and Alaska Regions also stated a requirement for HPC guidance products. Consistent with these HIWG requirements, the value of HPC products was recently documented in the NOAA Technical Memorandum NWS ER-87 (Krzysztofowicz and Drake, 1993) entitled "Usage of Guidance Products in Preparing Probabilistic QPFs for River Basins" wherein NWSFO Pittsburgh (PBZ) forecasters ranked HPC products most valuable in the local preparation of QPFs/PQPFs.

In support of the national transition to probabilistic QPF and hydrologic forecasting, HPC plans to extend the range of their manual forecast products through Day 3, and routinely provide gridded, areal average, value-added QPF/PQPF and PoP guidance products to WFOs and RFCs for both the 1200-1200 UTC and 0000-0000 UTC forecast cycles.

7.2. HPC Forecast and Guidance Products

HPC forecasters produce and disseminate QPF and other forms of value-added guidance to help the WFOs generate improved forecasts for the CONUS. The full implementation of AWIPS will facilitate the generation of gridded guidance products and improve NCEP WFO/RFC coordination (see Appendix A). HPC forecasters will have the capability to directly initialize grid editors with centrally produced QPF/PQPF guidance (or climatological guidance), which will facilitate the generation of value-added forecast products. The HPC's primary sources of initial QPF/PQPF and PoP guidance will be a combination of gridded TDL Model Output Statistics (MOS) and LAMP QPF, and EMC single model and ensemble-based products.

Tables 5 and 6 specify current and planned HPC CONUS products, respectively, necessary to extend the range of forecaster value-added QPFs through Day 3, and support a national transition to probabilistic quantitative precipitation and AHPS-based hydrologic forecasting. Expanded products and services embodied in table 6 include:

- increasing the temporal resolution of the Day 2 QPF from 24 to 12 hours,

- issuing Day 1 and Day 2 QPFs for 0000 *and* 1200 forecast cycles,

- issuing *probabilistic* QPFs, and

- extending the range of forecast products through Day 3.

Table 5: Current Hydrometeorological Prediction Center quantitative precipitation forecast and guidance product suite and issuance times.

Current HPC Forecast and Guidance Products			
Issuance Time (UTC)	***Valid Time (UTC)***	***AFOS Header*** *(AWIPS Header for gridded products TBD)*	***Product Description*** ** Winter Issuance Only* *** Product Issued if Necessary* *(Special Rainfall Discussion [QPFSRD] issued as needed)*
0000	0000 - 0600	91E	0 - 6 hour liquid equivalent QPF
0215	0600 - 1200	92E	4 - 10 hour QPF
	1200 - 1800	93E	10 - 16 hour QPF
	0600 - 1800	93S	4 - 16 hour Heavy Snow Forecast (4" contours)*
	1800 - 0600	94S	16 - 28 hour Heavy Snow Outlook*
	0300 - 1200	94E	Rainfall Potential Exceeding Flash Flood Guidance Values and/or 5" during forecast valid time**
0300	0600 - 0600	QPFHSD	Heavy Snow Discussion accompanying the 93S and 94S*
	0300 - 1200	QPFERD	Excessive Rainfall Discussion accompanying the 94E**
0600	0600 - 1200	91E	0 - 6 hour liquid equivalent QPF
	1200 - 1800	92E	6 - 12 hour QPF
	1800 - 0000	93E	12 - 18 hour QPF
	1200 - 1200	94Q	6 - 30 hour (Preliminary Day 1) QPF
	1200 - 0000	93S	6 - 18 hour Heavy Snow Forecast (4" contours)*
	0000 - 1200	94S	18 - 30 hour Heavy Snow Outlook*
	1200 - 1200	94E	Rainfall Potential Exceeding Flash Flood Guidance Values and/or 5" during forecast valid time
0700	1200 - 1200	QPFPFD	Discussion accompanying 94Q
	1200 - 1200	QPFHSD	Heavy Snow Discussion accompanying the 93S and 94S*
	1200 - 1200	QPFERD	Excessive Rainfall Discussion accompanying the 94E
0830	1200 - 1200	98Q	27.5 - 51.5 hour (Day 2) QPF
1000	1200 - 1800	92E	2 - 8 hour QPF
	1800 - 0000	93E	8 - 14 hour QPF
	0000 - 0600	9EE	14 - 20 hour QPF
	0600 - 1200	9FE	20 - 26 hour QPF
	1200 - 1200	94Q	2 - 26 (Final Day 1) hour QPF

Table 5 : Current Hydrometeorological Prediction Center quantitative precipitation forecast and guidance product suite and issuance times. (continued)

Issuance Time (UTC)	***Valid Time (UTC)***	***AFOS Header*** *(AWIPS Header for gridded products TBD)*	***Product Description*** ** Winter Issuance Only* *** Product Issued if Necessary* *(Special Rainfall Discussion [QPFSRD] issued as needed)*
1100	1200 - 1200	QPFPFD	Discussion accompanying 94Q and 98Q
1200	1200 - 1800	91E	0 - 6 hour liquid equivalent QPF
1415	1800 - 0000	92E	4 - 10 hour QPF
	0000 - 0600	93E	10-16 hour QPF
	1800 - 0600	93S	4 - 16 hour Heavy Snow Forecast (4" contours)*
	0600 - 1800	94S	16 - 28 hour Heavy Snow Outlook*
	1500 - 1200	94E	Rainfall Potential Exceeding Flash Flood Guidance Values and/or 5" during forecast valid time
1500	1800 - 1800	QPFHSD	Heavy Snow Discussion accompanying the 93S and 94S*
	1500 - 1200	QPFERD	Excessive Rainfall Discussion accompanying the 94E
1800	1800 - 0000	91E	0 - 6 hour liquid equivalent QPF
	0000 - 0600	92E	6 - 12 hour QPF
	0600 - 1200	93E	12 - 18 hour QPF
	1200 - 1800	9EE	18 - 24 hour QPF
	1800 - 0000	9FE	24 - 30 hour QPF
	1200 - 1200	98Q	18 - 42 hour (Day 2 Update) QPF
	0000 - 1200	93S	6 - 18 hour Heavy Snow Forecast (4" contours)*
	1200 - 0000	94S	18 - 30 hour Heavy Snow Outlook*
	2100 - 1200	94E	Rainfall Potential Exceeding Flash Flood Guidance Values and/or 5" during forecast valid time
1900	1200 - 1200	QPFPFD	Discussion accompanying 98Q
	0000 - 0000	QPFHSD	Heavy Snow Discussion accompanying the 93S and 94S*
	2100 - 1200	QPFERD	Excessive Rainfall Discussion accompanying the 94E

Table 6: Planned HPC forecast and guidance product suite and issuance times in support of a national transition to probabilistic quantitative precipitation forecasting (new products in boldface).

Planned HPC Forecast and Guidance Products			
Issuance Time (UTC)	***Valid Time (UTC)***	***AFOS Header*** *(AWIPS Header for gridded products TBD)*	***Product Description*** * *Winter Issuance Only* *New Products in Boldface* *(Special Rainfall Discussion [QPFSRD] issued as needed)*
0215	0600 - 1800	93S	4 - 16 hour Heavy Snow Forecast (4" contours)*
	1800 - 0600	94S	16 - 28 hour Heavy Snow Outlook*
	0300 - 0000	**94E**	**Rainfall Potential Exceeding Flash Flood Guidance Values and/or 5" during forecast valid time**
0300	0600 - 0600	QPFHSD	Heavy Snow Discussion accompanying the 93S and 94S*
	0300 - 0000	**QPFERD**	**Excessive Rainfall Discussion accompanying the 94E**
0600	0600 - 1200	91E	0 - 6 hour liquid equivalent QPF
	1200 - 1800	92E	6 - 12 hour QPF
	1800 - 0000	93E	12 - 18 hour QPF
	0000 - 0600	**9EE**	**18 - 24 hour QPF**
	0600 - 1200	**9FE**	**24 - 30 hour QPF**
	1200 - 1200	**94Q**	**6 - 30 hour (Day 1) Probabilistic QPF**
	1200 - 0000	93S	6 - 18 hour Heavy Snow Forecast (4" contours)*
	0000 - 1200	94S	18 - 30 hour Heavy Snow Outlook*
	1200 - 1200	94E	Rainfall Potential Exceeding Flash Flood Guidance Values and/or 5" during forecast valid time
0700	**1200 - 1200**	**QPFPFD**	**Discussion accompanying probabilistic 94Q**
	1200 - 1200	QPFHSD	Heavy Snow Discussion accompanying the 93S and 94S*
	1200 - 1200	QPFERD	Excessive Rainfall Discussion accompanying the 94E
0800	**1200 - 1200**	**98Q**	**28 - 52 hour (Day 2) Probabilistic QPF**
	1200 - 0000	**TBD**	**28 - 40 hour QPF**
	0000 - 1200	**TBD**	**40 - 52 hour QPF**
	1200 - 1200	**TBD**	**52 - 76 hour (Day 3) Probabilistic QPF**

Table 6: Planned HPC forecast and guidance product suite and issuance times in support of a national transition to probabilistic quantitative precipitation forecasting (new products in boldface) (continued).

Issuance Time (UTC)	*Valid Time (UTC)*	*AFOS Header* *(AWIPS Header for gridded products TBD)*	*Product Description* ** Winter Issuance Only* *New Products in Boldface* *(Special Rainfall Discussion [QPFSRD] issued as needed)*
1000	**1200 - 1200**	**QPFPFD**	**Discussion accompanying probabilistic 98Q and Day 3 PQPF**
1400	1800 - 0600	93S	4 - 16 hour Heavy Snow Forecast (4" contours)*
	0600 - 1800	94S	16 - 28 hour Heavy Snow Outlook*
	1500 - 1200	94E	Rainfall Potential Exceeding Flash Flood Guidance Values and/or 5" during forecast valid time
1500	1800 - 1800	QPFHSD	Heavy Snow Discussion accompanying the 93S and 94S*
	1500 - 1200	QPFERD	Excessive Rainfall Discussion accompanying the 94E
1800	1800 - 0000	91E	0 - 6 hour liquid equivalent QPF
	0000 - 0600	92E	6 - 12 hour QPF
	0600 - 1200	93E	12 - 18 hour QPF
	1200 - 1800	**9EE**	**18 - 24 hour QPF**
	1800 - 0000	**9FE**	**24 - 30 hour QPF**
	0000 - 0000	**94Q**	**6 - 30 hour (Day 1) Probabilistic QPF**
	0000 - 1200	93S	6 - 18 hour Heavy Snow Forecast (4" contours)*
	1200 - 0000	94S	18 - 30 hour Heavy Snow Outlook*
	0000 - 0000	94E	**Rainfall Potential Exceeding Flash Flood Guidance Values and/or 5" during forecast valid time**
1900	**0000 - 0000**	**QPFPFD**	**Discussion accompanying probabilistic 94Q**
	0000 - 0000	QPFHSD	Heavy Snow Discussion accompanying the 93S and 94S*
	0000 - 0000	**QPFERD**	**Excessive Rainfall Discussion accompanying the 94E**
2000	**0000 - 0000**	**98Q**	**28 - 52 hour (Day 2) Probabilistic QPF**
	0000 - 1200	**TBD**	**28 - 40 hour QPF**
	1200 - 0000	**TBD**	**40 - 52 hour QPF**
	0000 - 0000	**TBD**	**52 - 76 hour (Day 3) Probabilistic QPF**
2200	**0000 - 0000**	**QPFPFD**	**Discussion accompanying probabilistic 98Q and Day 3 PQPF**

7.3. HPC Quantitative Precipitation Information Requirements

7.3.1. Requirements for Observations, QPE, Related Hydrologic Guidance Products, and Systems Capabilities

In support of the provision of improved and expanded hydrometeorological services, HPC requires:

In Situ Observations

- RFC-produced, SHEF-formatted Daily Hydrometeorological (HYD) bulletins containing all 24-hour precipitation gage observations for the 1200-1200 UTC and 0000-0000 UTC periods. These bulletins should include *all* quality-controlled gage precipitation observations used in the 1200 and 0000 UTC NWSRFS model runs and should be transmitted by the RFC as soon as these data are input into NWSRFS. Gage reports of zero precipitation must also be included.

Radar

- Near real-time, WSR-88D, national, 15-minute a) 2-km, 1 dBZ (8-bit, 256 level) DHR and b) 4-km (4 bit, 16 level) VIL mosaics. These national mosaics are required within 10 minutes of the mosaic valid time, will be comprised of the most recent data available, and will not include any radar data with a valid time more than 15 minutes previous to the valid time of the mosaic.

Satellite

- NESDIS satellite-derived QPEs (see section 6.3.1) and direct consultation with SAB satellite analysts (SAB forecasters are co-located with the HPC FOB QPF forecasters in the NPPU).

Multi-Sensor Analyses

- Near real-time, 4-km, hourly, valid on the hour, NCEP Stage IV multi-sensor rainfall analyses integrating WSR-88D, ASOS, other gage rainfall data (e.g., ALERT, AHOS-T, IFLOWS, GOES DCP, state Mesonets, etc.) and satellite-derived rainfall estimates.

- NCEP Stage IV HRAP-gridded, quality-controlled 6-hour aggregate and 24-hour post-analyses of precipitation for the 1200-1200 UTC and 0000-0000 UTC forecast cycles.

Hydrologic Guidance Products

- A national composite of RFC-produced, modernized, high resolution, GIS-based, 1-, 3-, 6-, 12-, and 24-hour threshold-runoff FFG, twice daily, with more frequent updates during active precipitation situations (Note: The minimum frequency at which the FFG is updated at each RFC may vary as a function of season).

Systems Capabilities

- The capability to display and interrogate precipitation and radar reflectivity and VIL mosaics and overlay GIS-based spatial reference data.

- The AWIPS capability to archive precipitation observations and analyses, and quantitative precipitation forecasts, especially for forecast verification.

7.3.2. Requirements for QPF/PQPF, Related Hydrometeorological Guidance Products, and Systems Capabilities

In order to satisfy expanded field office requirements for longer-range, value-added, probabilistic hydrometeorological guidance products, HPC forecasters require(given the ETE Forecast Process described in section 2.1, note the similarity of the following requirements to those specified for the WFO in section 6.3.2):

NWP Model Guidance

An optimum combination of:

- High resolution (horizontal spatial resolution $\leq$ 10 km), longer-range (0-84 hour), EMC mesoscale NWP model runs twice per day for the 0000 and 1200 UTC initial times;

- EMC global ensemble NWP model runs through Day 7 (0-168 hour), once per day at a spatial resolution $\leq$ 105 km (T126);

- EMC 0-84 hour regional ensemble NWP model runs, twice per day (for the 0000 and 1200 UTC initial times), at a horizontal spatial resolution of < 40 km (these projected minimal resolutions will be updated pending the results of the EMC regional ensemble assessment -- see section 9.3);

- EMC 0-30 hour, high resolution (horizontal spatial resolution $\leq$ 3 km) storm-scale NWP model runs (event driven);

Statistical Guidance

- Gridded probabilistic guidance based on operational EMC high resolution mesoscale NWP model and regional ensemble simulations -- this includes:
    - QPF/PQPF and PoP guidance in the projected format specified in section 4.2, which

supports an operational methodology designed to satisfy the minimum RFC requirements for probabilistic hydrologic forecasting (see section 5.3.2),

- probabilistic precipitation type and freezing level forecasts, and

- probabilities of exceeding pre-determined rainfall amount thresholds;

- Gridded 20-km Local AWIPS MOS Program (LAMP) QPF products with a temporal resolution of 1 hour to a range of 5 hours, 3 hour in the 4-10 hour range, and 6 hour in the 7-22 hour range.

- Gridded climatological PoP and conditional and unconditional QPF/PQPF guidance provided in a format consistent with the requirements of the WFO/RFC (see section 5.3.2).

Systems Capabilities

- The point/grid editing and display capabilities listed in Appendix A which support the preparation, coordination, and verification of QPFs/PQPFs within AWIPS.

7.4. Verification of QPI

As with the RFC HAS and WFO forecasters, verification of the officially issued HPC manual QPFs/PQPFs and PoPs, as well as the other centrally produced guidance products is essential to provide forecasters timely and objective feedback to calibrate and improve their skill. The NCEP Stage IV precipitation analysis -- including a mosaic of the RFC-produced aggregate Stage III (or their equivalent) post-analyses of precipitation accumulation -- will be utilized as the ground validation for verification. HPC computed measures of QPF/PQPF skill will be consistent with those specified in section 11.3 for the National ETE verification program.

8.0. Observational and Model-Derived Statistical Guidance Products

The routine provision of statistical guidance products from operational NCEP NWP models is necessary to support a national transition to probabilistic QPF and hydrologic forecasting. NCEP NWP models without PQPF guidance will have limited utility for HPC, WFO, and RFC applications. Furthermore, the routine local generation of accurate and reliable short-range, high resolution, observational- and model-based QPF/PQPF guidance is critical for flash flood prediction and warning.

8.1. Historical Perspective

TDL has produced statistical quantitative precipitation forecasts based on operational synoptic-scale NWP models for over two decades. Although much of the statistical guidance that has been disseminated routinely to the field has been in categorical form, probabilistic forecasts have long been an integral part of TDL QPF systems. This is an outgrowth of the method by which the regression-based MOS technique is commonly employed in QPF equation development. By partitioning the continuum of observed precipitation amounts into a number of binary predictands which indicate the occurrence or non-occurrence of precipitation exceeding various breakpoint amounts, the MOS technique yields equations which estimate the probability (or equivalently, the event relative frequency) that precipitation will equal or exceed each of the breakpoints. This procedure is often referred to as Regression Estimation of Event Probability, or REEP (see Glahn et al., 1991a).

The first application of the MOS technique to quantitative precipitation forecasting (Bermowitz, 1975) utilized output from the six-layer Primitive Equation (6LPE) model and TDL's Trajectory model. Equations to predict the probability of precipitation occurrence for five precipitation intervals were developed and applied for over 200 stations in the contiguous United States. A few years later, this system was upgraded to employ multiple sets of regionalized forecast equations (Bermowitz and Zurndorfer, 1979), and an algorithm to produce categorical forecasts from the probability estimates was added. This system was implemented operationally to generate routine forecast guidance twice daily; an "early" set of forecasts was available based on output from the LFM, while a later issuance was based on the original combination of output from the 6LPE and Trajectory models.

Whereas these first QPF systems produced forecasts valid for projections of 12 to 48 hours and used precipitation data from the regular synoptic observation network to define the predictand, an effort was undertaken in the 1980's to develop very short-range ($\leq$9h), subsynoptic-scale statistical QPF guidance based on higher resolution data. Charba (1983; 1987) introduced an automated statistically-based system that produced 0-6 and 3-9 h precipitation forecasts on an 80-km grid. This system used hourly precipitation data from the U.S. cooperative observer network (approximately 3000 stations) to define the predictand and to develop a high-resolution gridded precipitation climatology (Charba, 1985) which was used as a predictor input. Other sub-synoptic scale predictor inputs were provided by conventional surface observations, manually-digitized radar data, and topography. Synoptic-scale NWP model input was provided from the LFM. Forecasts from this system became available on the NWS Automation of Field Operations and Services (AFOS) communications network in early 1987 and were continued until operational use of the LFM was discontinued in early 1996.

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 over 500 stations throughout the contiguous U.S. and 60 stations in Alaska (Antolik, 1997). Categorical forecasts are available in alphanumeric form via the FOUS14 and FOAK25-29 bulletins, and corresponding probabilistic and expected-value forecasts in graphical form are made available to the NCEP Hydrometeorological Prediction Center.

The above synoptic-scale package of TDL QPF guidance will soon be supplemented by short-range guidance from the Local AWIPS MOS Program (LAMP) QPF model (Charba, 1998a,b; Charba et al., 1998b). 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 synoptic-scale predictor 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 is provided by objective analyses of conventional surface observations together with the use of simple numerical models. Mesoscale predictor input is provided by a high-resolution precipitation climatology (Charba et al., 1998a), hourly antecedent precipitation analyses, and topography. Further details of the LAMP system are discussed in section 8.3.

8.2. Centrally-Produced Guidance

Centrally generated, model-based, statistical QPFs/PQPFs and PoPs in support of site-specific main-stem hydrologic forecasting, must be unbiased, gridded, and provided in a format consistent with the spatial and temporal requirements of the RFC. Extending the range of RFC-required forecaster value-added QPFs through Day 3 and effecting a transition to the generation of PQPFs and PoPs will increase the HPC's, WFOs', and RFCs' reliance on centrally-produced guidance products. Further, short-range statistical forecast products, based on the combined high resolution output from NCEP meso- and storm-scale NWP models and regional ensemble simulations will be used to assess the areal potential for flash flooding within SCAN and WHFS. TDL statistical guidance is critical for satisfying fundamental HPC, WFO, and RFC requirements. In light of the growing need for statistical guidance, TDL plans to develop MOS systems for the operational EMC NWP models, including the global ensemble and the soon to be implemented regional Short-Range Ensemble Forecasting (SREF) system.

Currently, the only operational model for which probabilistic (TDL MOS) QPF guidance is generated is the Nested Grid Model (NGM) (Glahn and Lowry, 1972; Glahn et al., 1991b; NWS, 1992; NWS, 1993c; Antolik, 1995; Antolik, 1996; Dallavalle, 1996), although EMC is routinely generating experimental, Internet-accessible, global ensemble-based, PQPF guidance products (http://sgi62.wwb.noaa.gov:8080/ens/prcp/psvt96_usa.html) (see also section 9.3). This experimental EMC guidance includes gridded probabilities of occurrence of the following rainfall amounts: ≥.25 mm (0.01 inches); ≥1.0 mm (0.04 inches); ≥2.54 mm (0.10 inches); ≥6.35 mm (0.25 inches); ≥12.7 mm (0.5 inches); ≥25.4 mm (1.0 inches), and ≥50.8 mm (2.0 inches). During FY 98, EMC will also provide calibrated (experimental) probabilities for these precipitation categories. Probabilities will be calibrated using a running total of verification statistics computed for the previous 30-day period.

Future TDL/EMC model-based statistical guidance will be provided via MOS and the newly emerging ensemble approach. TDL recently developed interim Eta MOS QPF equations for the CONUS (Dallavalle and Antolik, personal communication, 1997) and will soon begin development of complete AVN MOS statistical guidance packages (including QPF) for the CONUS, AK, HI, and Puerto Rico. TDL will also investigate the development of MOS QPF guidance for the global and regional ensemble systems as resources become available.

Proposed HIWG-supported improvements to MOS include the development of a *gridded* (vs. the current point) MOS QPF/PQPF system which will utilize the Stage III-IV precipitation analyses (or their equivalent) as the predictand and ground validation (Antolik, 1998). Therefore, the Stage III-IV precipitation analyses must be quality-controlled and archived. HIWG also *strongly recommends* efforts to explore the operational utility of *alternative and advanced statistical processing techniques* which include:

- *Ensemble-based MOS* (Erickson, 1996);
- *Multiple-model MOS* (Vislocky and Fritsch, 1995a);
- *Non-parametric regression* (Vislocky and Fritsch, 1995b);
- *Adaptive (recursive) techniques* (Ross, 1989; Ross, 1992; Ross and Strudwicke, 1996); and
- *Neural networks* (McCann, 1992; Gillispie, 1993; Hall, 1996).

The rapid evolution of NCEP operational modeling systems in recent years may limit the development of statistical guidance via the traditional MOS approach (Glahn and Lowry, 1972), given that the traditional approach yields the best results when long samples of model data are available for development (Antolik and Dallavalle, 1997, personal communication). Additionally, the rapid development of modeling systems makes it increasingly difficult for operational forecasters to develop the keen understanding of model biases necessary to mitigate the impact of these biases through value-added adjustments. This correspondingly heightens the need for statistical guidance and underscores the need for progressive MOS approaches which are more efficient and adaptable to rapid model evolution. These MOS techniques need to evolve with the current NCEP operational models and produce guidance at 10KM or better resolution. Higher resolution guidance is required to accurately assess the impact of forecast precipitation in small hydrologic basins, particularly in regions of complex terrain. TDL is currently developing a new MOS software system, termed MOS-2000, which is designed to be more responsive to NCEP model changes (Dallavalle, 1997, personal communication).

8.3. Locally-Produced Guidance

As described in section 6.3, WFOs require short-range, high resolution, observational- and model-based QPFs/PQPFs for advance warning and the risk-based areal assessment of flash flooding within SCAN and WHFS.

- *Extrapolative-Statistical Precipitation Products*

TDL has developed a WSR-88D-based, extrapolative-statistical algorithm for generating local 1-hour, 4-km resolution, probabilistic rainfall forecasts (Kitzmiller, 1996) (http://tgsv5.nws.noaa.gov/tdl/radar/radar1.htm). This algorithm:

- uses low-level reflectivity and vertically integrated liquid (VIL) water as predictors,
- accounts implicitly for echo decay and uncertainty in the extrapolation process,
- uses the operational WSR-88D Z-R relationship to convert reflectivity to rain rates, and
- produces probabilities that the WSR-88D-estimated rainfall will be ≥ 0.1, ≥ 0.25, ≥ 0.5, and ≥ 0.75 inches, within each box of a 4-km grid, during the next hour.

Similar to the current MOS approach, regression equations were derived to relate sensible weather observations to predictors. These equations correlate extrapolative forecasts of reflectivity and VIL with Stage III multi-sensor rainfall analyses for a large number of historical cases. The velocity of the reflectivity field is estimated by lag-correlation pattern matching in stratiform conditions, and is taken to be the average storm cell velocity indicated by the WSR-88D tracking algorithm in convective events. The 0-1 hour QPF algorithm is scheduled for implementation in AWIPS Build 4.1.

Efforts are underway to expand the algorithm to produce 0-3 hour forecasts, by integrating national (mosaicked) radar, satellite, and model data. TDL is presently testing two 0-3 hour extrapolative-statistical QPF algorithms for the CONUS. One is based on radar reflectivity from the Aviation Weather Center (AWC)-produced 10-km Radar Coded Message (RCM) mosaic and Nested Grid Model (NGM) output, while the other is based on GOES infrared observations and NGM output (Kitzmiller and Sun, 1997; Kitzmiller, 1998). The algorithms produce the probability that the average rainfall within some HRAP grid element (16 square kilometer area) will be ≥ 0.1, ≥ 0.5, ≥ 1.0, or ≥ 2.0 inches within each 40-km grid box of a grid covering the

CONUS. The rainfall probability is proportional to the maximum reflectivity or minimum cloud-top temperature over the local region in question, and to humidity and stability as indicated by the surface-500 mb mean relative humidity and the K index. Similar to the 0-1 hour algorithm, the probability relationships were derived by correlating extrapolation forecasts of reflectivity and satellite IR temperatures with Stage III multi-sensor rainfall estimates for a large number of historical cases. The extrapolation velocity of the reflectivity or cloud-top temperature patterns is estimated by lag-correlation pattern matching, or is assumed to equal the 700-mb wind velocity. Though the algorithms' probability equations were derived from data from the 1996 warm season, they have yielded promising results during the 1996-1997 cool season, based on comparisons with NCEP Stage IV multi-sensor precipitation analyses. Eventually, these two 0-3 hour algorithms will be merged, with the final probability forecasts depending on radar data where available, and satellite temperatures over areas where radar data are missing or where clouds are present but the radar is not observing precipitation. Additionally, TDL is experimenting with utilizing model output from the Eta and RUC models in real-time to derive the model-based stability and relative humidity parameters.

- *Local AWIPS MOS Program (LAMP) QPF*

The LAMP QPF model (Charba, 1998a,b; Charba et al., 1998b), in essence, produces hourly updates of MOS QPFs in the 1-22 hour period with higher spatial and temporal resolution than MOS. The improved resolution stems from the use of data from the high density U.S. Climatic Hourly Precipitation Network to specify the predictand, and from the inclusion of a number of additional high resolution data types to specify the predictor set. Specifically, the model produces gridded (20 km), hourly probabilistic forecasts for multiple intervals of precipitation amount. The precipitation intervals are 0.00-0.09, 0.10-0.24, 0.25-0.49, 0.50-0.99, 1.00-1.99, and $\geq$ 2.00 inches, and best category and expected precipitation products are derived from the probabilities. The temporal resolutions of these products are:

- 1 hour for the 1-5 hour forecast range,
- 3 hours for the 4-10 hour forecast range, and
- 6 hours for the 10-22 hour forecast range.

The predictors used in the LAMP QPF model development were derived from a variety of data inputs, which are:

- NGM MOS probabilities for 6-hour precipitation of $\geq$0.10, $\geq$0.25, $\geq$0.50, and $\geq$1.00 inches;
- Forecasted 850-mb u- and v-wind components, precipitable water, and 500-mb height from the NGM;

- Objectively analyzed and advected fields of variables based primarily on conventional hourly surface observations;

- Objectively analyzed and advected fields of 1- and 3-hour precipitation amount from the U.S. Climatic Hourly Precipitation Network;

- High resolution precipitation amount climatologies (Charba et al. 1992; Charba et al., 1998a);

- High resolution topography (Charba, 1998b).

Some of the above data inputs are used to compute predictors that add physically meaningful mesoscale detail to the LAMP forecasts. For instance, the fine scale topography is used together with the 850-mb u- and v-wind components to provide a terrain-induced vertical velocity predictor input. Also, the fine scale precipitation climatology variables are used by combining them with current environmental variables, such as low-level moisture and the MOS probabilities. Further, variables derived from the analyses and forecasts of observed surface parameters add subsynoptic detail to the LAMP QPFs. During real-time application of the model, a multi-sensor precipitation analysis (NCEP Stage IV) will substitute for the antecedent precipitation analysis based on climatic hourly (gage) precipitation data. This analysis, coupled with the output from higher resolution NCEP NWP models, will enable for the realtime provision of higher resolution ($\leq$10 km) gridded LAMP QPF guidance.

The LAMP QPF model is currently being run at TDL on an experimental basis on a prototype AWIPS workstation with a 3-hour cycle time. Projected implementation of LAMP QPF at WFOs is with AWIPS Build 5.0. Real-time graphic products are being made available to local NWS offices through N-AWIPS and through the TDL home page (http://www.nws.noaa.gov/tdl/lamp/qpf.shtml). Early results (Charba, 1998a; Charba et al., 1998b) reveal that the 6-hour products provide significant improvement on NGM MOS QPFs, especially in mountainous regions. Further, the 1- and 3-hour products have high spatial detail.

Prior to expected implementation on AWIPS at local NWS offices, several enhancements to the model will be made. One is that a multi-sensor precipitation analysis (NCEP Stage IV) will be substituted for the current real-time analysis based on reported hourly precipitation from ASOS and estimated hourly precipitation from basic weather observations (Charba, 1992). Another is that the model will be configured to run on an hourly cycle. The model will also utilize Eta MOS (in lieu of NGM MOS) and Eta 850-mb wind forecasts as soon as Eta MOS QPF becomes available operationally. Finally, additional post-processing of the unconditional QPF products will be applied to enhance their utility for flash flood watches and warnings within SCAN (Charba, 1998, personal communication).

- *System for Convection Analysis and Nowcasting (SCAN)*

SCAN will couple the following applications into one integrated approach to detect, analyze, and monitor convection and generate short-range probabilistic forecasts and warning guidance automatically within AWIPS (see figures 15 and 16):

- *NCAR's Auto-nowcaster* (Wilson and Mueller, 1993; Gould et al., 1993; Henry et al., 1996; Mueller and McDonough, 1996) (http://www.rap.ucar.edu/raps95.html);

- *NSSL's Warning Decision Support System* (WDSS) (Eilts et al., 1996; Johnson et al., 1998) (http://www.nssl.noaa.gov/srad/rapid/WDSS.html);

- *OSD's AWIPS Thunderstorm Product* (Smith and Churma, 1996; Churma and Smith, 1998) which includes TDL's Extrapolative-Statistical WSR-88D-based algorithm (http://tgsv5.nws.noaa.gov/tdl/storm/storm.html); and

- *OH's WFO Hydrologic Forecast System* (Office of Hydrology, 1996) (http://hsp.nws.noaa.gov/oh/hrl/).

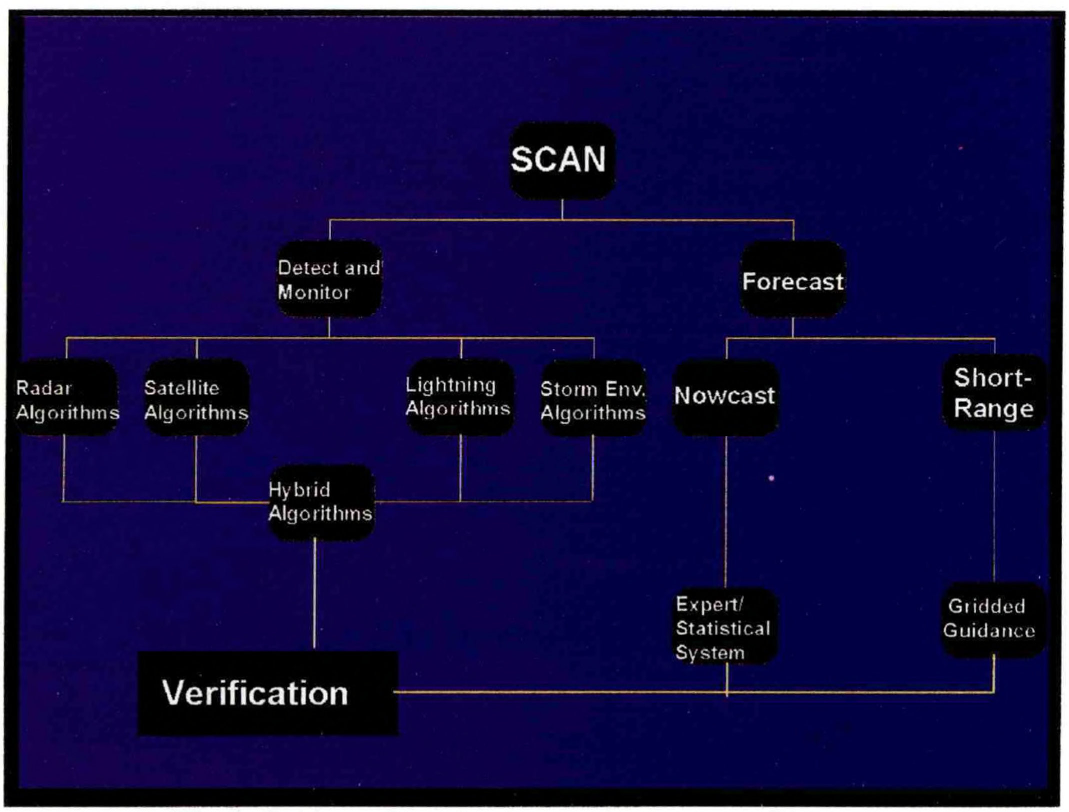

Figure 15: Functionality framework for SCAN (from Smith et. al, 1998).

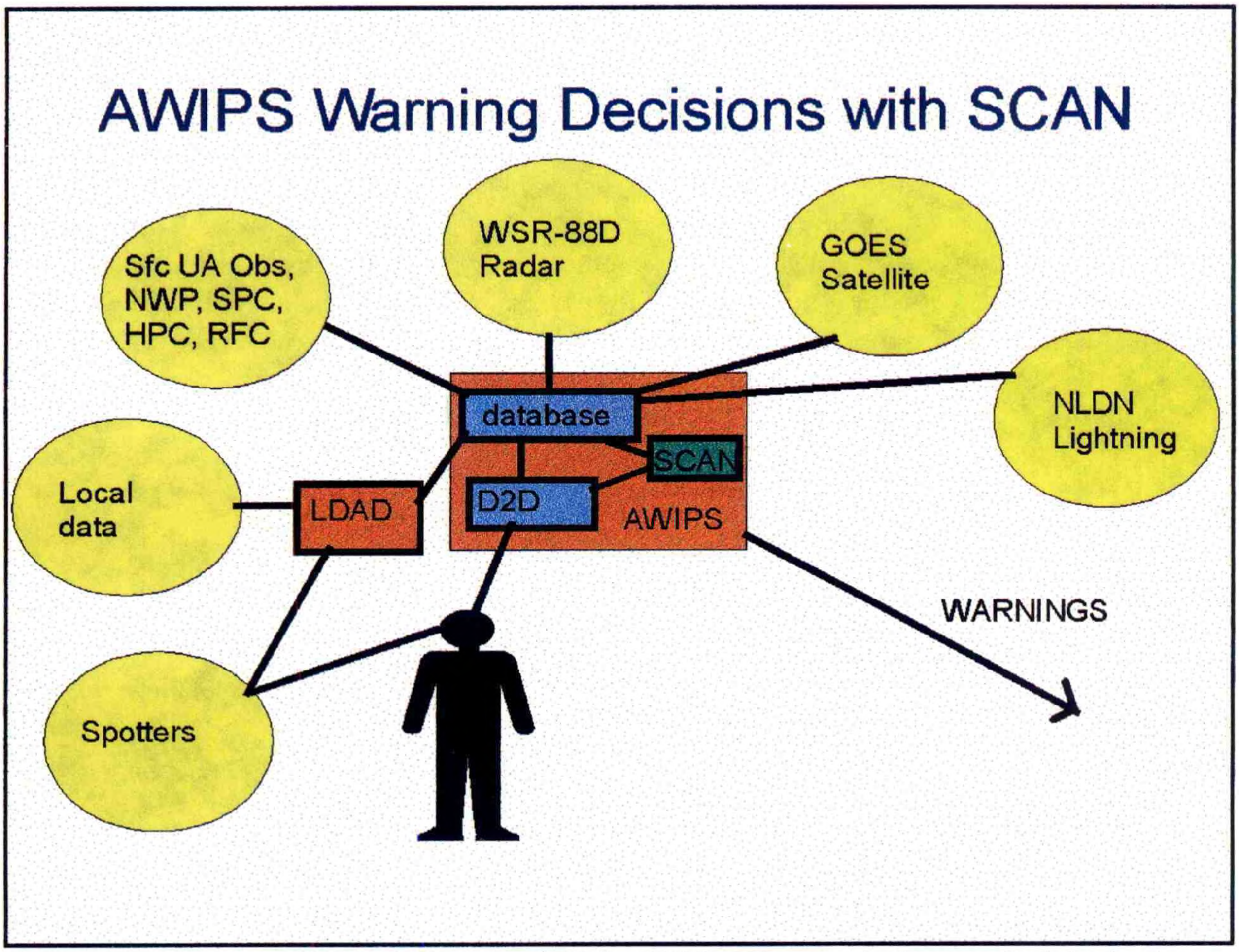

Figure 16: Relationship of SCAN to D2D within AWIPS. SCAN will improve the forecaster flash flood and severe weather watch/warning decision process by enabling for the integration, easy access, and display of all decision-critical information within D2D (courtesy of Stephan Smith, OSD).

OH's WFO Hydrologic Forecast System will be "coupled" to the extent that AWHPS-like flash flood threat products will be generated automatically within SCAN (see section 6.1). SCAN will enable forecasters to display these flash flood threat products with companion data and products within the AWIPS D2D. SCAN will compute SCTIs and enable forecasters to access and display WHFS products with companion meso- and microscale observational and forecast data sets and analyses within the D2D to assist in the preparation and issuance of improved risk-based flash flood watches and warnings.

Research and operational testing of these individual software applications have successfully demonstrated their respective benefits. A primary motivation for SCAN is to integrate theseapplications and develop a system whose whole is greater than the sum of its parts. The primary goal of SCAN is to provide operational forecasters with a more efficient, effective, and consistent means of issuing timely and accurate warnings (e.g., severe weather, flash flood, tornado, etc.), through the provision of automated and forecaster editable warning guidance. SCAN supports the modernized ETE Forecast Process by providing a framework to integrate and make optimal use of the enormous volume and broad spectrum of advanced observational data (WSR-88D, GOES, ASOS, NLDN), NWP and statistical model output, analyses, and HPC and SPC guidance within AWIPS. The functionality to be incrementally implemented in SCAN includes automated storm detection, phenomenon classification, severity and flash flood monitoring, and nowcasting that will allow the forecaster to make better informed watch and warning decisions. Furthermore, it will serve as a vehicle for the implementation of future nationally- and locally-developed applications within AWIPS.

During the 1997 convective season, a SCAN prototype consisting of an integration of NSSL's Warning Decision Support System, NCAR's Thunderstorm Auto-nowcaster and the NWS's Thunderstorm Product was tested at the Washington D.C.-Baltimore forecast office in Sterling, Virginia. The purpose of the field test was to integrate these software applications and examine the usefulness of the combined products as a tool for the short-term and warning forecaster. The 1997 test results and forecaster feedback was overall very positive. The capability of the second generation SCAN prototype, successfully tested at Washington D.C.-Baltimore forecast office during the 1998 convective season, was significantly enhanced. A more complete integration of advanced guidance products, enhanced training, and the introduction of AMBER-based flash flood threat products were manifested as markedly improved verification skill scores (see figure 17).

Version 1.0 of SCAN, which includes the NWS' AWIPS Thunderstorm Product and 0-1 hour WSR-88D based extrapolative-statistical probabilistic QPF guidance, was delivered with AWIPS Build 4.1 in the Fall of 1998. SCAN version 2.0, which incorporates WDSS functionality and the integration of flash flood threat products, is currently scheduled for field implementation in the year 2000.

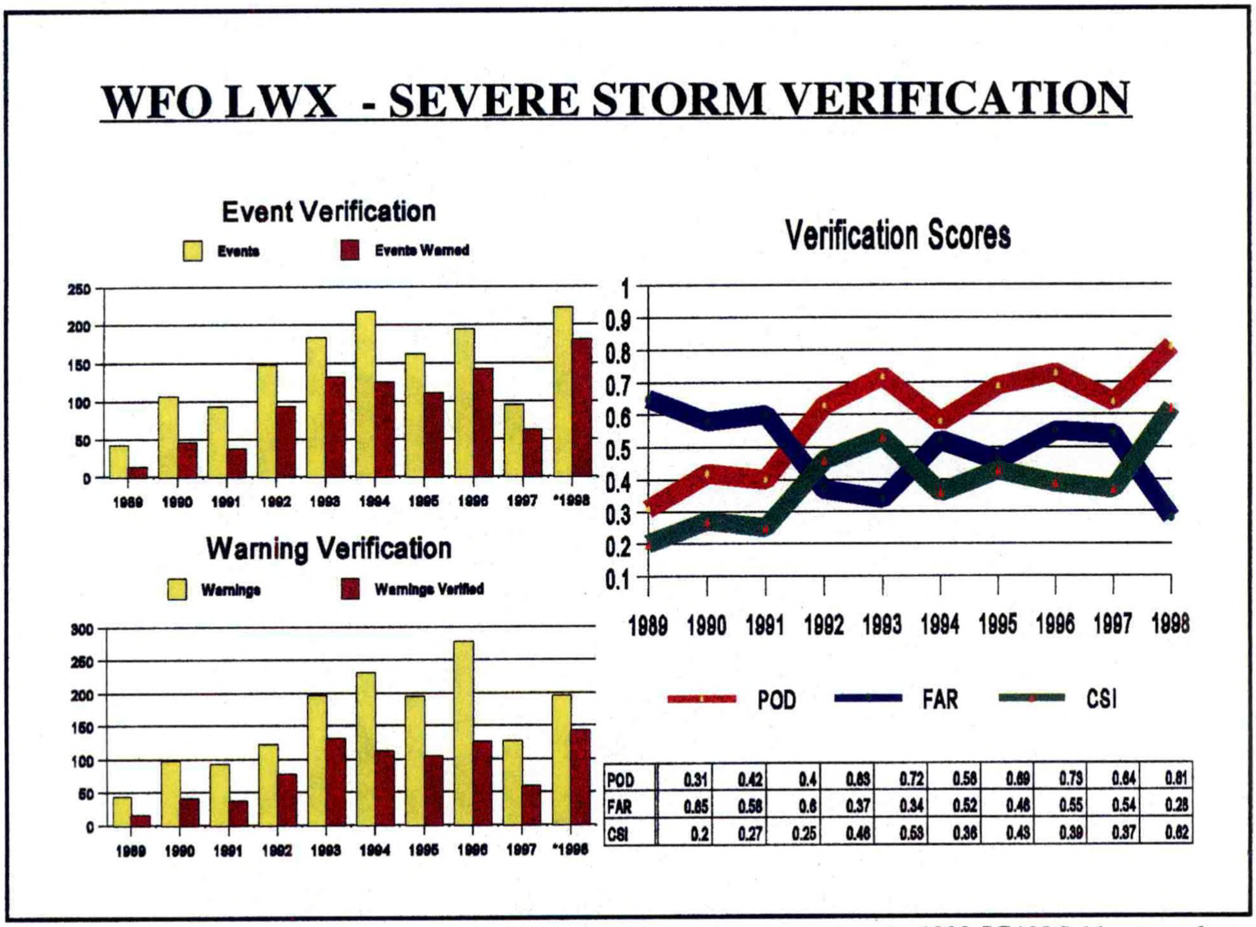

Figure 17: WFO Sterling, VA severe weather verification statistics contrasting the 1998 SCAN field test results to previous years (courtesy of Barbara Watson and Steve Zubrick). Flash flood statistics are not presented, due to a limited number of events.

9.0. Data Assimilation and Atmospheric Model Requirements

Fundamental to improving operational quantitative precipitation forecasting is the development and implementation of improved data assimilation techniques and optimum strategies for maximizing the utility of improved global and regional NWP models and ensemble prediction systems. [1]

9.1. Data Assimilation

An important element of any effort to increase the prediction skill of meso-β and meso-γ precipitation systems is the accurate specification of model initial conditions at a commensurate scale. Data assimilation is becoming increasingly important because of 1) the asynoptic nature of a nearly continuous data stream from many different types of observation platforms, 2) the unique characteristics of these observation platforms both in situ and remotely sensed, and 3) the need to take advantage of the strengths and avoid the weaknesses of each platform. The observational data and derived products necessary to support increasingly sophisticated mathematical data assimilation techniques are being made available through the NWS MAR. The operational assimilation of this broad spectrum of remotely-sensed and in-situ observational data, spanning multiple spatial and temporal scales, presents a significant challenge to the NWS and the meteorological community. Through the optimal combination of these individually incomplete and diverse data sets (see section 10.0), the horizontal and vertical distributions of mass, momentum, and moisture can be adequately specified for use by the numerical model systems, both limited area mesoscale and global.

To properly analyze the current mesoscale state of the atmosphere and accurately simulate its evolution, it is *critical* to develop and employ more advanced data assimilation techniques. EMC is engaged in development efforts to operationally:

- utilize advanced data assimilation methods (Lin et al., 1995; Lin et al., 1996c; Rogers et al., 1996a; Rogers et al., 1996b; Parrish et al., 1996), that include 3- and 4-D variational techniques to assimilate quality-controlled:
    - WSR-88D radial velocity and reflectivity data;
    - Aircraft Communications, Addressing and Reporting System (ACARS) data;
    - Geostationary Earth Orbiting (GEO)- and Lower Earth Orbiting (LEO)-based satellite temperature and moisture radiance data;
    - GEO-based wind and precipitation products;

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[1] *For a detailed history of numerical weather prediction at NCEP, the reader is referred to Shuman (1989).*

- LEO-based precipitation products;
- Global Positioning Satellite (GPS) water vapor data;
- Ground-based GPS precipitable water measurements;

- test and employ advanced strategies for targeted observations (Langland et al., 1998)
- assimilate the NCEP/EMC-produced Stage IV precipitation analysis for physical (diabatic) initialization (Lin et al., 1994; Mitchell, 1994; Lin et al., 1996a; Lin et al., 1996b; Baldwin and Mitchell, 1997; Lin et al., 1997).

The development and operational implementation of these advanced assimilation techniques, and the full utilization of these data, are necessary to satisfy the HPC, WFO, and RFC requirements for QPFs/PQPFs.

9.2. NCEP Atmospheric Models

Over the past 35 years, operational forecasters have exhibited a steady increase in QPF forecast skill (Olson et al., 1995). This documented improvement in the skill of value-added QPFs paralleled the implementation of enhanced operational NWP systems. Future increases in QPF forecast skill will largely be predicated upon the provision of improved numerical forecast guidance (Mesinger, 1998). Many improvements to NCEP operational models have recently been implemented, or are forthcoming, which will help satisfy HIWG requirements and provide more accurate, reliable, and higher resolution numerical model QPFs (Kulogowski, 1996; DiMego et al., 1998). Improved resolution (on the order of 10 km or less) and improved model physics, coupled with improved data assimilation, are needed to correctly forecast precipitation in complex terrain and to begin to correctly resolve and forecast significant convective events. Improved model QPFs, together with the appropriate TDL/EMC statistical post-processing, will serve as a basis for the planned national transition to probabilistic forecasting. Operational model improvements include:

- improving land-surface modeling and the parameterization of turbulence fluxes of momentum, and sensible and latent heat (Janjic, 1994: Berbery et al., 1996; Chen et al., 1996a; Chen et al., 1996b; Mesinger et al., 1996; Xue et al., 1996; Zeng et al., 1996; Chen and Mitchell, 1997; Chen et al., 1997; Duan et al., 1997);
- increasing the regional scope, resolution, and temporal frequency of mesoscale model simulations (Black, 1994; Baldwin and Black, 1996; Burks and Staudenmaier, 1996; Gartner et al., 1996);
- extending the range of mesoscale model predictions through Day 3;

- improving the parameterization of cloud turbulent and microphysical processes (Manikin et al., 1996; Zhao et al., 1996a; Zhao et al., 1996b; Zhao et al., 1996c);

- developing global and regional ensemble systems (Toth and Kalnay, 1993; Tracton and Kalnay, 1993; Du et al., 1996; Du et al., 1997; Tracton et al., 1996; Toth et al., 1997; Tracton et al., 1998);

- developing collaboratively the next generation, high resolution, non-hydrostatic, Weather Research and Forecasting (WRF) mesoscale model with NCAR and other NOAA laboratories (Janjic et al., 1998); and

- performing storm-scale (cloud resolving) simulations with explicit microphysics.

9.3. Ensemble Prediction

As a complimentary strategy for satisfying the HIWG requirement for QPFs/PQPFs, ensemble systems allow for the operational provision of event-based, short- through medium-range QPF/PQPF guidance. Ensemble systems employ multiple runs of coarser resolution models. This trade-off is required given a finite operational computing capacity. Assuming the most significant model errors are caused by uncertainties in the model initial conditions and model physics[2], ensemble systems produce a spread of forecasts and offer the advantage of providing event-based probabilistic guidance. Ensemble techniques are encouraging, but continued scientific study is needed to evaluate 1) the sources and relative magnitude of forecast (observational and model) uncertainties to appropriately account for these uncertainties, 2) the optimal combination of ensemble size (i.e., the number of members), model (grid) resolution, model configuration (i.e., variations in model physics and parameterizations), and ensemble composition (i.e., single vs. multiple models) given limited computing resources, 3) the best mix of high resolution models and coarser resolution ensemble techniques. The following several paragraphs summarize the progress and issues to date.

During the past 6 years EMC/NCEP developed an operational global medium-range ensemble weather forecast system (Toth and Kalnay, 1993; Tracton and Kalnay, 1993). With this development, NCEP became the first numerical weather prediction center offering the benefits of ensemble prediction to its users. Operational ensemble forecasting began at NCEP in December 1992 and the operational global system was upgraded in March 1994. Currently, 17 global forecasts are run every day: Two of these runs are made at T126 resolution (105 km) while the remainder are run at T62 resolution (215 km) (see table 7). The performance and utility of the global ensemble system has been assessed via subjective evaluation (Toth et al., 1997) and objective verification (Zhu et al., 1996; Toth et al., 1998), and it is clear that the ensemble system provides increased skill and utility relative to the single T126 control. The impact of model resolution and ensemble size on

[2] *The current SREF system under development employs a multiple model approach. This design is based upon preliminary verification results which indicate a need to also account for model uncertainties.*

forecast value is currently being evaluated. Global ensemble-based forecasts have been favorably received and routinely used by NWS weather forecasters at NCEP (Danaher, 1996) and Weather Forecast Offices. Global ensemble-based products have also received a favorable reception from a wide range of users external to the NWS, including U.S. Air Force (USAF) field personnel (Doran et al., 1998).

The NCEP global ensemble system provides probabilistic forecasts of many parameters, including QPF. By determining the fraction of ensemble members that predict a particular weather event, one can derive the likelihood of that event. Since neither the model nor the ensemble formation is perfect, these probabilities need to be calibrated. The calibration of ensemble-based probabilistic forecasts is a relatively straightforward process which yields very reliable forecasts (Toth et al., 1998). Experience has shown that probabilistic geopotential height forecasts derived from the global ensemble have great value. The advantage of ensemble-based forecasts, relative to more traditional categorical or point forecasts (usually based only on a single model integration), is that crucial information on forecast reliability and event-based probabilities is included. Currently, there are no other practical methods by which this information, which includes event predictability, could be derived (Ehrendorfer, 1997).

Since the fall of 1996, probabilistic quantitative precipitation forecasts have been generated from the ensemble by simply counting the number of forecasts (C, out of the 17 total NWP model runs every day, T) that exceed specified thresholds. The ratio C/T yields the ensemble-based probability of an event. Experimental 24 hour global ensemble-based probabilities of exceedance are currently available for several precipitation thresholds (0.01, 0.1, 0.25, 0.5, 1 and 2 inches) to a range of 14 days for the 0000 and 1200 UTC forecast cycles (see figure 18) (for additional details and realtime products see: http://sgi62.wwb.noaa.gov:8080/ens/ens_imp_news.html).

No objective verification of the NCEP global ensemble-based PQPFs are available yet, but the initial subjective evaluation is very encouraging (Zhu et al., 1998). Pending the availibility resources, EMC/NCEP plans to conduct a rigorous objective verification of the ensemble-based PQPFs and calibrate them using verification statistics from the most recent months. (Such a simple calibration method results in very well-calibrated probabilistic forecasts of geopotential height and is expected to do the same for PQPF.) A full probability distribution of forecast precipitation amount (probabilities for exhaustive precipitation categories) will be provided in a gridded format at a 2.5 by 2.5 lat/lon resolution. Probabilistic temperature and wind forecasts, which should also be very useful for flood forecasting, will be developed using a similar approach.

The basic concept and principles of ensemble prediction apply equally well to short ranges and smaller spatial scales. In an effort to define an operationally acceptable model strategy and prepare for the operational provision of regional SREF-based forecast guidance, EMC is currently engaged in an assessment to (Tracton et al., 1998):

- develop and explore methodologies for the generation of short-range regional model ensembles for QPF,

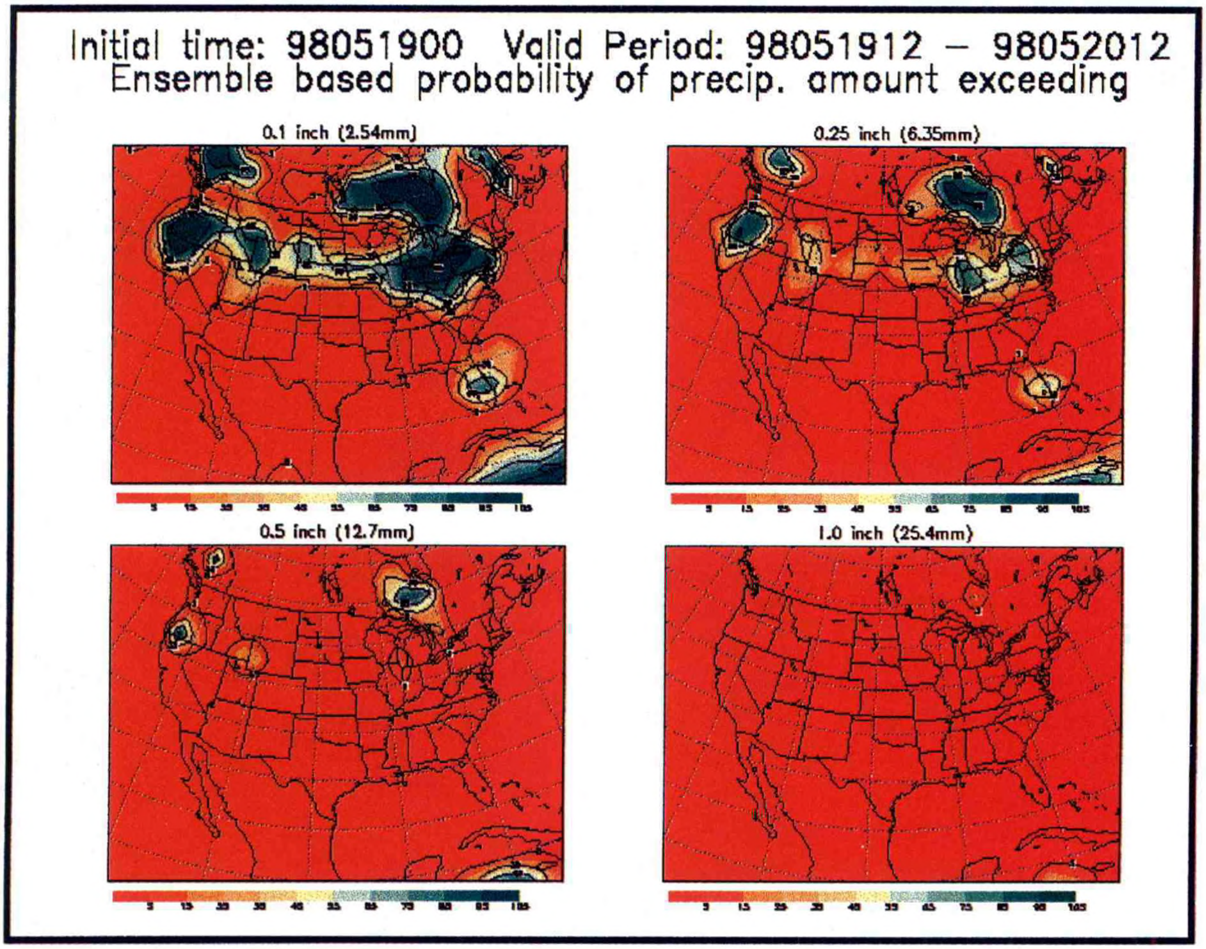

Figure 18: Experimental NCEP Global Ensemble-based 24-hour probabilistic QPF products. Exceedance probabilities depicted are for the 0.1, 0.25, 0.5, and 1.0 inch thresholds (image courtesy of Zoltan Toth, NCEP/EMC).

- test and evaluate strategies for perturbing initial conditions and quantifying model uncertainty,
- investigate options with regard to model resolution and ensemble size,
- evaluate the trade-off between high resolution single model runs and coarser resolution ensembles, and
- demonstrate the value-added/utility of regional ensembles for QPF/PQPF applications.

A breeding system has been developed for the RSM and Eta models. Experimental multi-model (RSM and Eta) ensembles are now being run routinely for selected events (see figure 19), and the preliminary results of the regional demonstration are encouraging. Sensitivity studies to test the impact of model resolution, ensemble size, and model physics are underway.

9.4. Current and Future Model Runs

Current and planned EMC modeling systems and their basic specifications are outlined in tables 7 and 8, respectively. The computer resources required to routinely run a regional ensemble system and high resolution mesoscale models make the provision of products from these models contingent upon the operational implementation of the next generation Class VIII computer in FY 99. The same applies to higher resolution global model and ensemble runs. Additionally, operational WRF mesoscale and stormscale model simulations are contingent upon the acquisition the Class IX computer, scheduled for 2002 or thereafter. Current targets are specified in table 8, but modifications could result from assessment of overall optimum model strategies: for example, tradeoffs between single higher resolution runs and ensemble-based systems.

Given the sensitivity of hydrologic models to current and forecast precipitation and the need to provide higher resolution guidance for the preparation of QPFs/PQPFs at HPC, WFOs, and RFCs to support AHPS-based stochastic modeling and flash flood forecasting, the NCEP must vigorously attempt to satisfy these NWP and data assimilation requirements.

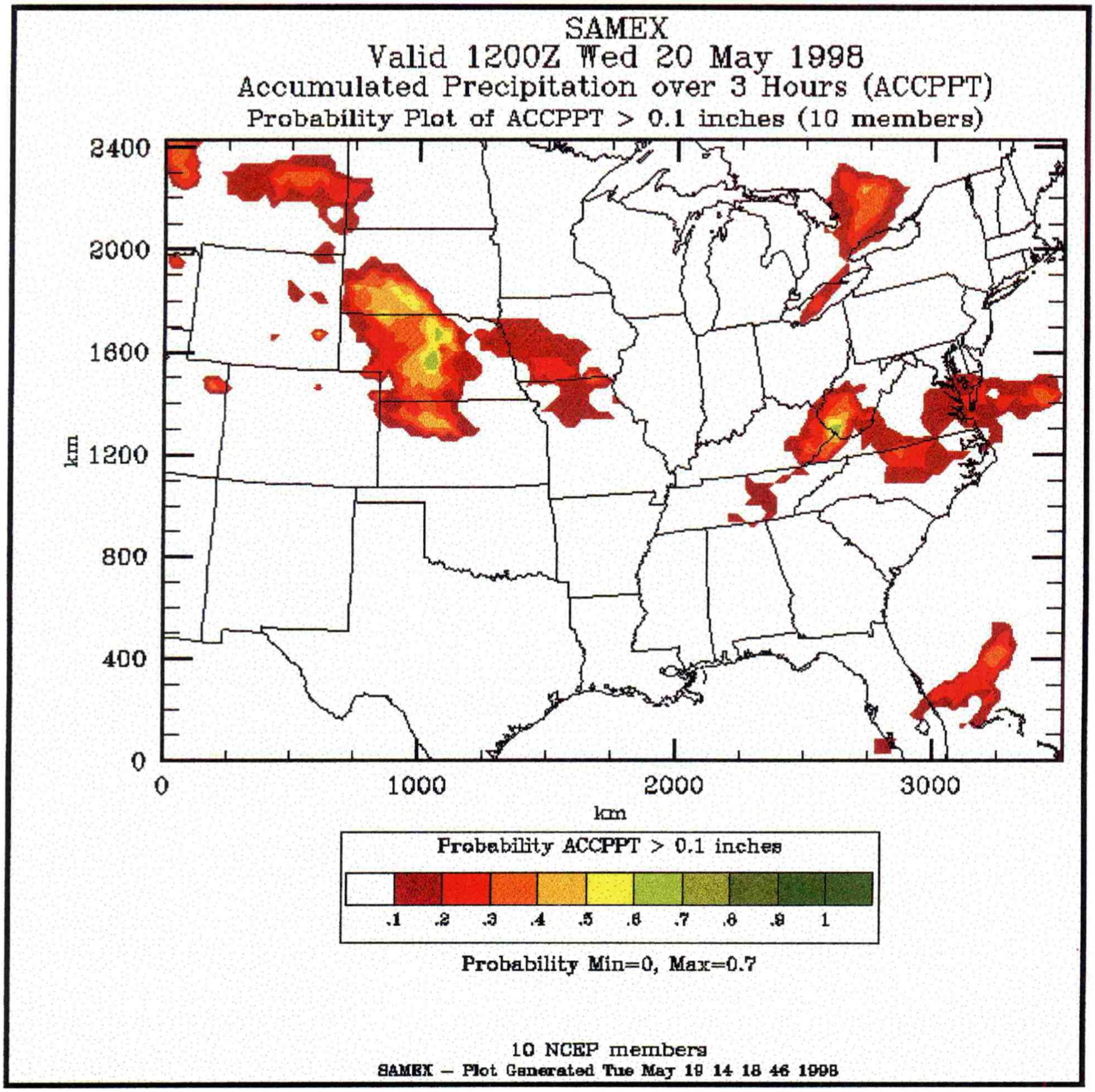

Figure 19: Experimental NCEP Regional Short-Range Ensemble Forecasting (SREF)-based 33 to36-hour probabilistic QPF product generated as a part of NCEP participation in the Storm and Mesoscale Ensemble Experiment (SAMEX). SAMEX was a multi-institutional numerical weather prediction experiment conducted over the central U.S. during the Spring 1998 convective season. Exceedance probabilities depicted are for the 0.1 inch threshold. The ten member NCEP ensemble is comprised of five Regional Spectral Model and five meso-Eta members run at a horizontal resolution of 32 km.(image courtesy of Steve Tracton, Jun Du, and Perry Shafran, NCEP/EMC)

Table 7: Current operational EMC model runs and their basic specifications.

Current Environmental Modeling Center Operational NWP Model Runs			
Model	***Resolution*** *(Native Model Grid)*	***Model Initial Times***	***Forecast Range***
Meso-Eta	*32 km / 45 vertical levels* [1]	*0000, 0300, 1200, 1800 UTC* [2]	*48 hours* [3]
Alaskan Meso-Eta	*15 km / 50 vertical levels*	*0300, 1500 UTC*	*24 hours*
Hawaiian Regional Spectral Model (RSM)	*10 km / 28 vertical levels*	*0300, 1500 UTC*	*48 hours*
Regional Analysis and Forecast System (RAFS) / Nested Grid Model (NGM)	*83 km (inner grid) / 16 vertical levels*	*0000, 1200 UTC*	*48 hours*
Rapid Update Cycle (RUC) [4]	*40 km / 40 vertical levels*	*hourly*	*3 hours, except 12 hours every 3 hrs beginning at 0000 UTC*
Global Spectral Model (GSM)			
Aviation (AVN)	*80 km / 42 vertical levels (T170)*	*0000, 0600, 1200, 1800 UTC*	*78 hours*
Medium Range Forecast (MRF)	*80 km / 42 vertical levels (T170) (days 1-3)* *105 km / 28 vertical levels (T126) (days 4-7)* *215 km / 28 vertical levels (T62) (days 8-16)*	*0000 UTC*	*16 Days*
Global Ensemble	*17 runs performed daily* *12 MRF model runs* [5] *5 AVN model runs* [6]	 *0000 UTC (MRF)* *1200 UTC (AVN)*	 *16 Days*
Climate MRF (18 member ensemble) [7]	*300 km /18 vertical levels (T40)*	*15th of each month*	*9 months (3 seasons)*

[1] Resolution of the Early meso-Eta will increase when the next generation Class VIII computer is operational (see table 8).

[2] Computer time for off-time 0600 and 1800 UTC runs from former 0300 and 1500 UTC initialized CONUS meso-Eta runs.

[3] Range will be extended for all initializations with Class VIII computer (see table 8).

[4] Upgrades effective NLT the fourth quarter of FY 98.

[5] Ten MRF runs at T62 (215 km) with perturbed initial conditions; one MRF run at T126 (105 km) out to day 7 and T62 thereafter; and one MRF control run at T62.

[6] One AVN run at T126 (105 km) through Day 3 and T62 (215 km) thereafter, and four AVN runs at T62 with perturbed initial conditions.

[7] Utilizes sea surface temperature forecast from the coupled oceanic-atmospheric GCM.

Table 8: Planned operational EMC model runs and their basic specifications.

Planned Environmental Modeling Center Operational NWP Model Runs			
Model	***Resolution*** *(Native Model Grid)*	***Model Initial Times***	***Forecast Range***
Meso-Eta [1]	*10 km / 60 vertical levels*	*0000, 0600, 1200, 1800 UTC*	*78 hours*
Regional Ensemble [1,2]	*~40 km / 40 vertical levels (~10 members: Eta and RSM)*	*0000, 1200 UTC*	*84 hours*
Weather Research and Forecasting (WRF) [3,4]	*< 10 km / 60 vertical levels*	*0000, 0600, 1200, 1800 UTC*	*78 hours*
Relocatable Storm-Scale [3,6]	*1-3 km / 60-75 vertical levels*	*event driven*	*30 hours*
Weather Research and Forecasting (WRF) Rapid Update Cycle (RUC) [3,5]	*10 km / 60 levels*	*hourly*	*3 hours, except 12 hours every 3 hrs beginning at 0000 UTC*
Global Spectral Model (GSM) [1]			
Aviation (AVN)	*70 km / 42 vertical levels (T213)*	*0000, 0600, 1200, 1800 UTC*	*72 hours*
Medium Range Forecast (MRF) [7]	*70 km / 42 vertical levels (T213) (days 1-3)* *105 km / 28 vertical levels (T126) (days 4-7)* *215 km / 28 vertical levels (T62) (days 8-16)*	*0000 UTC*	*16 Days*
Global Ensemble	*22 runs performed daily* *11 model runs* [8]	*0000 and 1200 UTC*	*16 Days*
New Climate MRF [1] *(18 member ensemble)*	*215 km /28 vertical levels (T62)*	*15th of each month*	*9 months (3 seasons)*

[1] Operational runs contingent upon the acquisition of the next generation Class VIII computer (FY 99).

[2] Resolution is projected to increase to ~30 km and 50 vertical levels with Class IX computer scheduled for FY 02.

[3] Operational runs contingent upon the acquisition of the Class IX computer.

[4] WRF will replace meso-Eta and will be run for CONUS, Alaska, and Hawaii.

[5] Weather Research and Forecasting (WRF) Rapid Update Cycle (RUC) model runs will replace current RUC.

[6] Stormscale model based on WRF.

[7] Serves as a 12th global ensemble member at 0000 UTC

[8] One control run and ten runs with perturbed initial conditions at T126 (105 km) out to Day 7 and T62 (215 km) thereafter.

10.0. Requirements for Observational Data

The flood warning and forecast mission of the NWS requires the regular and routine collection of atmospheric and river data. At a time when steady improvements in NWP and the implementation of the NWS's MAR are enabling the provision of more precise and timely hydrometeorological services to the Nation, the present observing system must evolve to provide the quality, amounts, and types of data required to continue the progress. While new and improved observing technologies offer the promise of greatly improved data sets, the operational access, integration, full utilization, and archiving of these data pose major scientific and technological challenges. The NWS must continue to support and be actively involved in programs which define the future of observing systems and specify strategies for the optimal use of these data.

10.1. Upper-Air

Upper-air data are critical for the assessment and prediction of atmospheric phenomena which produce precipitation leading to flash and river flooding, and other hazardous weather. As stated in section 9.1., the accuracy of NWP model runs are heavily reliant on the access and assimilation of these data. NOAA is addressing upper air data requirements for the United States and North America through the North American Atmospheric Observing System (NAOS) Program. NAOS was founded to 1) assess and make recommendations on the short-term steps that can be taken to improve the utility of the existing observing program and to reduce costs, 2) define the "best mix" of observing systems, strategies, and technologies that meet the requirements in the most cost-effective way for the evolving Composite Observing System for the 21st Century (COS-21); and 3) describe the steps needed to implement and operate the COS-21 and to effectively use the resulting data.

Current and future NAOS-identified (NAOS, 1997) sources of upper-air and remotely-sensed data required to support improved NWS hydrometeorological forecast and warning services include:

- radiosondes and dropwindsondes (with the potential for adaptive observation strategies),
- WSR-88D Doppler weather radars,
- Terminal Doppler Warning radars,
- Tropospheric Doppler wind profilers,
- Radio-Acoustic Sounding Systems (RASS),
- Imagers and Sounders onboard Geostationary Operational Environmental Satellites (GOES),
- Imagers and Sounders onboard Polar Operational Environmental Satellites (POES),

- Global Positioning Satellites (GPS),
- Aircraft Communications Addressing and Reporting System (ACARS)-equipped and reconnaissance aircraft,
- Doppler Lidar, and
- Lightning Detection Networks.

Under the auspices of NAOS, the NWS will continue to play a significant role in defining the most cost-effective and optimal combination of observing platforms and near- and longer-term observing strategies in support of hydrometeorological and other forecast operations.

10.2 Surface

Surface observations, and their integration with radar and satellite data, are critical for the quantitative estimation of rainfall and assessment and prediction of flooding conditions at all steps of the ETE Forecast Process (i.e., numerical and statistical models, HPC, WFOs, RFCs). While the immediate focus of NAOS is on the upper-air observing system, similar issues surround the state and future of surface observations. The NWS's in-situ surface observing network which includes the Automated Surface Observing System (ASOS), Cooperative Observer Program (COOP), Automated Hydrologic Observing Program (AHOS), and marine ship and buoy programs, is designed to support the needs of hydrometeorology, aviation, climate and public safety (Kuligowski, 1997). However, as the 21st century approaches, there is a growing set of requirements for surface observations that support the missions of government agencies at all levels and the needs of private industry, which go beyond the requirements of the NWS. As a consequence of technological innovations in communications and instrumentation, separate, specialized networks have been and continue to be established to measure environmental parameters that support specific public and private needs (Tucker, 1997). A large disadvantage of these heterogeneous data collection systems is that there is much overlap and duplication of effort from one network to the next. Another disadvantage is the difficulty of sharing data amongst user groups owing to disparities in data requirements, observing standards, calibration, maintenance, and communication protocols. Moreover, at the same time there is an increasing need for improved observations, and networks are coming under stress to consolidate because of budgetary limitations.

The real-time acquisition, quality-control, and archiving of surface observations, particularly rain gage observations which satisfy NWS standards, is critical to all components of the ETE Forecast Process. Applications include flash flood forecasting, atmospheric and hydrologic model initialization, and verification. Consequently, during the July 1996 meeting, HIWG members collectively supported a recommendation to assess the number and increase the availability of hourly real-time, all-season, rain gage observations. These gages must be sited according to NWS standards, which has not always been the case in the past. Further, the OH stated via HIWG that a *minimum* of 30 (with a target of 50) spatially-distributed rain gauges per WSR-88D radar umbrella are needed to adequately compute the mean field bias correction[1] for the Stage I precipitation product (see sections 5.3.1 and 6.3.1 for explicit requirements). The implication is significant considering the Stage I product is used directly for flash flood assessment in the WHFS and serves as the basis for the multi-sensor Stage II-IV products. The production and real-time accessibility of the Stage I-IV multi-sensor precipitation analyses, based in part on these surface data and also on the full integration of remotely sensed data (radar and satellite), must be provided and archived as required by components of the ETE Forecast Process. The complete implementation of the Automated Surface Observing System (ASOS), along with the proposed retrofit of ASOS tipping buckets with weighing gauges, will substantially increase the real-time availability of all-weather gage observations of precipitation. This effort, and the quality control and archiving of these data, is critical to support NWS hydrometeorological operations and should be accelerated if possible. However, additional gage observations over that provided by ASOS will likely be needed to satisfy minimum NWS requirements.

The OH is currently assessing the availability of hourly real-time rain gage data available from multiple networks, including those operated by state water resource managers involved in the user forums which helped establish the overall requirements. This assessment will enable the spatial density of, and additional requirements for, hourly real-time rain gauge data to be determined for each NWS WSR-88D. Further, the OM is conducting a study of the status of all Federal, state, county, local, and private surface observational networks nationwide and the prospects for integrating these observations into a real-time national network. An integrated surface observation network would maximize the utility and cost-effectiveness of the national investment in surface observations by leveraging the information and resources of the multitude of independent surface observation sources that exist throughout the country. Many challenges are associated with properly developing and maintaining such an integrated network. Historically, official observations have come from NWS installed, operated, supervised, and maintained stations. Standard representative weather observations are fundamental in preserving the NWS's scientific credibility and record of outstanding public service. Therefore, it will be advantageous to promote the development and adherence of observation standards, while recognizing that observations from non-standard networks will only contribute significantly toward improved services if information about the quality of the data is known a priori and can be appropriately factored into the integrated system. For instance, it may be necessary to stratify non-standard observations according to various characteristics that include the:

- siting and exposure,
- regular and routine calibration,

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[1] *Rainfall bias corrections are planned to be performed in the future and are contingent upon the operational implementation of the ORPG.*

- regular and routine maintenance of the instrumentation, and
- the quality control of the data.

Such a stratification would allow for the prudent use of observations derived from non-standard networks and would enable user groups to make informed decisions about the quality of the instruments that they purchase and the utility of the data they provide. Examples of integrated surface observing regional networks include the FSL Regional Observation Cooperative (ROC) in the Denver/Boulder, CO, area (Stamus et al., 1997), the Bay Area MESONET Initiative (BAMI) in Central, CA, and the Utah Mesonet (Horel et al., 1996). Further, the NWS is a partner in an NESDIS/Environmental System Data and Information Management (ESDIM) project with the National Ocean Service (NOS) and the University of Maryland to assemble, under a single electronic cover (i.e., a single site on the World Wide Web), an interactive GIS-based spatially-explicit catalog of metadata for surface networks and the other major observing systems excepting satellites. This interactive, national-scale catalog would serve as an on-line reference to information about operational observing systems, providing easily-accessible visual displays of geographic and technical data.

11.0. Verification

Verification of direct NWP model, statistical, and forecaster value-added QPFs and PoPs is necessary to quantify and improve the skill of QPF/PQPF and PoP forecasts, and to assess the value-added to these forecasts at each step of the NWS ETE Forecast Process.

11.1. Overview

To measure forecast skill and assess areas where improvement is needed, the NWS will develop a uniform verification program that will be national in scope. Most of the computations will be performed centrally at a HIWG-proposed National Verification Unit (NVU) located in the NOAA Science Center (NSC) at Camp Springs, Maryland, and disseminated to field offices via AWIPS. The implementation of the NVU is, however, contingent upon the availability of the necessary resources.

The timely computation and provision of QPF and PoP verification scores to HPC, WFO, and RFC forecasters is critical to establishing an operationally beneficial program. PoP is defined as the probability of 0.01 inch or greater precipitation for a defined area or location. Forecasters will utilize verification data to assess their performance, calibrate their skill, explore opportunities for improvement, and ensure that their QPFs/PQPFs add value. Modelers in EMC will also rely on these verification statistics to assess the performance of the operational NCEP models and to test and quantify the impact of planned model upgrades and advanced data assimilation techniques on QPF skill.

Uniform QPF and PoP verification must be performed at *every* step of the ETE Forecast Process, and verification techniques must, account for end-user applications and assess the quality of probabilistic forecasts where applicable. Since QPF is issued primarily in support of RFC operations, QPF verification will be performed in parallel with river forecast verification.

11.2. Current NWS Verification Procedures

The NCEP, the TDL, the NWS Regions, and OM currently perform verification of forecaster value-added, statistical, and direct NWP model QPFs and PoPs.

11.2.1. National Centers for Environmental Prediction QPF Verification

- *Hydrometeorological Prediction Center* (Olson et al., 1995)

  All HPC 24-hour (Day 1 and Day 2) QPFs and their parallel numerical model QPFs are verified against a daily 1200-1200 UTC rainfall analysis based on approximately 10,000 rain gages across the contiguous 48 states. The network is dense east of 105°W and sparse to the west. Objective analysis (Cressman, 1959) with a grid spacing one-sixth the LFM (31.7 km at 60°N and 27.7 km at 40°N) is then performed on this data set for the area east of 105°W whereby all nonzero gage observations within the circular influence area of each grid point are weighted inversely with distance according to a quadratic function. West of 105°W, the terrain is complex and the rain gage network is sparse, so a manual analysis is performed. A meteorologist then quality controls the gage data by assessing the synoptic situation and making inferences from satellite and radar information. Where the data or analysis is suspect, manual adjustments are made. When the final analysis is complete, threat score and forecast bias (Junker et al., 1989) are computed for all HPC forecasters and applicable EMC models at the following precipitation thresholds: 0.50 inch, 1.00 inch, 2.00 inches, 3.00 inches and 4.00 inches. A threshold is defined as a category in which the amount of precipitation equals or exceeds one of the aforementioned specified amounts. Mathematical definitions for Bias (B) and Threat Score (T) are provided in section 11.2.5.

- *Environmental Modeling Center*

The EMC performs a separate verification of QPF from the NGM, Aviation (AVN)/Medium Range Forecasting (MRF), and Eta models. Verification procedures at the EMC are similar to HPC; however, some differences exist. Instead of the 1/6 LFM (approximately 30 km) grid used at HPC, precipitation is verified according to the native grid of the model which in most cases is on the order of 80 km[1] (Mesinger, 1996). To keep the 48 km Early Eta verification scores consistent with the other models, the data are remapped to the original 80 km NGM grid. Forecast Bias and the Equitable Threat Score (defined in section 11.2.5) for categorical precipitation amount forecasts are then computed.

11.2.2. Office of Systems Development QPF Verification

- *Techniques Development Laboratory*

TDL routinely tests all new versions of centrally-produced MOS QPF guidance prior to implementation. These tests are performed by withholding data from the development to serve as an independent sample. The performance of the operational guidance is also monitored on a periodic basis. TDL MOS guidance is verified at the point locations for which forecasts are valid; statistics are calculated on a regional basis as well as over the entire U.S. As in Antolik (1995), the MOS categorical QPF is evaluated in terms of the Critical Success Index (CSI) and bias scores for each cumulative precipitation category comprising the system. Verification statistics are customarily computed for all forecast

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[1] *The NGM is a sigma vertical coordinate gridpoint model with approximately an 80 km horizontal grid over the contiguous 48 states. For verification purposes, the 48 km Eta grid is remapped to the original 80 km NGM grid for consistency with other models. The AVN/MRF model is a global spectral sigma system model with triangular 126 truncation (T126).*

projections. Complete contingency tables and associated Heidke Skill Scores (HSS) (defined in section 11.2.5) for the categorical system are also evaluated.

Evaluation of MOS probabilistic forecasts is somewhat more complex. In addition to measuring skill, the bias and reliability of probabilistic guidance also are considered. By virtue of the least-squares nature of the regression technique, MOS probability forecasts are usually unbiased. By unbiased, we mean that the observed relative frequency of the forecast event is, over a long period of record, equal to the average forecast probability. While a probabilistic forecast system can be unbiased in an overall sense, it is possible for probabilistic forecasts to contain biases over a given sub-interval of forecast values. When statistical forecasts remain strictly unbiased in *piecewise* fashion over the entire range of forecast probabilities, the forecasts are also said to be *reliable*. Antolik (1996) has observed good reliability with the current NGM MOS QPF system.

For evaluating the skill of a set of ordered probabilistic forecasts such as those which underlie the NGM MOS QPF, TDL historically has employed the Ranked Probability Score (RPS; Epstein, 1969) (see section 11.2.5 for a discussion of the RPS).

11.2.3. Regional QPF Verification

Generally, QPFs are routinely produced at and issued by the NWSFOs/NWSOs[2] (future WFOs) once or twice a day. After receiving these forecasts, the HAS forecasters at the RFCs prepare a mosaic QPF for direct input of basin-averaged QPF to the river forecast models.

QPFs at the NWSFOs (and in some cases NWSOs) are generally made for 6-hour intervals out to 24 hours, although WR weather forecast offices supporting the Sacramento and Portland RFCs routinely issue QPFs with a range to 72 hours. Further, NWS forecast offices which typically generate 24-hour QPFs often provide longer range QPFs during potential flooding events, as requested by the servicing RFC. Verification systems vary with region; however, they have some similarities. Generally, forecasts of mean areal (basin-averaged) precipitation (MAP) are verified against observed MAP, and verification statistics are calculated according to (1) NWSFO or NWSO Hydrologic Service Area (HSA) and (2) mean areal precipitation (MAP) area or river forecast group[3].

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2 *A small number of NWSOs have not yet assumed responsibility for the preparation of official QPFs for input to NWSRFS.*

3 *Generally, a major river basin serviced by a single RFC, such as the Ohio River Basin, is broken into 400-500 MAP areas. Each MAP area represents the smallest geographic unit over which data are averaged and input to the river forecast models. A river forecast group is a concatenation of MAP areas, e.g. 20-30 predefined MAP areas often define one river forecast group (Tress and Manousos, 1996). Since rain gages tend to be non-uniformly distributed, observed MAP is calculated using an appropriate weighted averaging scheme, such as the Thiessen method (Linsley et al., 1975).*

- *Deterministic*

  - *QPFVFCN*

QPFVFCN is a Central Region (CR)-developed, PC-based computer program which is used by the Central and Southern Regions. Contingency tables of observed vs. forecast precipitation are prepared with the following categories: 0.01-0.09, 0.10-0.24, 0.25-0.49, 0.50-0.99, 1.00-1.99, and 2.00 inches or greater. NWSFO/NWSO forecasts as well as RFC (HAS forecaster) mosaic forecasts are all verified. Statistics are calculated for river forecast groups and NWSFO/NWSO HSA areas. For each contingency table, a Heidke Skill Score (HSS) is calculated. Also, for each categorical breakdown of observed precipitation, the following are calculated:

- number of correct forecasts (within the correct category),
- percent correct,
- mean absolute error,
- root mean square error,
- bias,
- probability of detection,
- false alarm rate,
- threat score,
- number of positive and negative errors, and
- number of positive and negative "significant" errors (i.e., 0.5 inch or greater).

QPFs in excess of 0.50 inch often cause a marked change in the river forecast, given normally saturated ground conditions (Schwein, 1996).

  - *QPSVER*

QPSVER is an Eastern Region (ER)-developed, PC-based program that compares observed and forecast precipitation amounts for NWSFO-defined river forecast groups (groupings of MAP areas) and prepares a verification table that contains the following information for each of these basins:

- 24-hour forecast amount,
- actual amount, and
- error amount.

Additionally, for each basin and the total NWSFO HSA, a contingency table of forecast vs. observed precipitation is prepared, and a Heidke Skill Score (HSS) is calculated. A total of nine user-defined precipitation amount categories are used.

- *Ohio River Forecast Center (OHRFC) Verification Software*

The Ohio River Forecast Center (OHRFC)-developed verification software verifies 24-hour QPFs according to river forecast groups and NWSFO/NWSO hydrological service areas (HSA)[4]. Bayesian Informativeness Scores (BIS) of deterministic QPFs are computed for each basin and each HSA area. The BIS takes into account climatic variability between geographic areas, making the comparison of scores between different areas possible. A sample size of several years is necessary to determine a statistically normal climatic distribution. At present and until this climatic distribution becomes available, the standard deviation of the precipitation climatology is set to unity (S=1 in the BIS, see section 11.2.5) so it will have no influence on the score. Also, the Probability of Detection (POD), False Alarm Rate (FAR), and Critical Success Index (CSI) are computed for the 0.01 inch threshold for each river forecast group and HSA. Definitions of the BIS, POD, FAR, and CSI are provided in the section 11.2.5.

- *Mountain Mapper*

Mountain Mapper (Henkel and Peterson, 1996) is a Western Region (WR)-developed set of programs used for specifying, processing, and displaying forecast and observed precipitation in mountainous locations. It is also usable in flat terrain. The ensemble of programs consists of :

- *specify_qpf*, which is used for the specification of QPF,
- *qc_daily*, which is used in the quality control of observed precipitation, and
- *verify*, which is used to display QPF fields, observed precipitation fields, and difference maps between the two.

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4 *For verification, the Ohio River forecast system is divided into 29 river forecast groups, each of which is a concatenation of smaller MAP areas. The MAP areas in the Ohio River Basin range in size from 20 to over 900 square miles (Figure 1, Tress and Manousos, 1996)*

The data can be displayed and modified at both the WFO and RFC within the three domains of operation: points (real or pseudo rain gages), HRAP grid, and MAP areas. The conversion from points to HRAP grid is made through the use of inverse distance weighing and is scaled to elevation through the use of PRISM high resolution, monthly climatological analyses (making the assumption that precipitation climatology can be used to specify topographic variations in a single precipitation event) (see section 4.2). The ability also exists to toggle back and forth between these three domains (points to HRAP grid to MAP areas), an important advantage in areas with complex terrain and isolated data points. When entering or modifying precipitation data, the user can simultaneously display background maps of topography and seasonal isohyets as a guide in specifying orographically-induced QPF. Drawing techniques exist that allow the user to specify (1) a limited number of free-floating pseudopoints, or (2) pseudopoints which define an axis (or back-bone) of maximum precipitation. Using PRISM climatological analyses, these pseudopoints are remapped as grids and MAPs for input to NWSRFS and verification.

- *Probabilistic*

Since 1990, Eastern Region has been testing a probabilistic QPF (PQPF) system at NWSFO Pittsburgh, Pennsylvania, for two river forecast groups: the Upper Allegheny (AGU01) and Lower Monongahela (MNL01). To date, the following verification statistics are computed for each of these river forecast groups: (1) a Bayesian Informativeness Score (BIS) for informativeness, and (2) a Calibration Score to help the forecasters calibrate their PQPFs for bias. A description of these verification statistics is presented in section 11.2.5.

11.2.4. Office of Meteorology and Office of Systems Development PoP Verification

- *OM Service Division and OSD Techniques Development Lab*

While areal averaged Probability of Precipitation (PoP) (i.e., precipitation greater than or equal to 0.01 inch) are required for PQPF, the NWS currently only issues point-specific PoPs. TDL derives point-specific MOS equations to support these forecasts from the NGM, AVN, and MRF models, and these equations are run operationally as forecast guidance twice daily (0000 and 1200 UTC cycles which respectively support the early morning and afternoon local forecast packages issued by the NWSFOs). OM and TDL verify the NGM and AVN guidance as well as the local PoP forecasts out to three 12-hour forecast periods (i.e., today, tonight and tomorrow for the early morning package; tonight, tomorrow, and tomorrow night for the afternoon package). Each NWSFO issues point-specific 12-hour PoPs out to three 12-hour forecast periods for arbitrary points in each forecast zone (zones usually correspond to counties or geographically similar portions of counties). Similar PoPs for specific cities (stations for which MOS PoPs are available) are included in the Coded City Forecasts (CCF). The verification software automatically takes the PoPs from the CCFs.

Because the PoPs in the zone forecasts are point-specific (i.e., for any specific point within that zone), the 12-hour PoP for a specific time interval for a given city in the CCF should agree with the corresponding zone forecast PoP at that same time interval. OM and TDL perform verification of the MOS PoPs and the local CCF PoPs at two cities per NWSFO for the three aforementioned 12-hour periods. At these points, the following statistics are computed for the local PoPs, the NGM MOS PoPs, and the AVN MOS PoPs:

- Mean PoP,
- Mean PoP when precipitation occurred,
- Mean PoP when no precipitation occurred,
- Brier Score (all cases),
- Brier Score when PoP ≥ 30 percent,
- Brier Score when precipitation occurred,.

Also calculated at each point are:

- Local Brier Score improvement over NGM guidance,
- Local Brier Score improvement over NGM guidance when PoP ≥ 30 percent,
- Climatological Brier Score,
- Local Brier Score improvement over climatology.

11.2.5. Measures of QPF Skill

- *Bias, Threat Score, Probability of Detection, and False Alarm Ratio*

Bias (B) and Threat Score (T) (Gilbert, 1884; Junker et al., 1989; Schaefer, 1990) (also known as the Critical Success Index (CSI)) are defined as follows:

$$B = \frac{F}{O}$$

$$T = CSI = \frac{H}{F + O - H}$$

where F is the number of points forecast to have at least a certain amount (threshold) of precipitation, O is the number of points observed to have at least that amount, and H is the number of points with correct forecasts for that threshold of precipitation. When the bias is less (greater) than unity for a given threshold, the forecast is underforecasting (overforecasting) the areal coverage for that amount. Geometrically, the Threat Score for a given threshold amount represents the ratio of the correctly predicted area to the threat area, defined as the envelope of forecast and observed areas for that threshold. A perfect forecast yields a Threat Score of 1, and a forecast with no areas correctly predicted receives a zero. The Threat Score, therefore, provides a measure of how accurately the location of precipitation is forecast within the valid period of the forecast. To receive a high Threat Score, forecast precipitation amount must be accurately specified -- both spatially *and* temporally. For example, if a 1.00-inch isohyet is forecast, and all the observed rainfall within that area ranges from 0.8- to 0.99-inch, the forecaster's 1.00-inch Threat Score would be zero. However, the 0.8 to 0.99 inch area would favorably affect the 0.5-inch Threat Score. Also, a forecast area that is adjacent to an observed area with no overlap produces a zero Threat Score, and forecasts that are incorrect by just a couple of hours may receive little or no credit. Closely related to the Threat Score are the Probability of Detection (POD) and the False Alarm Rate (FAR) which are expressed as:

$$POD = \frac{H}{O}$$

$$FAR = \frac{F - H}{F}$$

- *Equitable Threat Score*

Equitable Threat Score (Gilbert, 1884; Schaefer, 1990; Gandin and Murphy, 1992; Mesinger, 1996) is similar to the standard Threat Score (used at HPC and defined in the previous paragraph) except the expected number of hits in a random forecast, E, is subtracted from the numerator and denominator:

$$T_e = \frac{H-E}{F+O-H-E}$$

where $E = FO/N$ and N is the total number of points being verified. E is substantial for low precipitation categories (i.e., 0.10 inch or less in 24 hours), small at intermediate categories, and negligible for high categories (i.e., 1 inch or more in 24 hours).

- *Heidke Skill Score (HSS)*

Heidke Skill Score (HSS) (NWS, 1982) is the fraction of possible improvement over chance afforded by a set of forecasts from a contingency table consisting of m categories of forecasts (columns) and observations (rows). Row and column totals are denoted with the subscript q (see table 9 below).

Table 9: Sample contingency table.

Observed Category	**Forecast Category**				
	1	**2**	**. . .**	***m***	**Total**
1	x_{11}	x_{12}	. . .	x_{1m}	x_{1q}
2	x_{21}	x_{22}	. . .	x_{2m}	x_{2q}
⋮	⋮	⋮	⋮	⋮	⋮
m	x_{m1}	x_{m2}	. . .	x_{mm}	x_{mq}
Total	x_{q1}	x_{q2}	. . .	x_{qm}	x_{qq}

The HSS is defined as:

$$HSS = \frac{NC-E}{T-E}$$

where:

the number correct (NC) is:

$$NC = \sum_{i=1}^{m} X_{ii}$$

the total number of cases (T) is: $T = X_{qq}$

and the expected value (E) is: $E = \frac{\sum_{i=1}^{m} X_{iq} X_{qi}}{T}$

- *Nash-Sutcliffe Efficiency Score (ES)*

The Nash-Sutcliffe Efficiency Score (ES) (Nash and Sutcliffe, 1970) measures the error of a forecast relative to climatology and is expressed as:

$$ES = \frac{\sum (y_i - \bar{y})^2 - \sum (y_i - x_i)^2}{\sum (y_i - \bar{y})^2}$$

where y_i = an observed event, x_i = a forecast event, and *"y bar"*= climatology. Values of ES range from +1 to $-\infty$. Negative values of ES imply that the variance of the errors (y_i - x_i) is greater than the variance of y_i. In other words, the forecast is not as good as using an estimate based on climatology.

- *Bayesian Informativeness Score (BIS)*

The BIS (formerly, the Bayesian Correlation Score) (Krzysztofowicz, 1992) employs a Sufficiency Characteristic (SC) which is defined as the ratio of the conditional standard deviation of the forecast error (σ) to the absolute value of the slope coefficient of the regression line between the forecast and observed states (|a|):

$$SC = \frac{\sigma}{|a|}$$

The units of SC are the same as the units of the forecast. For the perfect forecast, SC=0. For the forecast produced by random guessing, SC is infinity. The BIS is defined by the expression:

$$BIS = \frac{1}{\sqrt{\frac{SC^2}{S} + 1}}$$

where S is the prior (climatic) standard deviation of the precipitation for which a sample size of several years is necessary to determine a statistically normal climatic distribution. This climatic adjustment to the BIS will account for the climatic variability between different areas, making for a proper comparison of scores between different areas.

In the past, the BIS has been calculated in conjunction with POD and FAR statistics for the occurrence of measurable precipitation (0.01 inch or greater). This is because two types of cases have been intentionally removed from the data set when calculating the BIS: (1) times when measurable precipitation was forecast, but none was observed (false alarms), and (2) times when no precipitation was forecast, but measurable precipitation was observed. A spatial data transformation is necessary to include these cases in the regression. Krzysztofowicz has developed and tested this transformation and will soon publish the results. With this spatial transformation, separate POD and FAR calculations will no longer be necessary since *all* cases will be considered in the BIS.

The BIS for *probabilistic* QPF is a multivariate version of the univariate score that is used for deterministic QPF (Roman Krzysztofowicz, personal communication, 1997). Instead of the univariate regression of forecast precipitation amount onto observed precipitation amount, a minimum of three thresholds or exceedance fractiles of QPF (e.g., the amounts of precipitation for which the forecaster believes there is a respective 25, 50, and 75 percent chance of occurrence) are regressed onto observed precipitation amounts. Note that the 50 percent exceedance fractile, x_{50}, also called the median, is an estimate of what is equally likely to be exceeded or not exceeded.

- *Calibration Score for PQPF*

The Calibration Score (CS) (Krzysztofowicz and Sigrest, 1999a) measures the bias of a set of forecasts. Well calibrated forecasts have a low bias and vice versa. The Calibration Score for a given location is a measure of the forecast calibration at three exceedance fractiles (x_{25}, x_{50}, x_{75}) and is computed by taking the root-mean-square difference between the empirical frequency, r_{100p}, (where p = 0.25, 0.50, 0.75 for x_{25}, x_{50}, x_{75}) and the forecast probability p = 0.25, 0.50, 0.75. The exceedance fractiles specified by a PQPF from a given set of forecasts are said to be well calibrated if $r_{100p} \approx p$ for p = 0.25, 0.50, 0.75.

$$CS=\sqrt{\frac{(r_{75}-0.75)^2+(r_{50}-0.50)^2+(r_{25}-0.25)^2}{3}}$$

The score is bounded, $0 \leq CS \leq 0.54$, with CS = 0 being the best. The upper bound arises when $r_{75} = r_{50} = r_{25} = 1$, or $r_{75} = r_{50} = r_{25} = 0$.

- *Ranked Probability Score*

The RPS is a multi-category generalization of the Probability Score (Brier, 1950) which takes into account the relative shapes of the forecast and observed (discrete) probability distributions. Thus, the RPS is sensitive to the "distances" between elements of the vector of probability forecasts and the particular category which is ultimately observed. In other words, a "near-miss" will receive more credit than a forecast which is blatantly incorrect. In its most common formulation (Murphy, 1971), the RPS is a negatively-oriented scoring measure; that is, the score decreases toward zero as the forecasts approach perfection. The RPS is most useful when scores of a given probabilistic forecast system are compared against those attained by some benchmark procedure. TDL most frequently uses the predictand climatology defined by the dependent data as the benchmark system for the RPS. In Antolik (1996), for example, forecasts prepared from a simple set of regression equations based only on geoclimatic variables were used as the benchmark system against which NGM MOS QPF probabilities were compared. The skill of the MOS QPF system was expressed in terms of the percentage improvement in RPS attained over that of the "pseudoclimatic" regression equations.

$$RPS = \left(\frac{1}{N}\right) \sum_{i=1}^{N} \left[\sum_{j=1}^{K} \left(\sum_{l=1}^{j} F_{il} - \sum_{l=1}^{j} O_{il} \right)^2 \right]$$

where:

N = the total number of paired forecasts and observations in the verification sample,

K = the number of possible mutually exclusive (exhaustive) probability categories,

F_{il} = probability of the l^{th} category for the i^{th} forecast,

$O_{il} = 0$, if the observation of the event does not fall into category l, and

$O_{il} = 1$, if the observation is of category l.

11.2.6. Measures of PoP Skill

- *Brier Score*

The Brier Score (BS) measures the mean square error between forecast and observation where f_i is the ith forecast PoP (0% ≤ PoP ≤ 100%), o_i is the *ith* corresponding observation (zero for no measurable precipitation, 100 percent for measurable precipitation), and N is the sample size:

$$BS = \frac{1}{N}\sum_{i=1}^{N}(f_i - o_i)^2$$

- *Climatological Brier Score*

The Climatological Brier Score (BS_c) is similar to the Brier Score except f_i refers to a mean relative frequency of the event (precipitation ≥ 0.01 inch) for a given location and month.

- *Reliability*

The Reliability is the relative frequency of the event stratified by forecast intervals compared with the average forecast for those same strata. The overall reliability is then a comparison of

$$\frac{1}{N}\sum_{i=1}^{N} f_i \quad with \quad \frac{1}{N}\sum_{i=1}^{N} o_i$$

If the former is larger (smaller) than the latter, the event was over forecast (under forecast).

11.3. Proposed Framework for a National End-to-End Verification System

All EMC-, TDL-, HPC-, WFO-, and RFC-issued QPFs/PQPFs and PoPs will be verified against:

(1) gridded 24-hour (1200-1200 UTC) gage-only analysis, and

(2) gridded multi-sensor (i.e., rain gage, radar, and satellite) temporally-aggregated, quality-controlled Stage III precipitation analyses or their equivalent.

As input to the multi-sensor analysis, RFCs will routinely provide 6- , 12-, and 24-hour HRAP-gridded (4 km) Stage III analyses or their equivalents to the WFOs and NCEP twice per day. NCEP will mosaic these Stage III analyses or their equivalents to generate the national Stage IV product which NCEP will make available to the NVU. Further, each RFC will provide the NVU with HRAP-gridded:

(1) mosaicked, unedited QPFs/PQPFs and PoPs received from WFOs within the RFC area of responsibility; and

(2) mosaicked QPFs/PQPFs and PoPs prepared by the HAS forecaster at each RFC.

The archiving at the NVU of all observed and forecast precipitation data sets is essential for the implementation of a national ETE verification system. HPC and TDL will have access to the NVU data archive, while RFCs and WFOs will archive these data sets to compute verification statistics for their respective forecast domains. Additionally, the archiving and access to these data, particularly the observed and NWP model forecast data sets, is necessary for statistical model and product development.

Centralized verification statistics will be computed at the NVU for forecast products produced by each component of the ETE Forecast Process (i.e., NCEP/EMC models, EMC/TDL statistical guidance, HPC guidance, and WFO and RFC/HAS value-added forecasts). Verification statistics will be computed for all combinations of the following (see also table 10):

(1) forecast projections[5]: 0-6, 6-12, 12-18, 18-24, 24-36, 36-48, 0-24, 12-36, 24-48, 36-60, 48-72 hours[6],

(2) spatial domains: entire nation, each NWS Region, each RFC area, each WFO area, each river forecast group, and each MAP area,

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[5] *For the gridded 24-hour (1200-1200 UTC only) gage-only analysis, verification statistics will be limited to the following forecast projections: 0-24, 24-48, and 48-72 hours*

[6] *PoPs will only be issued and verified for 24-hour long periods (i.e., 0-24, 24-48, and 48-72 hours).*

(3) temporal domains: day, week, month, season, year, and multi-year composites of each month, season and year[7], and any user-specified interval(s).

Localized verification statistics will be computed at each RFC and WFO for all of the above forecast projections and temporal domains. At each RFC, statistics will be computed for the following spatial domains: the RFC area, each WFO area (within the respective RFC area), each river forecast group (RFG), and each MAP area. At each WFO, statistics will be computed for the following spatial domains: the WFO area, each RFG, (within the respective WFO area), and each MAP area. For comparison, the above will also be computed for each step of the ETE forecast process, as appropriate.

Efforts within the OM to develop the software code necessary to compute these statistics in support of routine verification at the NVU, HPC, RFCs, and WFOs are underway.

11.3.1. Verification/Skill Scores, Measures of Performance

Verification scores that will measure the skill of QPFs and the value-added at each step in the forecast process include the:

- Threat Score (T) and Equitable Threat Score (T_e) for the following thresholds: 0.5 inches, 1.00 inches, 2.00 inches, 3.00 inches, 4.00 inches, etc.,
- Bayesian Informativeness Score (BIS),
- Mean Error (ME),
- Bias (B),
- Mean Absolute Error (MAE),
- Root Mean Square Error (RMSE), and
- Correlation Coefficient (between observed and forecast precipitation),
- Nash-Sutcliffe Efficiency Score (Nash and Sutcliffe, 1970),
- Large Error Tally (e.g., absolute errors $\geq$ 0.5 inches) (Schwein, 1996), and
- possibly others.

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[7] *Seasons are defined as follows: winter: Dec-Feb, spring: Mar-May, summer: Jun-Aug, autumn: Sep-Nov. For consistency with these meteorological seasons, a year is defined as Dec-Nov.*

Verification scores that will measure the skill of PQPFs and the value-added at each step in the forecast process include the:

- Bayesian Informativeness Score (BIS),
- Heidke Skill Score (HSS),
- Calibration Score (CS),
- Ranked Probability Score (RPS), and
- possibly others.

Verification scores that will measure the skill of PoPs and the value-added at each step in the forecast process, include the:

- Brier Score (BS),
- Reliability by 10 percent intervals,
- possibly others.

Brier scores and PoP reliability calculations will only be calculated for the 24-hour periods listed in table 10 (0-24 hour, 24-48 hour, 48-72 hour).

11.3.2. Grid Size and Verification Data Computation/Display

All models, guidance, and forecasts will be verified against the:

(1) gridded 24-hour (1200-1200 UTC) gage-only analysis, and

(2) Stage III multi-sensor observed precipitation product (or its equivalent in areas of complex terrain such as the mountainous Western CONUS including Alaska).

For areas whose spatial domain is at least as large as a WFO area, each model and guidance product will be verified on its native grid, *n*. Verification statistics computed for areas smaller than the WFO (e.g., river forecast groups and MAP areas) will use the area- averaged observed and forecast precipitation information for those domains. Additionally, model forecasts will be interpolated to and verified on coarser grids which represent multiples of the native model grids (i.e., *2n*, *3n*, *4n* etc.). For example, the 32 km Eta would be verified at 32, 64, 96, 128 km, etc. For comparative purposes, verification statistics for each model will be plotted as a function of the log of the spatial resolution. In this context, spatial resolution is defined as the aggregate grid area or, in a less uniform sense, the area of a hydrologic basin which may be a river forecast group or MAP area (see figure 20). From these plots, verification statistics from models of varying spatial resolution, as well as forecaster prepared QPFs, can be compared to one another at a constant user-specified spatial resolution. Separate plots will be made for each verification statistic at each forecast period (see table 10) for the following spatial domains or appropriate combinations thereof:

- each WFO area,
- each RFC area,
- each NWS Region, and
- the entire Nation,

and the temporal domains listed in section 11.3.[8] For example, a verification statistic computed from the 32-km Eta QPF would be computed on its native grid (32 km) and multiples thereof (64, 96, 128, km, etc.) with the score plotted vs. the log of the spatial resolution (see figure 20). Similarly, the same score for each of the other models would be calculated on their respective native grids and multiples thereof and plotted vs. the log of the spatial resolution. TDL- and EMC-prepared statistical (i.e., MOS[9], ensemble) guidance, HPC guidance, WFO forecasts, and RFC/HAS mosaicked forecasts will be verified on an appropriate, still to be determined grid and aggregates thereof.[10] These data will also be included in the aforementioned plots to demonstrate the value added at each stage of the ETE Forecast Process.

WFO and RFC forecasts will also be evaluated at the resolutions of MAP area, river forecast group, and WFO area. Each score, will also be computed for each MAP area and plotted on the aforementioned graphs as a function of the size of the MAP area. Collectively, a plot of all MAP area scores within the user-defined spatial domain would appear on the graph as a scatter plot (i.e., cloud of points) due to the variation in size of MAP areas (i.e., open circles in figure 20, red for

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[8] *Upon calling up a plot, the user must specify each of the following (from menus): verification statistic (e.g., Equitable Threat Score), forecast period (e.g., 0-6 hour), and spacial domain (e.g., WFO Sterling, Mid-Atlantic RFC, entire nation), and temporal domain (e.g., July 1997, all Julys 1995-1997, summer 1997, all of 1997). "Seasons" and "years" are defined in Section 11.3.*

[9] *MOS QPF guidance is currently issued for predetermined forecast points; however, Stage III gridded precipitation analyses will eventually enable TDL to develop gridded, areal-averaged MOS QPF guidance.*

[10] *For recent verification at HPC, a grid of approximately a 30 km (1/6 the LFM) has been used. Whatever grid is selected for this purpose, it must be applied consistently as the basic unit of measurement when computing statistics for the following spatial domains: national, each RFC area, and each WFO area. When computing statistics at the smaller spatial domains (river forecast group and MAP area), the basic unit of measurement must be the river forecast group or MAP area.*

RFCs, blue for WFOs). Similarly, each score will also be computed for each river forecast group within the WFO area and "scatter plotted" as a function of size of the river forecast group (i.e., solid triangles in figure 20, red for RFCs, blue for WFOs).

While figure 20 portrays verification statistics as a function of spatial resolution , many users may also desire to view scores as a function of forecast projection time at a constant user-specified spatial resolution. By specifying a constant grid area (resolution) in addition to all the other aforementioned parameters, the user should receive a plot of verification statistic vs. projection time, i.e., 6, 12, 18, 24, 36, 48, and 72 hours, at a constant grid area resolution (e.g., 1000 square kilometers) (see figure 21).

11.3.3. Climatological Data

All quality controlled rain gage observations and Stage III multi-sensor precipitation data (or their equivalent) must be archived for the development of Local climatological guidance (LCG) and use in verification calculations. Local climatological guidance (LCG) plays an important role in forecasting and verification. For the forecaster, LCG provides the climatological likelihood of exceeding a given threshold amount of precipitation. In verification, climatology provides a benchmark for comparing forecasts from different locations with different climatologies. Hence, skill scores that measure the utilitarian usefulness of forecasts, such as the Bayesian Informativeness Score (BIS), are standardized with the standard deviation of the precipitation distribution.

Six-, 12-, and 24-hour LCG will be computed for (1) each month, (2) each grid point[11], (3) each MAP area, and (4) each RFG. Archived hourly precipitation observations from the NWS national Cooperative Network (Kuligowski, 1997) will be used to compute precipitation climatologies. The observations from approximately 2700 automated weighing rain gages will be used to compute the 6-hour precipitation climatology. In addition to these automated gauges, approximately 8,000 cooperative observers provide manual rainfall observations using standard non-recording gauges. However, the manual observations are only taken in 24-hour intervals; therefore, they can only be used to compute the 24-hour precipitation climatology. Since QPF and PQPF are issued and verified for mean areal precipitation, and rain gages are nonuniformly distributed in space, the data for each MAP area and RFG should be spatially averaged with an appropriate weighing scheme. This is a three step process:

(1) Interpolate rain gage climatology to the grid. In mountainous terrain where the data are sparse and rainfall amounts are strongly dependent upon elevation, precipitation climatology

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[11] *This verification grid has not yet been defined, but 32 km is being considered since it is a multiple of the 4 km HRAP grid and similar to the operational verification grid at HPC (one-sixth the LFM or 27.7 km at 40 °N and 31.5 km at 60 °N).*

should be specified with a system that is sensitive to topography, e.g., the PRISM data set which is utilized by Mountain Mapper.

(2) Estimate the spatially averaged precipitation amounts for each MAP area and RFG.

(3) Fit a Weibull distribution to the 6-, 12-, and 24-hour data for each MAP area, each RFG, and each grid point. From the Weibull distribution determine the standard deviation for the BIS.

11.3.4. Local Verification Statistics

Software will be provided to each WFO, RFC, and the HPC so all of the aforementioned statistics may be calculated for each individual forecaster and displayed for the appropriate spatial domains. The full suite of skill scores will be computed after the receipt of the ground validation analyses. Additionally, to assist forecasters in predicting flash flood potential and to provide immediate real-time feedback on short-term forecast performance, simple errors (i.e., forecast minus observed rainfall) will be computed. These data will be displayable (via grids, MAPs, or points) in a user-friendly manner, such as error depiction on detailed background maps utilizing an approach similar to the *verify* component of Mountain Mapper (Henkel and Peterson, 1996).

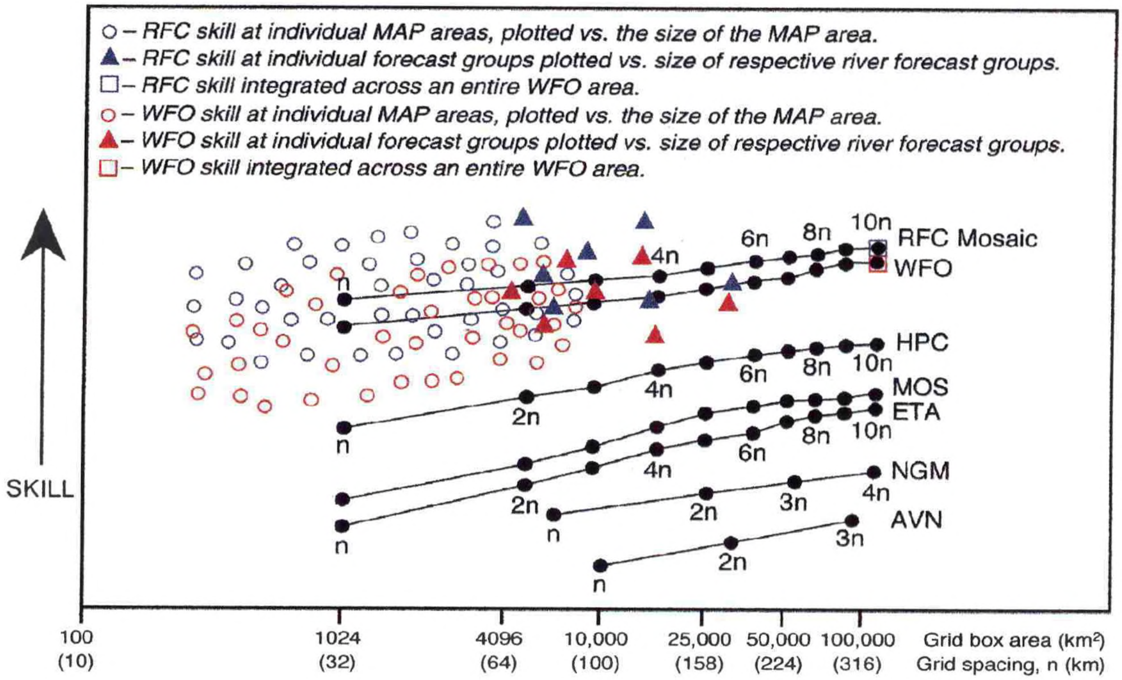

Figure 20: Hypothetical plot of skill vs. spatial resolution where spatial resolution is defined as the grid area/aggregate grid area (n^2) of a model. The grid spacing, n, is also given in parentheses. For the MOS, HPC, WFO, and RFC forecasts, n has not yet been determined but is assumed to be 32 km.

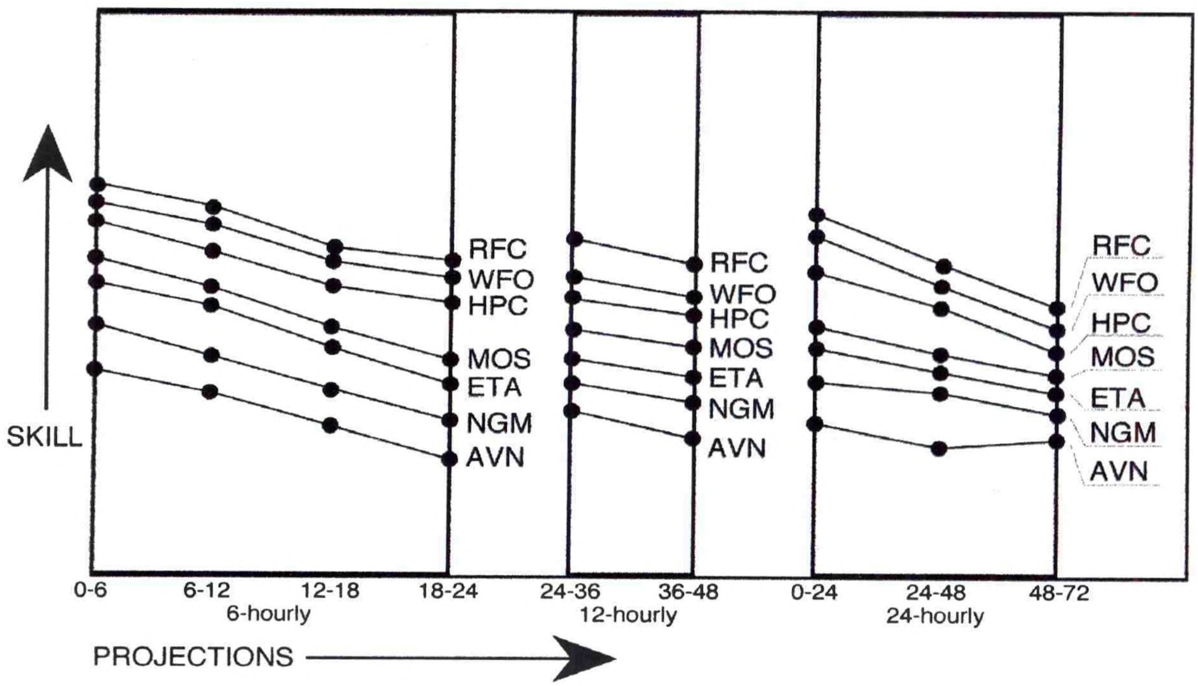

Figure 21: Hypothetical plot of skill vs. Forecast period at a constant user-specified spatial resolution.

Table 10: Forecast periods (temporal resolution) and spatial domains for which verification statistics will be computed at the NVU for each component of the ETE Forecast Process for QPF/PQPF.

Temporal Resolution / Forecast Periods[1,2,3]			***Geographic Boundaries / Spatial Domains***					
			National	***Each NWS Region***	***Each RFC Area***	***Each WFO Area***	***Each River Forecast Group*** [4]	***Each MAP Area*** [4]
DAY 1	**12-12 UTC Forecast Cycle**	**12-18 UTC**						
		18-00 UTC						
		00-06 UTC						
		06-12 UTC						
		12-12 UTC						
	00-00 UTC Forecast Cycle	**00-06 UTC**						
		06-12 UTC						
		12-18 UTC						
		18-00 UTC						
		00-00 UTC						
DAY 2	**12-12 UTC Forecast Cycle**	**12-00 UTC**						
		00-12 UTC						
		12-12 UTC						
	00-00 UTC Forecast Cycle	**00-12 UTC**						
		12-00 UTC						
		00-00 UTC						
DAY 3	**12-12 UTC Forecast Cycle**	**12-12 UTC**						
	00-00 UTC Forecast Cycle	**00-00 UTC**						

[1] PoPs will only be issued and verified for 24 hour long periods (i.e., 00-00 UTC and 12-12 UTC).

[2] Temporal domains are defined in the text (section 11.3).

[3] When verifying from the 24-hr gage-only data, the only forecast periods verified will be 12-12 UTC.

[4] Verification statistics computed for these spatial domains will use the area-averaged observed and forecast precipitation information.

12.0. Summary

The primary mission of NOAA's NWS Hydrologic Services Program is to provide advanced, short-range river and flood forecasts and warnings for the protection of life and property, and basic hydrologic forecast information for the Nation's economic and environmental well-being, including short- through long-range forecast information for water resource management. In support of these missions, and to improve hydrometeorological services, this QPI concept document applies the modernized ETE Forecast Process which includes collecting and assimilating observations, running NWP and statistical models, preparing forecasts and warnings, and coordinating these products with a diverse user community.

The HIWG applied a requirements concept to the QPI problem by inverting the ETE Forecast Process and systematically working in reverse order from the needs of the diverse user community to articulate specific requirements on various forecast components within the NWS, and to address the scientific and technical issues which form a basis for the anticipated advances. The collective input of the HIWG served as the basis for this QPI document. This document complements other NWS documents, such as the "Hydrometeorological Service Operations for the 1990's" and the "Office of Meteorology 1996-2005 Strategic Operating Plan," which have identified these improvements as one of the highest priorities for the NWS over the next 10 years.

This QPI concept document specifies an operational framework which efficiently and effectively couples advanced meteorological and hydrological prediction. Through the full implementation of this plan, the NWS will improve the accuracy, reliability, resolution, information content, temporal span and timeliness of hydrometeorological forecasts and warnings provided to the nation. In response to requirements from users and in light of the service-science linkage which forms the basis of the modernized NWS, national, regional, and local NWS field offices plan to advance and expand current NWS services to include the routine generation and use quantitative precipitation and river forecast products which quantify forecast uncertainty and convey risk. The transition to stochastic forecasting is planned to occur over the next 5-10 years. The many requirements which must be satisfied along with the scientific and technological issues which must be resolved, to improve hydrometeorological services and enable the NWS to implement probabilistic forecasting nationally, have been specified. The effective resolution of these technical and scientific issues requires a sustained and aggressive applied research effort conducted under the auspices of the USWRP and the CSTAR Program. Performing this applied research, conducting associated risk reductions and training, and implementing new modeling systems requires funding via the normal budget initiative process associated with the ASTWF Team.

For over a decade, users, such as Emergency Managers and state and local officials have recognized and articulated an increasing need for NWS hydrometeorological guidance products which quantify forecast uncertainty and convey risk. Probabilistic forecast and warning guidance will enable local officials to weigh forecast probability and lead time vs. potential flood severity to utilize resources most effectively to preserve life and property. Further, short- through long-range probabilistic streamflow guidance, which accounts for the uncertainty in future atmospheric and land surface events, will enable water resource managers to make more informed decisions regarding the utilization of water and the operation of water systems. The provision of this short- through long-range guidance is particularly important given that the demand for water for domestic hydropower, industrial, and agricultural applications is beginning to exceed its available supply in some regions of the country.

As detailed in this plan, 1) the technological benefits of the NWS MAR program combined with the operational implementation of applied research planned to be conducted under the auspices of the USWRP and the CSTAR Program, and 2) funding via the normal budget initiative process associated with the Advance Short Term Warning and Forecast Process, are necessary and should enable the NWS to modernize the ETE Forecast Process for QPI and achieve the following projected forecast goals:

5-Year QPI Goals

- Increase the skill of the Day 1 operational NWP model QPFs by 50 percent.
- Increase the skill of the Day 2 and Day 3 operational NWP model QPFs by one day (i.e., increase skill of Day 2 QPF to current Day 1, and increase skill of Day 3 to current Day 2).
- Add value to the operational NWP model QPFs at each subsequent step of the NWS ETE Forecast Process (e.g., HPC, WFOs, RFCs).
- Introduce forecaster-prepared, value-added probabilistic QPFs (PQPFs) through Day 3 for use in AHPS[1].
- Improve the nationally-averaged lead time of flash flood warnings by more than 30 percent (from 45 minutes[2] to 60 minutes).

Meeting these QPI goals will impact each component of the forecast process and place new requirements on their associated partners (i.e., RFCs, WFOs, HPC, Statistical Guidance, NWP models, observations). Associated service goals, also based upon USWRP and CSTAR Program applied research and ASTWF funding, and achievable via the implementation of a Modernized ETE Forecast Process which includes AHPS, are projected to be as follows:

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[1] *The introduction of PQPFs will be focused on, but not limited to, HPC and WFOs which support RFCs utilizing AHPS.*

[2] *Nationally-averaged lead time for flash flood warnings issued in 1997 (Paul Polger, personal communication, 1998)*

10-Year HydrometeorologicalService Goals

- Introduce AHPS short- through long-range site-specific, probabilistic river stage forecasts (PRSFs) at RFCs utilizing value-added PQPFs[3].

- Prepare, issue, and verify PQPFs and hydrologic forecast and warning products at WFOs nationwide.

- Extend the range of forecaster-prepared, value-added QPFs/PQPFs produced by the HPC and WFOs and assimilated by the RFC through Day 3[4].

- Provide improved and expanded centrally-produced Model Output Statistics (MOS) QPF/PQPF guidance products based on operational NWP models, including global and regional ensembles.

- Implement statistically-based models, expert systems, and other techniques on AWIPS to provide high resolution, short-range, statistical QPF/PQPF guidance products. These guidance products, coupled with advanced decision assistance and product preparation tools such as WHFS and SCAN, will enable WFOs to more accurately and efficiently assess and predict the areal potential for flash flooding.

- Implement improved data assimilation techniques, improved and higher resolution regional mesoscale NWP models, regional and stormscale NWP models, and a regional ensemble prediction system at the Environmental Modeling Center (EMC) of NCEP.

- Expand the real-time use and integration of QPEs, based on various sources of in situ and remotely sensed data, utilizing continuing advances on verifying, optimally merging, and quality controlling gage, radar, and satellite estimates.

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[3] *National implementation of AHPS is contingent upon the approval and continuance of funding. The transition to probabilistic river forecasting is contingent upon 1) the implementation of AHPS, 2) the development, successful testing, documentation, and implementation of methodologies which produce short-range PRSFs and accurately quantify and account for hydrologic uncertainties, and 3) regional risk reductions wherein a quantitative assessment of associated resource requirements is conducted to ensure enhanced services can be provided with projected staffing and computational capabilities.*

[4] *The incremental extension of the range of forecaster-prepared QPFs/PQPFs (from Day 1 to Day 2, and from Day 2 to Day 3) is contingent upon forecaster skill exceeding that of the operational NWP models by an amount to be specified by the HIWG in the forthcoming companion implementation plan.*

- Improve the real-time access, integration, and utilization within AWIPS of surface rain gage data, and data from new and improved observing technologies.

- Implement 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 ETE Forecast Process. Verification data will be utilized to ensure the ETE Forecast Process represents the most efficient use of resources to produce quality QPI for hydrologic services.

This strategic plan reflects a partnership amongst the various organizations that comprise the modernized ETE Forecast process to meet the requirements of a diverse user community and ensure a national implementation over the next 10 years.

13.0 Appendices

13.1. Appendix A

W/OM21:TMG

Final Summary[1]: Advanced Weather Interactive Processing System (AWIPS) Quantitative Precipitation Forecasting (QPF) Meeting
Colorado Basin River Forecast Center (CBRFC)
3-5 September 1997

Objective:

The National Weather Service (NWS) Office of Meteorology (OM) sponsored a two and one-half day meeting at the CBRFC in Salt Lake City, Utah from 3-5 September to specify prioritized requirements for point and grid editing and display capabilities in support of the preparation, coordination, and verification of QPFs within AWIPS. These requirements:

- define capabilities which can be used on a spectrum of geographic scales (i.e., national through local);

- collectively satisfy the needs of operational forecasters at all steps of the NWS ETE Forecast Process for QPF; and,

- provide definition to requirements outlined in sections 3.1.4.2.2.4.1 (Prepare Digital Forecast Data) and 3.1.4.2.2.4.2 (Prepare Gridded QPF Data Set) of the NWS AWIPS System/Segment Specification (Type-A) Document, Number SSS-001-1994, dated December 16, 1994.

The operational implementation of these capabilities would eliminate the need for the development and maintenance of multiple grid editing applications within the NWS (i.e., RFC Hydrometeorological Analysis and Support (HAS) Forecasters, and WFO and NCEP forecasters would utilize the same AWIPS application). Many of the requirements are not specific to the QPF and support the preparation of forecasts of other meteorological parameters. Further, these capabilities also support the NWS' proposed national transition to stochastic QPF forecasting, and will be updated based upon the results of the Probabilistic ETE Risk Reduction Exercise scheduled to begin in FY-99.

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[1] *Preliminary Summary prepared 9/24/97; Preliminary Summary updated 11/5/97; Final Summary prepared 11/24/97. Preliminary results presented to IFPS Forecaster Working Group (IFWG) at NWSH on 6 November 1997. The final summary was distributed to all workshop attendees, OM Managers and AWIPS personnel, the Regional SSD Chiefs, and MSM, OSD, and HPC personnel.*

Attendees:

The meeting was organized and chaired by Tom Graziano of OM and Greg Rishel of Western Region Headquarters (WRH), and hosted by the CBRFC Hydrologist In Charge (HIC) Dave Brandon. Attendees totaling twenty-four included representatives of the:

- *National Oceanic and Atmospheric Administration's (NOAA) Forecast Systems Laboratory (FSL)*
  - Tom LeFebvre
  - Dave Howard
- *NWS Regions*
  - Jason Hess, Alaska Region (AR)
  - Noreen Schwein[2], Central Region Headquarters (CRH)
  - Mark Fenbers, Eastern Region (ER)
  - Peter Gabrielsen[2], Eastern Region Headquarters (ERH)
  - Roger Pierce[2], Pacific Region (PR)
  - Mike Sierchio, Pacific Region Headquarters (PRH)
  - Ed May[2], Southern Region Headquarters (SRH)
  - Owen Rhea, Western Region (WR)
  - Craig Peterson, WR
  - Larry Dunn, WR
  - Dave Brandon, WR
  - Art Henkel[2], WR
  - John Jannuzzi, WR
  - Tyree Wilde, WR
  - Andy Edman, Western Region Headquarters (WRH)
  - Mark Mollner[2], WRH
  - Greg Rishel, WRH
- *Techniques Development Lab (TDL) of the Office of Systems Development (OSD)*
  - Dave Ruth
- *Hydrometeorological Prediction Center (HPC) of the National Centers for Environmental Prediction (NCEP)*
  - Wes Junker

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2 *Member of the Hydrometeorological Information Working Group (HIWG)*

- *Office of Hydrology (OH)*

    - Jay Breidenbach
    - Jeff Zimmerman

- *Office of Meteorology(OM)*

    - Tom Graziano[2]

Background:

During the July 1996 meeting of the Hydrometeorological Information Working Group (HIWG), AWIPS requirements for QPF generation and coordination were discussed, and HIWG representatives from the six NWS regions were given the action to poll their respective forecast offices and compile a list of salient functionality/capabilities of *WinQPF* and *Mountain Mapper* which need to migrate into AWIPS. *WinQPF* and *Mountain Mapper* are the primary QPF software applications used to generate QPFs for input to the NWS River Forecast System (NWSRFS). *WinQPF* is currently utilized by Eastern, Southern, and all but a few Central Region forecast offices to prepare QPFs. Additionally, *WinQPF* is used by three Western Region forecast offices in Montana east of the continental divide (TFX, BYZ, GGW) which support the Missouri Basin River Forecast Center (MBRFC). The remainder of the Western Region forecast offices (and two Central Region offices which support WR RFCs) are being equipped with and trained to use *Mountain Mapper* to specify QPFs, and Alaska Region offices plan to utilize *Mountain Mapper* by the summer of 1998. Response to the regional HIWG polls indicated that forecasters generally requested that the full capabilities of these software applications, with a few minor additions (such as the capability to initialize points/grids with direct model output or value-added guidance, etc.), be available within AWIPS. In light of this response, the meeting was designed to demonstrate and compare the capabilities of these applications to those currently scheduled for AWIPS: specifically, TDL's *Grid Modification (GMOD)* and *Slider Servers* and FSL's *Graphical Forecast Editor (GFE)* (http://www-md.fsl.noaa.gov/eft/publications/brochure/brochure.html). The *GMOD Server* will be the AWIPS standard through Build 4, and encompasses many of the capabilities inherent in *WinQPF*. The *GFE,* which will replace the *GMOD Server,* and the *Slider Server* are scheduled for AWIPS implementation with Build 5 (late CY-98).

Presentations/Discussion:

Through the course of the demonstrations of *WinQPF* and *Mountain Mapper,* and their comparison to scheduled AWIPS functionality/capabilities, workshop attendees discussed and answered the following questions:

- Have all of the current and necessary capabilities of *WinQPF* been integrated into AWIPS?

- What *Mountain Mapper* functionality/capabilities need to be integrated into AWIPS?

- What additional QPE/QPF functionality/capabilities need to be integrated into AWIPS?

Mark Fenbers, the Senior HAS forecaster at the Ohio River Forecast Center (OHRFC) and developer of *WinQPF*, demonstrated and discussed the operational utility of this application. The developers of *Mountain Mapper*, Craig Petersen and Art Henkel, the Senior HAS and Development and Operations Hydrologist (DOH) at the CBRFC, respectively, demonstrated the full capabilities of the primary components of *Mountain Mapper*:

- *specify_qpf*, which is used for the specification of QPFs,

- *qc_daily*, which is used in the quality control of observed precipitation, and

- *verify*, which is used to display QPF fields, observed precipitation fields, and difference maps (i.e., Forecast-Observed precipitation).

As a result of these presentations and the ensuing discussions, several capabilities of these applications were identified for AWIPS implementation. Dave Ruth, the Chief of the Products Development Branch in TDL, discussed and demonstrated the current AWIPS grid editing capabilities (i.e., the *GMOD Server*), and scheduled near term enhancements with emphasis on model interpretation using the *Slider Server*. Tom LeFebvre, a senior meteorologist and software developer in FSL, provided a detailed demonstration of the capabilities of the *GFE*, which served as the benchmark to establish the prioritized requirements list.

Results:

<u>AWIPS Requirements</u>

I. QPF Preparation (applicable to WFO, RFC, and NCEP forecast domains)

A. Drawing Tools

1. capability to specify *point QPFs* and related parameters (e.g freezing level, temperatures)

    a. fixed points (e.g., predetermined geographic locations)

    b. pseudo points (e.g., case-specific, user-defined geographic locations)

2. capability to manually specify *gridded QPFs* utilizing drawing tools (similar to *WinQPF*) and "backbone" technique (*Mountain Mapper* enables forecasters to specify an axis or

"backbone" of maximum precipitation which is re-rendered as a grid utilizing climatological precipitation data)

B. Initialization Methods

1. capability to directly initialize of *points/grids* with existing grids/guidance (i.e., previous WFO QPF, meso-eta, Rhea Model, ensembles, Model Output Statistics (MOS), HPC guidance, climatology, etc.), or user-controlled "blend" of models/guidance

2. capability for HAS to directly initialize RFC domain with mosaic of WFO grids

C. Patterning Methods for Point QPFs or "Backbones"

1. capability to utilize monthly climatological Parameter-elevation Regressions on Independent Slopes Model (PRISM) data from the USDA Natural Resources Conservation Service Water and Climate Center at Oregon State University (http://www.ocs.orst.edu/prism/prism_new.html)

2. capability to utilize case-specific meteorological data (i.e., patterning based upon current NWP models/guidance and/or satellite-based precipitation patterns, etc.)

3. capability to utilize locally specified patterns (e.g., conditional climatology patterns stratified by flow regime, etc.)

D. Editing Tools

1. capability to overlay/underlay observed data (e.g., radar and satellite images, precipitation gage reports, etc.)

2. capability to overlay contoured or underlay images (color-filled) of forecast NWP gridded model output and derived fields (e.g., layer average convergence of the Q-vector, moisture convergence, etc.)

3. capability to edit for timing/intensity of precipitation (e.g., TDL-developed Slider Bar application)

4. capability to define and apply user-specified, geographically and/or meteorologically weighted grid editing tools

5. capability to underlay high resolution topographic data (similar to *Mountain Mapper*)

6. capability to overlay contoured or underlay images (color-filled) of gridded FFG or user-specified difference fields (e.g., QPF-FFG, QPF-climatology)

7. Capability to mosaic WFO- and RFC-prepared QPFs

- RFCs require capability to mosaic all WFO-prepared QPFs within the RFC area of hydrologic responsibility (this is particularly important to the *preparation* of HAS value-added QPFs)

- WFOs require the capability to mosaic QPFs prepared by neighboring WFOs/RFCs (note: many WFOs support multiple RFCs)

E. Forecast Methodology

1. enable forecasters to prepare QPFs via aggregation *or* disaggregation

2. provide display with user-specified running total (e.g., 24, 48 hours, etc.) for aggregation method

3. capability to specify temporal range/projection and temporal resolution within that range (e.g., 6 hours for Day 1, 12 hours for Day 2, etc.)

4. provide capability to perform disaggregation via hierarchical approach (as will be done during the forthcoming Probabilistic ETE Risk Reduction Exercise utilizing software developed at UVA)

5. provide capability to overlay (toggle on) previous user-specified QPF *or* display multiple panels (with multiple panels "active" window would be largest, similar to D2D display of WFO Advanced)

Results of regional surveys -- forecaster preference/regional consensus is for multiple panels:

- WR-- prefer multiple panels but toggle method acceptable
- AR-- no preference stated
- CR-- strongly prefer multiple panels: 26 offices polled, average response was 4.3 for multiple panels (5=essential; 1=not required)
- ER-- prefer multiple panels
- PR-- no preference stated
- SR-- strongly prefer multiple panels

F. Display

1. capability to display information specific to cursor location (e.g., latitude/longitude, QPF value, elevation, etc.)

2. capability to overlay hydrologic basin boundaries, counties, cities, etc.

G. WFO-RFC Data Transfer and Data Presentation

1. transfer gridded QPFs between WFO-RFC via lambert conformal grids at ~ 4km spatial resolution *(conversion to HRAP will occur at RFC prior to input into NWSRFS)*

2. transfer SHEF-encoded MAPs and point data (in addition to grids) between WFO-RFC

3. capability to locally specify grid resolution (i.e., 1, 4, 8 km, etc.)

II. QPF Coordination

A. enable RFC/WFOs to view unedited WFO and HAS edited mosaicked QPFs (points/grids/MAPs)

B. provide capability to annotate QPFs with plain language message

C. provide capability to mask WFO QPF output to delineate boundaries of forecast domains

D. provide WFOs/RFC automatic update flag to alert forecasters of the arrival of new QPFs

III. Verification and Data Quality Control

A. provide capability to view, in real time, differences between observed rainfall (Stage II/III/IV or equivalent QPEs) and QPFs (points/grids/MAPs) for user-specified time frames (e.g., 6, 12, 24 hours, etc.) -- i.e., provide full functionality of Mountain Mapper *verify* component

B. provide full functionality of Mountain Mapper *qc_daily*[3] component

C. provide capability to compute verification statistics for user-specified temporal projections including short-term forecasts (hours to days) and longer time historical analysis

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[3] *The consensus of the meeting attendees was that this functionality should be integrated into the Hydroview component of the WFO Hydrologic Forecast System (WHFS)*

Prioritization

Requirement	Requirement Prioritization (5 = essential; 1 = not-required; N/A = not applicable)								
	NWS Region						NCEP	Average	Rank (*t*=tie)
	WR	CR	SR	ER	AR	PR	HPC		
I. QPF Preparation									
A. Drawing Tools									
1. capability to specify *point QPFs* and related parameters via:									
a. fixed points	5	2	5	1	5	3	5	*3.7*	*24*
b. pseudo points	5	2	4	1	2	3	4	*3.0*	*30*
2. capability to manually specify *gridded QPFs* utilizing drawing tools (*WinQPF*) and "backbone" technique (*Mountain Mapper*)	5	5	5	5	2	3	5	*4.3*	*t13*
B. Initialization Methods									
1. capability to directly initialize *points/grids* with existing grids/guidance (i.e., previous WFO QPF, meso-eta, Rhea Model, ensembles, Model Output Statistics (MOS), HPC guidance, climatology, etc.), or user-controlled "blend" of models/guidance	5	5	5	5	5	5	5	*5.0*	*1*
2. capability for HAS to directly initialize RFC domain with mosaic of WFO grids	5	5	5	5	3	5	N/A	*4.7*	*t2*
C. Patterning Methods for Point QPFs or "Backbones"									
1. capability to utilize monthly climatological PRISM data	5	3	3	2	5	4	3	*3.6*	*t25*
2. capability to utilize case-specific meteorological data	4	2	5	2	5	4	3	*3.6*	*t25*
3. capability to utilize locally specified patterns	5	2	5	2	4	4	3	*3.6*	*t25*

Requirement	Requirement Prioritization (5 = essential; 1 = not-required; N/A = not applicable)								
	NWS Region						NCEP	Average	Rank
	WR	CR	SR	ER	AR	PR	HPC		(*t*=tie)
I. QPF Preparation -- Contd.									
D. Editing Tools									
1. capability to overlay/underlay observed data (e.g., radar and satellite images, precip gage reports, etc.)	5	3	5	5	5	4	5	*4.6*	*t6*
2. capability to overlay contoured or underlay images (color-filled) of forecast NWP gridded model output and derived fields (e.g., layer average convergence of the Q-vector, moisture convergence, etc.)	4	4	5	5	4	4	5	*4.4*	*t10*
3. capability to edit for timing/intensity of precipitation (e.g., TDL-developed Slider Bar application)	5	3	5	5	3	4	2	*3.9*	*22*
4. capability to define and apply user-specified, geographically and/or meteorologically weighted grid editing tools	5	3	5	5	3	4	3	*4.0*	*t18*
5. capability to underlay high resolution topographic data	5	5	5	5	5	4	4	*4.7*	*t2*
6. capability to overlay contoured or underlay images (color-filled) of gridded FFG or user-specified difference fields (e.g., QPF-FFG, QPF-climatology)	5	3	4	5	3	4	5	*4.1*	*t16*
7. capability to mosaic WFO- and RFC-prepared QPFs -- see also item II.A.	5	4	5	5	5	N/A	3	*4.5*	*9*
E. Forecast Methodology									
1. enable forecasters to prepare QPFs via aggregation *or* disaggregation	5	5	3	5	4	4	5	*4.4*	*t10*
2. provide display with user-specified running total (e.g., 24, 48 hours, etc.) for aggregation method	5	5	5	5	4	4	5	*4.7*	*t2*
3. capability to specify temporal range/projection and temporal resolution within that range (e.g., 6 hours for Day 1, 12 hours for Day 2, etc.)	5	2	5	5	4	4	5	*4.3*	*t13*

Requirement	Requirement Prioritization (5 = essential; 1 = not-required; N/A = not applicable)								
	NWS Region						NCEP	Average	Rank
	WR	CR	SR	ER	AR	PR	HPC		(*t*=tie)
I. QPF Preparation -- Contd.									
E. Forecast Methodology -- Contd.									
4. provide capability to perform disaggregation via hierarchical approach	5	3	3	3	2	4	5	*3.6*	*t25*
5. provide capability to overlay (toggle on) previous user-specified QPF *or* display multiple panels	5	4	4	4	4	4	4	*4.1*	*t16*
F. Display									
1. capability to display information specific to cursor location (e.g., lat/lon, QPF value, elevation, etc.)	5	3	4	4	4	4	4	*4.0*	*t18*
2. capability to overlay hydrologic basin boundaries, counties, cities, etc.	5	5	5	5	4	4	3	*4.4*	*t10*
G. WFO-RFC Data Transfer and Data Presentation									
1. transfer gridded QPFs between WFO-RFC via lambert conformal grids at ~ 4km spatial resolution *(conversion to HRAP will occur at RFC prior to input into NWSRFS)*	5	5	3	5	4	2	N/A	*4.0*	*t18*
2. transfer SHEF-encoded MAPs and point data (in addition to grids) between WFO-RFC	5	5	5	5	4	2	N/A	*4.3*	*t13*
3. capability to locally specify grid resolution (i.e., 1, 4, 8 km, etc.)	4	1	3	3	3	2	2	*2.6*	*31*
II. QPF Coordination									
A. capability to display unedited WFO and HAS edited mosaicked QPF (points/grids/MAPs)-- see item I.D.7	5	4	5	5	5	N/A	3	*4.5*	*9*
B. provide capability to annotate QPFs with plain language message	4	4	5	5	3	N/A	3	*4.0*	*t18*
C. provide capability to mask WFO QPF output to delineate boundaries of forecast domains	5	2	5	2	2	N/A	N/A	*3.2*	*29*

Requirement	Requirement Prioritization (5 = essential; 1 = not-required; N/A = not applicable)								
	NWS Region						NCEP	Average	Rank (*t*=tie)
	WR	CR	SR	ER	AR	PR	HPC		
II. QPF Coordination -- Contd.									
D. provide WFOs/RFC automatic update flag to alert forecasters of the arrival of new QPFs	5	3	4	5	2	N/A	N/A	*3.8*	*23*
III. Verification and Data Quality Control									
A. capability to view, in real time, differences between observed rainfall (Stage II/III/IV or equivalent QPEs) and QPFs (points/grids/MAPs) for user-specified time frames (e.g., 6, 12 , 24 hrs, etc.)--i.e., provide full functionality of Mountain Mapper *verify* component	5	4	5	5	5	4	5	*4.7*	*t2*
B. provide full functionality of *qc_daily* component *(in WHFS)*	5	5	5	5	5	4	3	*4.6*	*t6*
C. capability to compute verification statistics for user-specified temporal projections including short-term forecasts (hours to days) and longer time historical analysis	5	3	5	5	5	4	5	*4.6*	*t6*

13.2. Appendix B

W/OM21:TMG

MEMORANDUM FOR: Distribution

FROM: W/OM - Louis W. Uccellini

SUBJECT: National WHFS, AMBER, and SCAN Workshop Summary

The National Weather Service (NWS) Office of Meteorology (OM) sponsored a one-day workshop to discuss the current status and the future design and integration of hydrologic software applications to improve NWS operational flash flood assessment, prediction, and warning within the Advanced Weather Interactive Processing System (AWIPS). These software applications include the Weather Forecast Office (WFO) Hydrologic Forecast System (WHFS), the Areal Mean Basin Estimated Rainfall (AMBER) Program, and the System for Convection Analysis and Nowcasting (SCAN). The meeting was organized and chaired by Dr. Thomas Graziano of OM, Dr. Stephan Smith of the Office of Systems Development (OSD), and Dr. Chuck Hoffeditz of the Office of Hydrology (OH), and held on February 11, 1998 at NWS Headquarters in Silver Spring, MD. Attendees included representatives from the following organizations (attachment 1):

- NWS: OM, OH, OSD, Eastern Region, Central Region, Southern Region, Western Region, Alaska Region, Pacific Region, the Office of Systems Operations (OSO), and the Modernization Systems Management (MSM) Office,

- Office of Oceanic and Atmospheric Research (OAR): National Severe Storms Laboratory (NSSL), and

- The University of Oklahoma (OU).

The primary objectives of the workshop were:

- Identify key operational AWIPS requirements and capabilities necessary to improve NWS flash flood operations,

- Define data, software, hardware, and human resource requirements to implement and test AMBER outside the NEXRAD Weather Service Forecast Office (NWSFO) in Pittsburgh, PA,

- Define a future operational relationship between WHFS and SCAN in AWIPS which optimizes resources for the assessment, prediction, and warning of flash flooding, and

- Discuss National Severe Storms Laboratory (NSSL) and cooperative NSSL/University of Oklahoma (OU) efforts to develop hydrometeorological applications and the potential for collaboration with the NWS.

Background

The National Workshop on WHFS, AMBER, and SCAN was designed to further address high priority flash flood issues raised at the recent NWS-sponsored First National Quantitative Precipitation Estimation (QPE) Workshop at the Cooperative Program for Operational Meteorology, Education and Training (COMET) in Boulder CO., held November 18-20, 1997. During the First National QPE workshop, requirements, operational applications, and supporting applied research on precipitation estimation were reviewed and discussed by a broad spectrum of participants from the NWS, OAR, the National Center for Atmospheric Research (NCAR), the National Environmental Satellite, Data, and Information Service (NESDIS), the National Aeronautics and Space Administration (NASA), and COMET. The provision of high resolution rainfall estimates and forecasts, coupled high resolution watershed definitions and software applications to assess and predict flash flood conditions, was identified as a top priority by representatives from the NWS Regions.

Flash floods are widely recognized as one of the most devastating and deadly weather-related hazards and a challenging operational forecast problem. Flash flooding occurs in all fifty United States and at all times of the year. Over the past thirty years, the average annual number of lives claimed by flash and river floods exceeds that due to tornadoes, lightning or hurricanes. Beginning in 1988, data for flash and river flood floods were archived independently. These data reveal that for the eight year period ending in 1995, 72 percent of the flood-related deaths (471 of a total 655) have been caused by flash flooding. In light of this and our limited capability to assess, predict, and warn for flash flood events, NWS Regional representatives deem critical and strongly support the rapid implementation of hydrometeorological applications which will enhance our operational flash flood capability.

Oral Presentations

Five morning presentations preceded an afternoon open discussion which addressed the aforementioned primary workshop objectives. A brief synopsis of these presentations is provided below.

1. The WFO Hydrologic Forecast System

Mr. Jon Roe of the Hydrologic Research Lab (HRL) in OH provided and overview of WHFS and discussed its current status and projected near-term enhancements. WHFS is an integrated system comprised of many HRL-developed applications that support the hydrology program at a WFO. WHFS capabilities include applications for data collection and management, data display, hydrometeorologic modeling, and product formatting and management functions. The WHFS is currently deployed and being tested at a number of WFOs. The hydrometeorologic modeling component of WHFS will include: 1) the Area Wide Hydrologic Prediction System (AWHPS) which will provide for the analysis and display of observed and forecast precipitation and flash flood guidance to provide WFO forecasters with a means of assessing the areal flash flood potential, and 2) the Site Specific Hydrologic Prediction System (SSHPS) which is a local hydrologic model that will provide WFO forecasters with a method of evaluating, and subsequently generating hydrologic forecasts for fast-response and headwater stream basins. AWHPS is designed to enhance a forecaster's ability to assess and predict flash flooding, and is scheduled for initial implementation in the Fall of 1998 with WHFS version 2.1 in AWIPS build 4.1. SSHPS will be available in a later build of AWIPS.

Introductory AWHPS capabilities include the direct comparison of precipitation estimates and forecaster prepared quantitative precipitation forecasts (QPFs) to flash flood guidance (FFG). These precipitation estimates include Hydrologic Rainfall Analysis Project (HRAP)-gridded (4 km) Stage I and Stage II analyses. Stage I analyses are hourly radar-only estimates updated every volume scan. Stage II analyses include both hourly gage only and multi-sensor gage-radar estimates valid on-the-hour. These gridded precipitation estimates can be spatially aggregated over counties, zones, and River Forecast Center (RFC)-defined mean areal precipitation (MAP) areas (basins), and temporally aggregated for 1, 3, 6, 12, and 24 hour durations. The comparison of QPFs and FFG will be performed on the MAP scale. Although available in HRAP-gridded format, FFG values are computed using RFC model soil moisture parameters effective on the coarser MAP scale. Over the next several years, FFG will significantly improve as OH implements a Graphical Information System (GIS)-based threshold-runoff technique to produce modernized, high resolution HRAP-gridded FFG at RFCs.

Planned enhancements to AWHPS include the incorporation of the higher resolution (1 km x 1 degree, 8-bit, every volume scan) WSR-88D Digital Hybrid Scan Reflectivity (DHR) product, comparisons of basin average DHR-based precipitation estimates with FFG over flash flood watersheds considerably smaller than MAP areas (i.e., on the order of one mile squared and larger), and the implementation of an automated short-term precipitation projection algorithm. HRL considers these enhancements a priority and hopes to implement them within AWIPS during the next two years, or at the earliest possible opportunity given the availability of the necessary resources.

2. The System for Convection Analysis and Nowcasting

Dr. Stephan Smith of the Techniques Development Laboratory (TDL) in OSD provided a brief history of and the impetus for the rapidly evolving SCAN effort. In addition, he described its conceptual architecture, current status, near-term goals, and projected AWIPS implementation. SCAN is a collaborative effort principally involving the NWS, NSSL, and NCAR, with increasing participation from NESDIS and COMET. The goals of SCAN are: 1) to detect, analyze, and monitor convection and generate short-term probabilistic forecasts and warning guidance automatically within AWIPS, and 2) to combine previous research and development efforts into one integrated approach to forecasting convection and related hazardous phenomena. These research and development efforts include the NSSL Warning Decision Support System (WDSS), the NCAR Auto-nowcaster, the NWS' AWIPS Thunderstorm Product, and WHFS.

The primary motivation for SCAN is to provide operational forecasters a more efficient, effective, and consistent means of issuing timely and accurate warnings (e.g., severe weather, flash flood, tornado, etc.), through the provision of automated and forecaster editable warning guidance. SCAN supports the modernized ETE Forecast Process by providing a framework to integrate and make optimal use of the enormous volume and broad spectrum of advanced observational data, model output, and value-added guidance within AWIPS. The functionality to be incrementally implemented in SCAN includes automated storm detection, phenomenon classification, severity and flash flood monitoring, and nowcasting that will allow the forecaster to make better informed watch and warning decisions. Furthermore, it will serve as a vehicle for the implementation of future nationally- and locally-developed applications within AWIPS.

During the 1997 convective season, a SCAN prototype consisting of an integration of NSSL's Warning Decision Support System, NCAR's Thunderstorm Auto-nowcaster and the NWS's Thunderstorm Product was tested at the Washington D.C.-Baltimore forecast office in Sterling, Virginia. The purpose of the field test was to integrate these software applications and examine the usefulness of the combined products as a tool for the short-term and warning forecaster. While the 1997 test results and forecaster feedback was overall very positive, without the capability to display flash flood products within the AWIPS Display 2 Dimensional (D2D), the SCAN prototype currently lacks a means of monitoring the areal potential for flash flooding. In light of this shortcoming, Dr. Smith, other members of the SCAN team, and regional representatives strongly recommend that AWHPS and/or AMBER guidance products be displayable within D2D via SCAN in the near term. This will enable forecasters to directly integrate flash flood products with companion high resolution observational and forecast data sets. The capability of the second generation SCAN prototype, scheduled to be tested at Washington D.C.-Baltimore forecast office during the 1998 convective season, will be enhanced significantly through the full integration of AMBER.

Version 1.0 of SCAN, which includes the NWS' AWIPS Thunderstorm Product and 0-1 hour WSR-88D based extrapolative-statistical probabilistic QPF guidance, is scheduled for initial field implementation with AWIPS build 4.1 in the Fall of 1998. SCAN version 2.0, which incorporates WDSS functionality, is currently scheduled for field implementation with AWIPS build 5.0.

3. Areal Mean Basin Estimated Rainfall Program

Mr. Bob Davis from Eastern Region provided a brief history of AMBER, described its basic architecture, and demonstrated its operational benefits for flash flood events that occurred within the Hydrologic Service Area (HSA) of NWSFO Pittsburgh. AMBER is a software application which utilizes the DHR product to compute radar rainfall estimates in flash flood watersheds every volume scan. A single rainfall estimate is computed for each 1 km x 1 degree range bin. All range bins, whose center point falls in a stream watershed, are averaged to compute the Average Basin Rainfall (ABR) for that watershed. The computed ABR values represent an area average accumulation of all radar rainfall estimates in a watershed, including zero accumulations. The 5-6 minute ABR values are summed to create rainfall accumulations for 0.5, 1, 2, 3 and 6 hours. The likelihood of flooding is determined by comparing the temporally aggregated ABR and rate of precipitation accumulation with RFC FFG; i.e.,the ABR needed to bring a stream to bankfull. The high resolution DHR rainfall grid enables AMBER to compute ABR in watersheds as small as one square mile in area. AMBER is currently utilized to compute ABR for more than 2,400 streams every radar volume scan for the NWSFO Pittsburgh HSA.

AMBER, developed by Mr. Davis in the early 1980s, has evolved significantly from over a decade of operational development at NWSFO Pittsburgh. Mr. Davis noted that lessons learned through the operational application of AMBER include: 1) flash floods typically occur in small watersheds on the order of 5 to 20 square miles, 2) operational forecasters must have access to these small watershed boundaries to determine flash flood potential, 3)forecasters need to estimate the volume of rainfall (ABR) within these small watersheds to effectively determine the flash flood threat, and 4) digital (DHR) WSR-88D radar rainfall provides sufficient time and space resolution to detect flash flood potential.

Mr. Davis stated that at least 3 arc-second digital elevation model (DEM) data sets should be used to accurately define small watersheds, and that using more coarse DEM data will lead to radar bin assignment errors, particularly for smaller watersheds whose domain is on the order of 1-2 square miles. Mr. Davis showed examples of events where high resolution basin definitions were necessary to accurately assess the flash flood threat. Mr. Davis also stated that the operational utility of AMBER would be enhanced if a Graphical User Interface (GUI) were developed which integrates a Graphical Information System (GIS). This would provide forecasters an areal depiction of threatened basins coupled with other geographic information which would assist the forecaster in the watch/warning process (e.g., schools, highways, railways, population centers, etc). Mr. Davis also stated the need for routing streamflow, and FFG based upon model parameters specific to each stream watershed. The provision of this capability and guidance, however, requires the operational implementation of a distributed hydrologic model.

4. AMBER Basin Requirements

Mr. Paul Jendrowski, from NWSFO Honolulu, outlined database requirements and development issues associated with the high resolution watershed specification required for AMBER implementation. Mr. Jendrowski previously served as the Science and Operations Officer at NWSFO Pittsburgh before assuming the same role in Honolulu. Consequently, he has experience with AMBER and is currently in the process of implementing AMBER operationally at NWSFO Honolulu.

Mr. Jendrowski outlined a multi-scale approach to watershed boundary specification. This approach begins with the specification of primary basins (<200 square miles), followed by multiple nesting levels to define successively smaller scale watersheds. Initial DEM processing, quality control, and basin delineation could be done centrally, but forecast offices would need to make local modifications. Given that urban areas often present unique flash flood problems, WFOs must have the capacity to locally customize and update basin boundaries to best define high threat areas. Consistent with Mr. Davis, Mr. Jendrowski stated that database requirements to assist forecasters in the issuance of warning products include the capability to edit and display spatial reference data such as parent and sub-basins, stream locations and names, reservoirs and dam locations, counties (name, state, code, zone, etc.), transportation routes (e.g., streets, highways, railways, etc.), and important landmarks (towns, schools, etc.).

A number of GIS software applications are available to delineate hydrologic basins. They include the Integrated Hydrologic Automated Basin Boundary System (IHABBS), and the commercial application ArcView. IHABBS was developed by the National Operational Hydrologic Remote Sensing Center (NOHRSC) of OH, and has been implemented at the 12 RFCs of the conterminous U.S. IHABBS is designed to allow RFC hydrologists to objectively generate hydrologic basin boundaries for use in NWSRFS. IHABBS uses a NOHRSC prepared data set of flow direction grids derived from 15 arc-second USGS DEM data sets and EPA river reach data (RF1). ArcView can also be used delineate hydrologic basins, and additionally provides the capability to create, edit, and display other aforementioned spatial reference data sets. ArcView is currently used by the AWIPS MSM personnel to generate map backgrounds, and meets the fundamental AWIPS requirements for both national- and local-scale map background specification and modification. The National Oceanic and Atmospheric Administration (NOAA) is currently negotiating with the Environmental System Research Institute (ESRI) to establish an license agreement wherein the NWS could supply field offices ArcView (with the spatial editor and some level of training) at a reduced cost.

Mr. Jendrowski utilized ArcView and 3 arc-second USGS DEM data to delineate watershed boundaries on a SOO/SAC HP 715/64. The process can be described in the following six steps (with associated time estimates assuming proficiency with ArcView):

- Collect and mosaic DEM files (1 day),
- Fill sinks in DEM data (8 hours of processing time),
- Compute flow direction (40 minutes),
- Compute flow accumulation (4 hours),
- Define primary and sub-basins (6 hours), and
- Mapping of radar data points to basins (1 hour).

A limitation of the process is that the DEM based stream network may not accurately represent actual streams and rivers. Therefore, it is imperative that basin delineations be quality controlled (constrained) by high resolution stream data (e.g., EPA RF3 data), as is done with the coarser resolution IHABBS data set. Further, detailed land usage data is required to accurately define basins in urban areas.

5. NSSL/Univ. of OK plans for Hydrologic Forecast Applications

Mr. Mike Eilts of NSSL discussed plans to develop, with the support of the Operational Support Facility (OSF) and in coordination with the HRL of OH, OSD, and OM, a prototype AMBER GUI for implementation and field testing within SCAN during the 1998 convective season at the Washington D.C.-Baltimore forecast office in Sterling, Virginia. OSF funding and input continues to be critical to the success of the SCAN development effort. NSSL recognizes and is responding to the need to display flash flood guidance products within D2D via SCAN in the near term. NSSL has a successful history of rapid prototyping and developing applications to extract and display salient information, and the 1998 SCAN field test should provide an excellent opportunity to develop a forecaster interface for AMBER.

Dr. Baxter Vieux of the University of Oklahoma, described the fundamental components and underlying science of the OU distributed hydrologic model. OU, in concert with NSSL and the Eastern region will test the operational utility of the OU distributed model for flash flood applications within the HSA of the Washington D.C.-Baltimore forecast office in Sterling, Virginia during 1998.

Issues and Recommendations

Issue: What AWIPS capabilities are necessary to improve NWS flash flood operations?

General Recommendation:

- The NWS should support a sustained and aggressive effort to develop and implement within AWIPS applications which enhance our operational flash flood capability.

Specific Recommendations:

- Provide field offices the high resolution Digital Hybrid Reflectivity product to compute rainfall estimates within AWIPS.

- Include AMBER capabilities in future versions of the AWHPS of WHFS (i.e., map DHR-based rainfall estimates in locally-defined high resolution basins and use ABR to compute flash flood threat).

- Provide WFOs the procedures, software, and training necessary to specify and/or modify local basin definitions using the OH Integrated Hydrologic Automated Basin Boundary System (IHABBS), ArcView, or other nationally-supported Commercial Off-The-Shelf (COTS) Geographic Information System (GIS) application.

- Provide the capability to create, edit, and display spatial reference data such as parent and sub-basins, stream locations and names, reservoir and dam locations, counties (name, state, code, zone, etc.), transportation routes (e.g., streets, highways, railways, etc.), and important landmarks (towns, schools, hospitals, etc.) to assist forecasters in the issuance of flash flood watches and warnings.

- Provide the capability to display AWHPS flash flood guidance products within the AWIPS D2D and store these products in the AWIPS data structure so that these products are accessible to SCAN algorithms.

- Provide modernized RFC-generated, high resolution, GIS-based threshold-runoff FFG to WFOs in AWIPS.

- Provide WFOs gridded high resolution (i.e., 1 km, 8-bit, every volume scan) regional radar mosaics (e.g., DHR) in near real-time to mitigate the impact of range degradation and other known radar deficiencies.

- Store the high temporal and spatial resolution QPF/PQPF output of SCAN algorithms (e.g., TDL's extrapolative-statistical precipitation algorithm within the AWIPS Thunderstorm Product and NCAR's Thunderstorm Auto-nowcaster) in the AWIPS data structure so that these products are accessible to WHFS for use in the:

    - AWHPS to compute the forecast ABR and predict flash flood threat, and

    - SSHPS to produce site-specific forecast time series for selected points in small, fast-responding (headwater) stream basins [While being able to identify flash flood potential, and possibly specifying the stream(s) most vulnerable to flooding is essential, being able to provide a forecast crest or categorical forecast of the magnitude of the event is equally critical. The SSHPS will incorporate the Soil Conservation Service (SCS) curve numbers as a method for computing stage forecasts. This method should be ideal for flash flood forecasting since it uses basin soil-type as a parameter for runoff calculations. This calculation of average basin soil-type is consistent with the GIS-based enhancement planned for WHFS].

Issue: What must be accomplished to implement and test AMBER outside the NWSFO Pittsburgh?

General Recommendation:

- Facilitate OSF, NSSL, and NWS Region near-term, limited, interim testing of AMBER.

Specific Recommendations:

- Provide field offices immediate access to the WSR-88D DHR product (AWIPS sites fitted with an A/B switch on the 56 Kbs line from the RPG, and WDSS sites, currently have access to the DHR product; availability at limited number of other sites may require the submission of a NEXRAD Change Request by OM).

- Utilize ArcView or IHABBS for local basin delineation. WFOs opting to use IHABBS should contact their RFC focal point for assistance.

- Collaborate with NSSL to develop and field test a Graphical User Interface for AMBER.

- Conduct concurrent testing of AMBER and AWHPS at the Washington D.C.-Baltimore forecast office in Sterling, Virginia during 1998 SCAN field test.

Attachment

Distribution:

W/OM - L. Uccellini
W/OM - M. Tomlinson
W/OM1 - R. Przywarty
W/OM11 - D. Wernly
W/OM11 - W. Alexander
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W/OM2 - G. Mandt
W/OM21 - L. Spayd
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W/OM22 - R. Lane
W/OM22 - R. Elvander
W/OH - D. Fread
W/OHx2 - J. Schaake
W/OH2 - E. Johnson

W/OH3 - L Larson
W/OH3 - C. Hoffeditz
W/OH3 - J. Roe
Wx22 - M. Glackin
Wx22 - D. Vercelli
Wx22 - S. Shipley
W/OSO - W. Telesetsky
W/OSO4 - J. Belville
W/OSO41 - D. Burgess
W/OSD - D. Sargeant
W/OSD2 - H. Glahn
W/OSD24 - S. Smith
W/OSD25 - D. Ruth
W/ER3 - G. Carter
W/WR3 - A. Edman
W/CR3 - R. Livingston
W/SR3 - D. Smith
W/PRx1 - M. Sierchio
W/AR1x3 - G. Hufford
W/SR2 - J. Nunn
W/ER2 - Solomon Summer
W/CR2 - Kenneth King
W/WR2 - Robert Tibi
W/AR1 - James Kemper
W/ER1 - Mickey Brown
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Attachment 1

NATIONAL WHFS/AMBER/SCAN WORKSHOP

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13.3. Appendix C

List of Referenced URLs for Internet Home Pages		
1	COMET Outreach Program	http://www.comet.ucar.edu/outreach/index.htm
2	SCAN Home page	http://tgsv5.nws.noaa.gov/tdl/scan/scan2.html
3	SCAN CWA Threat Indices	http://tgsv5.nws.noaa.gov/tdl/scan/scti.html
4	NCEP NPA (Stage IV)	http://nic.fb4.noaa.gov:8000/research/gcp/hdpprec.html
5	AMBER Program at WFO PBZ	http://www.nws.noaa.gov/er/pit/tamber.htm
6	OH HRL Home Page	http://hsp.nws.noaa.gov/oh/hrl/
7	OH Modernized FFG	http://hsp.nws.noaa.gov/oh/hrl/ffg/ffgplan.htm
8	AE Verification Home Page	http://www.ncep.noaa.gov/hpc/roz/verify/
9	NESDIS ORA Flash Flood Home Page	http://orbit-net.nesdis.noaa.gov/ora/ht/ff
10	SPC Heavy Rain MD	http://www.nssl.noaa.gov/~spc/products/meso/mesoform.htm
11	NCEP Ensemble Implementation News	http://sgi62.wwb.noaa.gov:8080/ens/ens_imp_news.html
12	NCEP Experimental Ensemble PQPF	http://sgi62.wwb.noaa.gov:8080/ens/prcp/psvt96_usa.html
13	USDA NRCS WCC PRISM Data	http://www.ocs.orst.edu/prism/prism_new.html
14	LAMP QPF Products	http://www.nws.noaa.gov/tdl/lamp/qpf.shtml
15	NSSL WDSS	http://www.nssl.noaa.gov/srad/rapid/WDSS.html
16	NCAR Thunderstorm Auto-nowcaster	http://www.rap.ucar.edu/raps95.html
17	TDL Thunderstorm Product	http://tgsv5.nws.noaa.gov/tdl/storm/storm.html
18	TDL Extrapolative-Statistical WSR-88D-based Products	http://tgsv5.nws.noaa.gov/tdl/radar/radar1.htm
19	IFPS and GFE	http://www-md.fsl.noaa.gov/eft/publications/brochure/brochure.html
20	Draft Summary of the USGCRP's 1997 Workshop on Climate Variability and Water Resource Management in the Southeastern U.S.	http://wwwghcc.msfc.nasa.gov/regional/assessment_national.html

14.0. List of References

Achutuni, R., R.A. Scofield, G. Vicente, and C. Tsai, 1996a: Inter-comparison of GOES-7 and GOES-8 longwave infrared imagery during heavy precipitation events over the continental U.S. and the development of an automatic GOES-8 rainfall estimation technique. Preprints, *8th Conference on Satellite Meteorology and Oceanography*, Atlanta, GA, January 28 - February 2, 1996, American Meteorological Society, Boston, pp. 119 - 123.

Achutuni, R., G. Vicente, C. Tsai, and R. Rabin, 1996b: The NOAA/NESDIS/ORA/FLASH FLOOD home page. Preprints, *15th Conference on Weather Analysis and Forecasting,* Norfolk, VA, August 19-23, 1996, American Meteorological Society, Boston, pp. 531 - 534.

Adams, Christopher R., 1995: National Weather Service Emergency Management Forum: Building Better Warning Partnerships. National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 34 pp. plus appendices.

Adams, T. E., E. Welles, and J. C. Schaake, 1999: Operational experience with ensemble streamflow prediction in the Upper Monongahela probabilistic forecast demonstration project. Preprints, *14th Conference on Hydrology*, Dallas, TX, January 10-15, American Meteorological Society, Boston, 8-11.

Alexandridis, M. G., and R. Krzysztofowicz, 1985: Decision models for categorical and probabilistic weather forecasts. *Applied Mathematics and Computation*, **17**, 241-266.

Anagnostou, E. N. and W. F. Krajewski, D. -J. Seo, and E. R. Johnson, 1997: Mean-field radar rainfall bias studies for NEXRAD. *Journal of Hydrologic Engineering*, American Society of Civil Engineers, accepted for publication.

Antolik, M. S., 1995: NGM-based quantitative precipitation forecast guidance: Performance tests and practical applications. Preprints, *14th Conference on Weather Analysis and Forecasting*, Dallas, American Meteorological Society, 182-187.

Antolik, M. S., 1996: Toward an objective NGM-based expected-value quantitative precipitation forecast system. Preprints, *13th Conference on Probability and Statistics in the Atmospheric Sciences*, San Francisco, American Meteorological Society, 57-64.

Antolik, M. S., 1997: NGM-based statistical quantitative precipitation forecast guidance for the contiguous United States and Alaska. *NWS Technical Procedures Bulletin*, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 29 pp.

Antolik, M. S., 1998: Eta-based MOS quantitative precipitation forecasts in an era of rapidly changing numerical models: How well can we do? Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 446-449.

Arnwine, B. C. and Whitlock, A. R., 1995: Using probabilistic quantitative precipitation forecasting to support operation of TVA's reservoir system, the first year's experience. Proceedings, *22nd Annual Conference on Integrated Water Resources Planning for the 21st Century*, American Society of Civil Engineers, pp 715-718 .

Baldwin, M., and T. Black, 1996: Precipitation forecasting experiments in the western U.S. with NCEP's Mesoscale Eta Model. Preprints, *11th Conference on Numerical Weather Prediction,* Norfolk, VA, American Meteorological Society, 19-23 August 1996, J109-J110.

Baldwin, M. E., and K. E. Mitchell, 1996a: The NCEP hourly multi-sensor U.S. precipitation analysis. Preprints, *11th Conference on Numerical Weather Prediction*, Norfolk, VA, American Meteorological Society, 19-23 August 1996, J95-J96.

Baldwin, M. E., and K. E. Mitchell, 1996b: The NCEP hourly multi-sensor U.S. precipitation analysis for operations and GCIP research. Preprints, *2nd International Conference on the Global Energy and Water Cycle*, Washington, DC, 17-21 June 1996, 232-233.

Baldwin, M., and K. Mitchell, 1997: The NCEP hourly multi-sensor U.S. precipitation analysis for operations and GCIP research. Preprints, *13th Conference on Hydrology*, Long Beach, CA, American Meteorological Society, 2-7 February 1997, 54-55.

Bermowitz, R. J., 1975: An application of model output statistics to forecasting quantitative precipitation. *Monthly. Weather Review*, **140**, 149-153.

Bermowitz, R. J., and E. A. Zurndorfer, 1979: Automated guidance for predicting quantitative precipitation. *Monthly. Weather Review*, **107**, 122-128.

Berbery, E., E. Rasmusson, and K. Mitchell, 1996: Studies of North American continental-scale hydrology using Eta model forecast products. *J Geophys. Res*., **101**, 7305-7319.

Black, T. L., 1994: The new NCEP mesoscale Eta model: Description and forecast examples. *Weather and Forecasting*, **9** (2), 265-278.

Borneman, R., 1988: Satellite rainfall estimating programs of the NOAA/NESDIS Synoptic Analysis Branch. *National Weather Digest*, **13**, 7-15.

Breidenbach, J. P., D. -J. Seo, and R. Fulton, 1998: Stage II and III post processing of NEXRAD precipitation estimates in the modernized Weather Service. Preprints, *14th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 263-266.

Brier, G. W., 1950: Verification of forecasts expressed in terms of probability. *Monthly Weather Review*, **78**, 1-3.

Bulluck, H. T. , 1995: Probabilistic temperature and precipitation forecasts to support a customer's needs: A vendors perspective. Proceedings, *22nd Annual Conference on Integrated Water Resources Planning for the 21st Century*, American Society of Civil Engineers, pp 718-722.

Burks, J. E., and M. J. Staudenmaier, 1996: A comparison of the Eta and the Meso Eta models during the 11-12 December 1995 storm of the decade. WR-Technical Attachment 96-21, Salt Lake City, UT.

Carbone, R., 1997: The World Weather Research Program. *U.S. Weather Research Program Stakeholders Meeting*, National Center for Atmospheric Reseach, Boulder, CO, 15-16 April, 1997.

Charba, J. P., 1983: Experiments in 0-9 hour objective quantitative precipitation forecasting. Preprints, *5th Conference on Hydrometeorology*, Tulsa, American Meteorological Society, 269-278.

Charba, J. P., 1985: Climatological relative frequencies of six-hour precipitation amount over the conterminous United States. Preprints, *6th Conference on Hydrometeorology,* Indianapolis, American Meteorological Society, 1-8.

Charba, J. P., 1987: Features of an operational 0-6 and 3-9 h system for forecasting heavy precipitation amounts. Preprints, *7th Conference on Hydrometeorology*, Edmonton, American Meteorological Society, 137-142.

Charba, J. P., 1992: Estimates of hourly precipitation amount from routine observations of current weather. Post-Prints, *Third National Heavy Precipitation Workshop*, Pittsburgh, National Weather Service, NOAA, U.S. Department of Commerce, 81-93.

Charba, J. P., A. W. Harrell, III, and A. C. Lackner, III, 1992: A monthly precipitation amount climatology derived from published atlas maps: Development of a digital database. TDL Office Note 92-7, National Weather Service, NOAA, U.S. Department of Commerce, 20 pp.

Charba, J. P., 1998a: Evaluation of LAMP quantitative precipitation forecasts. Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 440-442.

Charba, J. P., 1998b: The LAMP QPF product. Part I: The model development. *Weather and Forecasting* (in press).

Charba, J. P., Y. Liu, M. H. Hollar, B. E. Exley, and A. Belayachi, 1998a: Gridded monthly climatic frequencies of precipitation amount for 1-, 3-, and 6-h periods over the conterminous United States. *Weather and Forecasting*, **13**, 25-57.

Charba, J. P., A. Belayachi, and B. E. Exley, 1998b: The LAMP QPF product. Part II: The model performance. Manuscript in preparation.

Chen, F., K. Mitchell, Z. Janjic, and M. Baldwin, 1996a: Land-surface modeling progress in the NCEP mesoscale Eta model. Preprints, *11th Conference on Numerical Weather Prediction*, Norfolk, VA, American Meteorological Society, 19-23 August 1996, 257-258.

Chen, F., K. Mitchell, Z. Janjic, and M. Baldwin, 1996b: Land-Surface Modeling Progress for GCIP in the NCEP Mesoscale Eta Model. Preprints, *2nd International Scientific Conference on the Global Energy and Water Cycle*, Washington, DC, 17-21 June 1996, 228-229.

Chen, F., and K. Mitchell, 1997: Simulation of global soil wetness by the land-surface model in the NCEP mesoscale Eta model. Preprints, *13th Conference on Hydrology*, Long Beach, CA, American Meteorological Society, 2-7 February 1997.

Chen, F., K. Mitchell, Z. Janjic, M. Baldwin, 1997: Coupling a land-surface model to the NCEP mesoscale Eta model. Preprints, *13th Conference on Hydrology*, Long Beach, CA, American Meteorological Society, February 2-7, 99-100.

Churma, M. E., and S. B. Smith, 1998: Evaluation of the AWIPS thunderstorm product. Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 472-474.

Corfidi, S. F., and K. E. Comba, 1989: The Meteorological Operations Division of the National Meteorological Center. *Weather Forecasting*, **4**, 343-366.

Cressman, 1959: An operational objective analysis system. *Monthly Weather Review,* **87,** 367-374.

Davis, R. S., and W. J. Drzal, 1991: The potential use of WSR-88D digital rainfall data for flash flood applications on small streams. *National Weather Digest*, **16**, 1-18.

Davis, R. S., 1993: AMBER: A prototype flash flood warning system. Preprints, *13th Conference on Weather Analysis and Forecasting*, Vienna, VA, American Meteorological Society, August 2-6, 379-383.

Davis, R. S., and P. Jendrowski, 1996: The operational areal mean basin estimated rainfall (AMBER) module. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, American Meteorological Society, 332-335.

Davis, R. S., 1998: Detecting time duration of rainfall: A controlling factor for flash flood intensity. Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 258-263.

Dallavalle, J. P., 1996: A perspective on the use of model output statistics in objective weather forecasting. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, VA, American Meteorological Society, 479-482.

Danaher, E. J., 1996: Ensemble forecasting - Early impressions and future prospects. Critical Path, Winter 1995-96, National Weather Service, Silver Spring, Md.

DiMego, G., M. Baldwin, T. Black, F. Chen, F. Mesinger, K. Mitchell, D. Parrish, E. Rodgers, and Q. Zhao, 1998: Enhancements to the operational "early" Eta analysis and forecast system at the National Centers for Environmental Prediction. Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 245-246.

Doran, J. A., W. P. Roeder, and Z. Toth, 1998: The AFGWC / 45 WS / NCEP ensemble test: An operational point verification of ensemble precipitation probability forecasts. Preprints, *12th Conference on Numerical Weather Prediction*, 11-16 January 1998, Phoenix, AZ, American Meteorological Society.

Du, J., S. L. Mullen, and F. Sanders, 1996: Short-range ensemble forecasting of quantitative precipitation. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, American Meteorological Society, J46-J49.

Du, J., S. L. Mullen, and F. Sanders, 1997: Short-range ensemble forecasting of quantitative precipitation. *Monthly Weather Review*, **125**, 2427-2459.

Duan, Q., J. C. Schaake, V. I. Koren, K. Mitchell, and F. Chen, 1997: A comparison study of calibrated and a priori parameters of land surface parameterizations: A case study for GCIP large-scale area southwest. Preprints, *13th Conference on Hydrology*, Long Beach, CA, American Meteorological Society, 2-7 February 1997, 101-104.

Eastern Region, 1990: Establishment of a Hydrometeorological Analysis and Support (HAS) Group at the Ohio River Forecast Center (OHRFC). National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 16 pp. plus figures.

Ehrendorfer, M., 1997: Predicting the uncertainty of numerical weather forecasts: A review. Submitted to Meteorologische Zeitschrift, Neue Folge.

Eilts, D. M., J. T. Johnson, E. D. Mitchell, S. Sanger, G. Stumpf, A. Witt, K. W. Thomas, K. D. Hondl, D. Rhue, and M. Jain, 1996: Severe weather warning decision support system. Preprints, *18th Conference on Severe Local Storms*, San Francisco, American Meteorological Society, 536-540.

Epstein, E. S., 1969: A scoring system for probability forecasts of ranked categories. *J. Appl. Meteor*, **8**, 985-987.

Erickson, M. C., 1996: Medium-range prediction of PoP and Max/Min in the era of ensemble model output. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, American Meteorological Society, J35-38.

Faich and Rose, 1979: Blizzard morbidity and mortality: Rhode Island, 1978. *American Journal of Public Health*, **69** (10), 1050-52.

Fair and Feit, 1978: The Blizzard of '78. *Mariners Weather Log*, **22** (4): 255-260.

Fenbers, M.J., 1993: HASQPF User's Guide, NOAA/Eastern Region, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 57pp.

Fenbers, M. J., 1995: WinQPF User's Guide. NOAA/Eastern Region Computer Programs NWS ERCP - 25MC, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 39pp.

Fread, D. L., R. C. Shedd, G. F. Smith, R. Farnsworth, C. N. Hoffeditz, L. A. Wenzel, S. M. Wiele, J. A. Smith, and G. N. Day, 1995: Modernization in the National Weather Service River and Flood Program. *Weather and Forecasting*, **10** (3) , 477-484.

Fread, D. L., 1998: A perspective on hydrologic prediction trends. Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J1-6.

Fread, D. L., J. Ingram, J. C. Schaake, and D. T. Braatz, 1999: Recent experience with ensemble streamflow prediction in the Des Moines River Basin. Preprints, *14th Conference on Hydrology*, Dallas, TX, January 10-15, American Meteorological Society, Boston, 4-7.

Friday, E. W. Jr., 1994: The modernization and associated restructuring of the National Weather Service: An overview. *Bulletin of the American Meteorological Society*, **75** (1), 43- 52.

Fritsch, J. M., R. A. House Jr., R. Adler, H. Bluestein, L. Bosart, J. Brown, F. Carr, C. Davis, R. H. Johnson, N. Junker, Y.-H. Kuo, S. Rutledge, J. Smith, Z. Toth, J. W. Wilson, E. Zipser, and D. Zrnic, 1998: Quantitative precipitation forecasting: Report of the eighth prospectus development team, U.S. Weather Research Program. *Bulletin of the American Meteorological Society*, **79** (2), 285-299.

Funk, T. W., 1991: Forecasting techniques utilized by the Heavy Precipitation Branch of NCEP during a major convective rainfall event. *Weather and Forecasting*, **6**, 548-564.

Fulton, R. A., J. P. Breidenbach, D. -J. Seo, D. Miller, and T. O'Bannon, 1998: The WSR-88D rainfall algorithm. *Weather and Forecasting*, **13**, 377-395.

Gandin, L. S. , and A. H. Murphy, 1992: Equitable skill scores for categorical forecasts. *Monthly Weather Review*, **120** (2), 361-370.

Gartner, W.E., M.E. Baldwin, and N.W. Junker, 1996: Regional analysis of quantitative precipitation forecasts from NCEP's early Eta and Meso-Eta models. Preprints, *15th Conference on Weather Analysis and Forecasting*, American Meteorological Society., Norfolk, VA, 169-171.

Gilbert, G. F., 1884: Finley's tornado predictions. *American Meteorological Journal*, **1,** 166-172.

Gillispie, M., 1993: The use of neural networks for making quantitative precipitation forecasts. NWS Southern Region Technical Attachment SR/SSD 93-42, Fort Worth, TX, 9 pp.

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

Glahn, H. R., A. H. Murphy, L. J. Wilson, and J. S. Jensenius, Jr., 1991a: Lectures and papers presented at the WMO training workshop on the interpretation of NWP products in terms of local weather phenomena and their verification, Wageningen, The Netherlands, World Meteorological Organization, Geneva, 340 pp.

Glahn, H. R., J. P. Charba, J. P. Dallavalle, and R. E. Saffle, 1991b: The production and use of quantitative precipitation forecasts in the modernized NWS and TDL's role in their production. TDL Office Note 91-06, National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 13 pp.

Glass, 1979: Health consequences of the snow disaster in Massachusetts, February 6, 1978. *American Journal of Public Health*, **69** (10): 1047-1049.

Gould, K., C. K. Mueller and J. W. Wilson, 1993: Rules for short-term forecast of thunderstorm initiation and evolution: Procedures for automation. Preprints, *13th Conference on Weather Analysis and Forecasting*, 621-626.

Graziano, T. M., 1998: The NWS end-to-end forecast process for quantitative precipitation information. Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J35-40.

Griffin, R., 1979: How Chicago coped (but barely) with the blizzard. *Fortune*, **99** (4), 36-38.

Gunderson, L. F., and R. Krzysztofowicz, 1999: Interface for displaying probabilistic river forecasts to decision makers. Preprints, *14th Conference on Hydrology*, Dallas, TX, January 10-15, American Meteorological Society, Boston, 39-42.

Hall, T., 1996: BRAINMAKER: A new approach to quantitative and probability of precipitation forecasting. NWS Southern Region Technical Attachment SR/HSD 96-2, Fort Worth, TX, 7 pp.

Helburn, N., 1982: Severe winter storms as natural hazards. *Great Plains - Rocky Mountain Geographical Journal*, **10** (1), 86-95.

Henkel A. and C. Peterson: 1996: Can deterministic quantitative precipitation forecasts in mountainous regions be specified in a rapid, climatologically consistent, and RFC-compatible manner with Mountain Mapper functioning as the tool for mechanical specification, quality control, and verification? Abstracts, *Fifth National Heavy Precipitation Workshop*, State College, PA, September 9-13, 1996, p 31.

Henry, S. G., C. K. Mueller and J. W. Wilson, 1996: Base-line statistical evaluation of the automated thunderstorm auto-nowcaster. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, American Meteorological Society, 344-346.

Henz, J. F., 1997: Probabilistic quantitative precipitation forecasts: Successes in Denver and Phoenix. Abstracts, *Second National Conference and Exposition of the National Hydrologic Warning Council*, St. Louis, MO, October 29-31, 1997, p 29.

Herr, H. D., and R. Krzysztofowicz, 1999: Hydrologic uncertainty processor for probabilistic river forecasting. Preprints, *14th Conference on Hydrology*, Dallas, TX, January 10-15, American Meteorological Society, Boston, 35-38.

Horel, J. D., J. Stiff, and L. B. Dunn, 1996: The evolution of winter storms over Utah as determined from the Utah mesonet. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, VA, American Meteorological Society, 52-53.

Janjic, Z., 1994: The step-mountain Eta coordinate model: Further development of the convection, viscous sublayer and turbulence closure schemes. *Monthly Weather* Review, **122**, 927-945.

Janjic, Z., T. L. Black, and G. DiMego, 1998: Contributions toward the development of a future community mesoscale model (WRF). Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 258-261.

Jendrowski, P., and R. S. Davis, 1998: Use of geographic information systems with the areal mean basin estimated rainfall algorithm. Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 129-133.

Johnson, J. T., K. Hondl, M. D. Eilts, M. Benner, J. W. Conway, V. Farmer, V. Ganti, M. Jain, Z. Jing, A. Jones, V. Lakshmanan, M. Lehman, R. J. Lynn, P. L. MacKeen, E. D. Mitchell, R. Rabin, T. M. Smith, P. L. Spencer, G. J. Stumpf, K. Thomas, M. Wee, A. Witt, A. Wyatt, and D. S. Zaras, 1998: Warning decision support system: The next generation. Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J25-28.

Johnson, N. L. And S. Kotz, 1970: Continuous Univariate Distributions. John Wiley & Sons, New York, pp. 250-267.

Junker, N. W., J.E. Hoke, and R.H. Grumm, 1989: Performance of NMC's regional models. *Weather and Forecasting,* **4,** 368-390.

Kelly, K. S, and R. Krzysztofowicz, 1996: A methodology for probabilistic river stage forecasting. Report to University Corporation for Atmospheric Research, COMET Cooperative Project, Subawards No. UCAR S94-43833 and S96-75677, 96 pp.

Kitzmiller, D. H., 1996: One-hour forecasts of radar-estimated rainfall by an extrapolative-statistical method. TDL Office Note 96-1, National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 26 pp.

Kitzmiller, D. H. and J. Sun, 1997: Probabilistic 0-3 hour rainfall forecasts from a radar extrapolative-statistical technique. Preprints, *28th Conference on Radar Meteorology,* Austin, TX, American Meteorological Society, P2.37-P2.38.

Kitzmiller, D. H., 1998: Probabilistic 0-3 hour rainfall forecasts form a satellite extrapolative-statistical technique. Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 453-455.

Koellner, W. H., 1998: Decision-making at water resources projects using the advanced hydrologic prediction system (AHPS). Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J13-17.

Krzysztofowicz, 1983: Why should a forecaster and a decision maker use Bayes' theorem? *Water Resources Research*, **19** (2), 327-336.

Krzysztofowicz, 1992: Bayesian correlation score: A utilitarian measure of forecast skill. *Monthly Weather Review,* **120,** 208-219.

Krzysztofowicz, R. and T. R. Drake, 1992: Probabilistic quantitative precipitation forecasts for river forecasting. Preprints, *Symposium on Weather Forecasting, 72nd Annual Meeting of the American Meteorological Society*, Atlanta, GA, American Meteorological Society, 66-71.

Krzysztofowicz, R., 1993: Probabilistic hydrometeorological forecasting system: A conceptual design. NOAA Technical Memorandum NWS ER-87, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 29-42.

Krzysztofowicz, R. and T. R. Drake, 1993: Usage of guidance products in preparing probabilistic QPFs for River Basins. NOAA Technical Memorandum NWS ER-87, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 43-50.

Krzysztofowicz, R., W. J. Drzal, T. R. Drake, J. C. Weyman, and L. A. Giordano, 1993: Probabilistic quantitative precipitation forecasts for river basins. *Weather and Forecasting*, **8** (4),424-439.

Krzysztofowicz, R., 1995: Recent advances associated with flood forecast and warning systems. *Reviews of Geophysics*, July Supplement, 1139-1147.

Krzysztofowicz, R., 1996: Probabilistic hydrometeorological forecast system. Cooperative Research Plan for the University of Virginia. Statement of Work. NOAA Grant Number NA67WD0486.

Krzysztofowicz, R., T. E. Adams, and T. Rossi, 1997: Probabilistic river stage forecasting. Final Report to University Corporation for Atmospheric Research, COMET Cooperative Project, Sub-awards No. UCAR S94-43833 and S96-75677, 1 January 1994 - 31 December 1996, 15 pp.

Krzysztofowicz, R, and T. A. Pomroy, 1997: Disaggregative invariance of daily precipitation. *Journal of Applied Meteorology*, **36** (6), 721-734.

Krzysztofowicz, R, and A. A. Sigrest, 1997: Local climatic guidance for probabilistic quantitative precipitation forecasting. *Monthly Weather Review*, **125**, 305-316.

Krzysztofowicz, R., 1998a: An integrated probabilistic hydrometeorological forecast system. Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J45-50.

Krzysztofowicz, R., 1998b: Probabilistic hydrometeorological forecasts: Toward a new era in operational forecasting. *Bulletin of the American Meteorological Society*, **79** (2), 243-251.

Krzysztofowicz, R., 1999: Bayesian theory of probabilistic river forecasting. Preprints, *14th Conference on Hydrology*, Dallas, TX, January 10-15, American Meteorological Society, Boston, 31-34.

Krzysztofowicz, R, and A. A. Sigrest, 1999a: Calibration of probabilistic quantitative precipitation forecasts. *Weather and Forecasting*, to appear.

Krzysztofowicz, R, and A. A. Sigrest, 1999b: Comparative verification of guidance and local quantitative precipitation forecasts: Calibration Analyses. *Weather and Forecasting*, to appear.

Kuligowski, R. J., 1996: An overview of NWS QPF products. TDL Office Note 96-3, National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 22 pp.

Kuligowski, R. J., 1997: An overview of National Weather Service quantitative precipitation estimates. TDL Office Note 97-4, National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 27 pp.

Kusselson, S. K., 1993: The operational use of passive microwave data to enhance precipitation forecasts. Preprints, *13th Conference on Weather Analysis and Forecasting*, Vienna, VA, American Meteorological Society, 434-438.

Larson, L. W., R. L. Ferral, E. T. Strem, A. J. Morin, B. Armstrong, T. R. Carroll, M. D. Hudlow, L. A. Wenzel, G. L. Schaefer, and D. E. Johnson, 1995: Operational responsibilities of the National Weather Service River and Flood Program. *Weather and Forecasting*, **10** (3), 465-476.

Lin, Y., K. Mitchell, J. Charba, M. Baldwin and E. Rogers, 1994: Assimilation of hourly rain gauge data into NCEP's Eta model. Preprints, *10th Conference on Numerical Weather Prediction*, Portland, OR, American Meteorological Society, 301-302.

Lin, Y., K. Mitchell, E. Rogers and G. DiMego, 1995: Impact of satellite moisture observations on forecasts made by NCEP's Eta model. Preprints, *14th Conference on Weather Analysis and Forecasting*, Dallas, TX, American Meteorological Society, 161-162.

Lin, Y., K. Mitchell, E. Rogers, and M. Baldwin, 1996a: Impact of hourly precipitation input on the NCEP Eta model. Preprints, *11th Conference on Numerical Weather Prediction*, Norfolk, VA, American Meteorological Society, 19-23 August 1996, 268-269.

Lin, Y., K. Mitchell, E. Rogers, and M. Baldwin, 1996b: Assimilation of hourly precipitation data and satellite-derived water vapor information to improve the water cycle components of NCEP's Eta model. Preprints, *2nd International Scientific Conference on the Global Energy and Water Cycle*, Washington DC, 17-21 June 1996, 230-231.

Lin, Y., E. Rogers, G. DiMego, K. Mitchell, and R. Aune, 1996c: Assimilation of GOES-8 moisture data into NCEP's Eta model. Preprints, *8th Conference on Satellite Meteorology*, Atlanta, GA, American Meteorological Society, 28 January - 2 February 1996, 518-520.

Lin, Y., K. Mitchell, E. Rogers, and M. Baldwin, 1997: Assimilation of hourly precipitation data to improve the water cycle components of NCEP's Eta model. Preprints, *13th Conference on Hydrology*, Long Beach, CA, American Meteorological Society, 2-7 February 1997, 52-53.

Linsley, R. K., M. A. Kohler, and J. L. H. Paulhus, 1975: Hydrology for Engineers, McGraw Hill, New York, 82-84.

Langland, R.H., Z. Toth, R. Gelaro, I. Szunyogh, M.A. Shapiro, S.J. Majumdar, R. Morss, G.D. Rohaly, C. Velden, N. Bond and C.H. Bishop, 1998: The North Pacific Experiment (NORPEX-98). Submitted to BAMS in December 1998.

Manikin, G., K. Mitchell, E. Rogers, and D.J. Stensrud, 1996: Predicting heavy rainfall events with the Kain-Fritsch convection scheme in the NCEP Mesoscale Eta Model. Preprints, *13th Conference on Hydrology*, Long Beach, CA, American Meteorological Society, 2-7 February 1996.

McCann, D. W., 1992: A neural network short-term forecast of significant thunderstorms. *Weather and Forecasting*, **7**, 525-534.

Mesinger, F., 1996: Improvements in precipitation forecasts with the Eta regional model at the National Centers for Atmospheric Prediction: The 48-km upgrade. *Bulletin of the American Meteorological Society,* **77**, 2637-2649.

Mesinger, F., R. Wobus, M. Baldwin, 1996: Parameterization of form drag in the Eta Model at the National Centers for Environmental Prediction. Preprints, *11th Conference on Numerical Weather Prediction*, American Meteorological Society, Norfolk, VA.

Mesinger, F., 1998: Quantitative precipitation forecasts of the "early" Eta model: An update. Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 184-186.

Meuller, C. K. and F. McDonough, 1996: Extrapolation of thunderstorm growth and decay based on storm characteristics and boundary layer convergence lines. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, American Meteorological Society, 355-357.

Miller, D., D. -J. Seo, J. P. Breidenbach, and R. Fulton, 1998: Evolution of the NEXRAD precipitation processing system (PPS) in the open systems era. Preprints, *14th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 259-262.

Mills, H. W. and R. Krzysztofowicz, 1998: Interactive software for probabilistic quantitative precipitation forecasting. Preprints, *14th International Conference on Interactive Processing Systems for Meteorology, Oceanography, and Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J12-16.

Mitchell, K., 1994: GCIP Initiatives in operational mesoscale modeling and data assimilation at NCEP. Preprints, *Fifth Conference on Global Change Studies,* Nashville, TN, American Meteorological Society, 23-28 January 1994.

Mitchell K., and F. Chen, 1997: Using the GEWEX/ISLSCP global soil wetness project to determine a land-surface data assimilation system for the NCEP mesoscale Eta model and GCIP. Preprints, *13th Conference on Hydrology*, Long Beach, CA, American Meteorological Society, 2-7 February 1996.

Murphy, A. H., 1971: A note on the ranked probability score. *J. Appl. Meteor.*, **10**, 155-156.

Nash, J. E. and J. V. Sutcliffe, 1970: River flow forecasting through conceptual models. Part I: A discussion of principles. *J. Hydrology,* **10,** 282-290.

National Oceanic and Atmospheric Administration, 1994: Natural Disaster Survey Report. The Great Flood of 1993. Washington, D. C., U.S. Department of Commerce, 281 pp.

National Oceanic and Atmospheric Administration, 1995: River and Flood Program. Washington, D.C.: U.S. Department of Commerce.

National Oceanic and Atmospheric Administration, 1996: National Implementation Plan for the Modernization of the National Weather Service. Department of Commerce, 182 pp. plus appendices.

National Oceanic and Atmospheric Administration, 1998a: Natural Disaster Survey Report. The Northeast Flood of 1996. Washington, D.C., U.S. Department of Commerce, 99 pp. plus appendices.

National Oceanic and Atmospheric Administration, 1998b: Natural Disaster Survey Report. The Northwest Flood of 1996. Washington, D.C., U.S. Department of Commerce, in preparation.

National Oceanic and Atmospheric Administration, 1998c: Service Assessment. The Ohio River Valley Flood of March 1997. Washington, D.C., U.S. Department of Commerce, 8 pp. plus appendices.

National Oceanic and Atmospheric Administration, 1998d: Service Assessment and Hydraulic Analysis. The Red River of the North 1997 Floods. Washington, D.C., U.S. Department of Commerce, 35 pp. plus appendices.

National Research Council, 1991: Opportunities in the Hydrologic Sciences. Committee on Opportunities in the Hydrologic Sciences, Water Science and Technology Board, Commission on Geosciences, Environment and Resources. Washington, D.C.: National Academy Press. 348 pp.

National Research Council, 1996: Toward a New National Weather Service -- Assessment of Hydrologic and Hydrometeorological Operations and Services. National Weather Service Modernization Committee, Commission on Engineering and Technical Systems. Washington, D.C.: National Academy Press. 51pp.

National Weather Service (NWS), 1982: National verification plan, Report of the National Verification Task Team.

National Weather Service, 1991a: Monthly and seasonal verification scores. Techniques Specification Package TSP-89-11, National Oceanic and Atmospheric Administration, Department of Commerce, 87 pp. plus appendices.

National Weather Service, 1992: NGM-based MOS Guidance: The FOUS 14/FWC Message. NWS Technical Procedures Bulletin No. 408, National Oceanic and Atmospheric Administration, Department of Commerce, 19 pp.

National Weather Service, 1993a: Multisensor Precipitation Analysis. Techniques Specification Package TSP 89-13-R1, National Oceanic and Atmospheric Administration, Department of Commerce.

National Weather Service, 1993b: Real-time gridded field analysis, NEXRAD Stage III precipitation mosaic. Techniques Specification Package TSP 90-01R-R1, National Oceanic and Atmospheric Administration, Department of Commerce.

National Weather Service, 1993c: NGM-based MOS Guidance for the Probability of Precipitation (PoP). NWS Technical Procedures Bulletin No. 409, National Oceanic and Atmospheric Administration, Department of Commerce, 14 pp.

North American Atmospheric Observing System (NAOS) Program, 1997: Draft Upper Air Observing System White Paper. National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 13 pp.

O'Bannon, T, 1998: The enhanced WSR-88D precipitation processing subsystem. Preprints, *14th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 267-270.

Office of Hydrology, 1996: Hydrometeorological Service Operations for the 1990's. National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 243 pp. plus appendices.

Office of Hydrology, 1997: Advanced Hydrologic Prediction System (AHPS): Demonstration of Modernized Hydrologic Services for the Des Moines River Basin, Iowa. Hydrologic Research Laboratory Publication #366. National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 19 pp. plus appendices.

Office of Meteorology, 1997: Summary of Natural Hazard Fatalities for 1995 in the United States. National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 12 pp.

Office of Systems Development, 1994: Algorithms for the Automated Surface Observing System (ASOS): Integrated Systems Laboratory (ISL) Office Note 94-4. National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 92 pp. plus appendices.

Olson, D. A., N. W. Junker, and B. Korty, 1995: Evaluation of 33 years of quantitative precipitation forecasting at NMC. *Weather and Forecasting,* **10,** 498-511.

Parrish, D., J. Purser, E. Rogers, and Y. Lin, 1996: The regional 3D-variational analysis for the Eta model. Preprints, *11th Conference on Numerical Weather Prediction*, American Meteorological Society, Norfolk, VA., August, 1996.

Perica, S., J. Schaake, and D. -J. Seo, 1999a: National Weather Service river forecast system (NWSRFS) operational procedures for using short and long range precipitation forecasts as input to ensemble streamflow prediction (ESP). Preprints, *14th Conference on Hydrology*, Dallas, TX, January 10-15, American Meteorological Society, Boston, 1-3.

Perica, S., M. Markus, J. Schaake, and D. -J. Seo, 1999b: Accounting for hydrologic model errors in ensemble streamflow prediction. Preprints, *14th Conference on Hydrology*, Dallas, TX, January 10-15, American Meteorological Society, Boston, 12-14.

Peroutka, M. R. and J. L. Partain; 1990: Making QPF forecasts on an ABT system. NOAA/Eastern Region computer program NWS ERCP - No. 10MC, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 31pp.

Rhea, J. O., 1998: Use and expansion of an objective orographic aid. Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, 283-286.

Roe, J., M. Glaudemans, C. Gobs, P. Taylor, and J. Zimmerman, 1998: Implementation of modernized hydrologic operations and services in the National Weather Service: Overview and status. Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J25-30.

Rogers, E., T. Black, D. Deaven, G. DiMego, Q. Zhao, M. Baldwin, N. Junker, and Y. Lin, 1996a: Changes to the operational "Early" Eta Analysis/Forecast System at the National Centers for Environmental Prediction. *Weather and Forecasting*, **11**, 391-413.

Rogers, E., D. Parrish, Y. Lin and G. DiMego, 1996b: The NCEP Eta data assimilation system: Tests with a regional 3-D variational analysis and continuous cycling. Preprints, *11th Conference on Numerical Weather Prediction*, American Meteorological Society, Norfolk, VA.

Ross, G. H., 1989: Model output statistics using an updatable scheme. Preprints, *11th Conference on Probability and Statistics in the Atmospheric Sciences*, Monterey, American Meteorological Society, 93-97.

Ross, G. H., 1992: Probability of precipitation using an updatable MOS model. Preprints, *12th Conference on Probability and Statistics in the Atmospheric Sciences*, Toronto, American Meteorological Society, 190-193.

Ross, G. H. and C. C. Strudwicke, 1996: Logistic regression using a Kalman Filter within an updatable MOS forecasting system. Preprints, *13th Conference on Probability and Statistics in the Atmospheric Sciences*, San Francisco, American Meteorological Society, 204-209.

Schaake, J. C., 1989: Importance of the HRAP grid to operational hydrology. *Proceedings of the United States/People's Republic of China Flood Forecasting Symposium/Workshop*, Portland, Ore., 29 March-4 April 1989, Pub. by Government Printing Office, 331-356.

Schaake, J. C., 1996: What are the Office of Hydrology's plans for probabilistic river forecasting? Abstracts, *Fifth National Heavy Precipitation Workshop*, State College, Pennsylvania, September 9-13, 1996, p 69.

Schaake, J. C. and L. W. Larson, 1997: A strategy for ensemble streamflow prediction (ESP). Preprints, *13th Conference on Hydrology*, Long Beach, CA, American Meteorological Society, Boston, J104-105.

Schaake, J. C. and L. W. Larson, 1998: Ensemble streamflow prediction: Progress and research needs. Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J19-24.

Schaake, J. C., D. -J. Seo, and S. Perica, 1999: Parameter estimation for short-range ensemble precipitation generation. Preprints, *14th Conference on Hydrology*, Dallas, TX, January 10-15, American Meteorological Society, Boston, 23-24.

Schaefer, J. T., 1990: The Critical Success Index as an indicator of warning skill. *Weather and Forecasting*, **5**, 570-575.

Schneider, R. S., N. W. Junker, M. T. Eckert, and T. M. Considine, 1996: The performance of the 29 km Meso Eta model in support of forecasting at the Hydrometeorological Prediction Center. Preprints, *15th Conference on Weather Analysis and Forecasting*, American Meteorological Society, Norfolk, VA. August, 1996.

Schwein, N., 1996: The effect of quantitative precipitation forecasts on river forecasts. NOAA Technical Memorandum NWS CR-110, U.S. Department of Commerce, 39 pp.

Scofield, R.A., 1984: The NESDIS operational convective precipitation estimation technique. Preprints, *10th Conference on Weather Analysis and Forecasting*, Clearwater Beach, FL, American Meteorological Society, 171-180.

Scofield, R.A., 1987: The NESDIS operational convective precipitation estimation technique. *Monthly Weather Review*, **115**, 1773-1792.

Scofield, R.A., and R. Achutuni, 1996: The satellite forecasting funnel approach for predicting flash floods. *Remote Sensing Reviews*, **14**, 251-282.

Scofield, R.A. and S. Kusselson, 1996: Quantitative precipitation forecasting (QPF) - the end-to-end forecasting process using satellite data and numerical weather prediction models. Preprints, *15th Weather Analysis and Forecasting Conference*, Norfolk, VA, August 19-23, 1996, American Meteorological Society, Boston, pp. J142 - 145.

Seo, D. -J., 1998a: Real-time estimation of rainfall fields using rain gage data under fractional coverage conditions. *Journal of Hydrology*, **208**, 25-36.

Seo, D. -J., 1998b: Real-time estimation of rainfall fields using radar rainfall and rain gage data. *Journal of Hydrology*, **208**, 37-52.

Seo, D. -J., 1998c: Real-time estimation of mean field bias in radar rainfall data. Submitted to *Journal of Hydrology*.

Seo, D. -J. and B. Finnerty, 1998: Simulation of precipitation fields in space and time from probabilistic quantitative precipitation forecasts. Preprints, *14th Conference on Probability and Statistics in the Atmospheric Sciences*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston.

Seo, D. -J., R. A. Fulton, and J. Breidenbach, 1998: Rainfall estimation in the WSR-88D era for operational hydrologic forecasting in the National Weather Service. Preprints, *Special Symposium on Hydrology*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J60-62.

Seo, D. -J., S. Perica, J. C. Schaake, and E. Welles, 1999: An ensemble precipitation processor (EPP) for generating precipitation ensembles for the next 24 hours. Preprints, *14th Conference on Hydrology*, Dallas, TX, January 10-15, American Meteorological Society, Boston, 21-22.

Shedd, R. C., and J. A. Smith, 1991: Interactive precipitation processing for the modernized National Weather Service. Preprints, *Seventh International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, New Orleans, LA, American Meteorological Society, Boston, 4 pp.

Shuman, F. G., 1989: History of numerical weather prediction at the National Meteorological Center. *Weather and Forecasting*, **4**, 286-296.

Smith, J. A., and W. F. Krajewski, 1991: Estimation of the mean field bias of radar rainfall estimates. *Journal of Applied Meteorology*, **30**, 397-412.

Smith, S. B. and M. E. Churma, 1996: An overview of the AWIPS thunderstorm product. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, American Meteorological Society, 297-300.

Smith, S. B., T. M. Graziano, R. A. Lane, W. O. Alexander, M. D. Eilts, D. W. Burgess, and J. Wilson, 1997: The system for convection analysis and nowcasting. *Briefing to NWS Senior Management at the February, 12, 1997, Modernization and Restructuring Meeting*, National Weather Service Headquarters, Silver Spring, MD.

Smith, S. B., T. M. Graziano, R. A. Lane, W. O. Alexander, M. D. Eilts, J.T. Johnson, J. W. Wilson, R. D. Roberts, D. W. Burgess, D. H. Kitzmiller, R. E. Saffle, R C. Elvander, S. M. Zubrick, J. T. Schaefer, S. J. Weiss, and D. A. Imy, 1998: The system for convection analysis and nowcasting (SCAN). Preprints, *Sixteenth Conference on Weather Analysis and Forecasting*, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, J22-24.

Stallings, E. A., and L. A. Wenzel, 1995: Organization of the River and Flood Program in the National Weather Service. *Weather and Forecasting*, **10** (3) , 457-464.

Stamus, P. A., T. W. Schlatter, R. J. Clark, and G. M. Wahl, 1997: The Regional Observation Cooperative. Preprints, *First Symposium on Integrated Observing Systems*, 2-7 February, 1997 Long Beach, CA, American Meteorological Society, Boston, pp. 120-124.

Stewart, K. G., 1995: Flood Warning Systems & Early Notification Procedures in Denver, Colorado. Preprints, *Current Issues in Total Flood Warning System Design*, Flood Hazard Research Centre, Middlesex University, London, England, UK, September 10-12, 1995.

Sullivan, B. E., 1993: The use of dynamical model guidance in short-range forecasting. Preprints, *13th Conference on Weather Analysis and Forecasting*, Vienna, VA, American Meteorological Society, 35-43.

Sweeney, T. L., 1992: Modernized areal flash flood guidance. NOAA Technical Memorandum NWS HYDRO 44. National Oceanic and Atmospheric Administration, Department of Commerce, 21 pp. plus appendices.

Toth, Z., and E. Kalnay: 1993: Ensemble forecasting at NMC: The generation of perturbations. *Bulletin of the American Meteorological Society*, **74**, 2317-2330.

Toth, Z., E. Kalnay, M. S. Tracton, R. Wobus, and J. Irwin: 1997: A synoptic evaluation of the NCEP ensemble. *Weather and Forecasting*, **12** (1), 140-153.

Toth, Z., Y. Zhu, T. Marchok, E. Kalnay, M. S. Tracton, and E. Kalnay, 1998: Verification of the NCEP global ensemble forecasts. Preprints, *12th Conference on Numerical Weather Prediction*, Phoenix, AZ, American Meteorological Society, Boston, 286-289.

Tracton, M. S., and E. Kalnay, 1993: Ensemble forecasting at NMC: Operational implementation. *Weather and Forecasting*, **8**, 379-398.

Tracton, M. S., R. Wobus, and Z. Toth, 1996: On the principles and operational utility of ensemble prediction. Preprints, *11th Conference on Numerical Weather Prediction*, Norfolk, VA, American Meteorological Society, Boston, J17-J18.

Tracton, M. S., J. Du, and H. Juang, 1998: Short-range ensemble forecasting (SREF) at NCEP/EMC. Preprints, *12th Conference on Numerical Weather Prediction*, Phoenix, AZ, American Meteorological Society, Boston, 269-272.

Tucker, D. F., 1997: Western United States surface mesonets. Preprints, *First Symposium on Integrated Observing Systems*, 2-7 February, 1997, Long Beach, CA, American Meteorological Society, Boston, MA.

Uccellini, L. W., P. J. Kocin, R. S. Schneider, P. M. Stokols, and R. A. Dorr, 1995: Forecasting the 12-14 March 1993 Superstorm. *Bulletin of the American Meteorological Society*, **76**, 183-199.

Uccellini, L. W., 1996a: Office of Meteorology 1996-2005 strategic operating plan. Office of Meteorology, National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, 56 pp. plus appendices.

Uccellini, L. W., 1996b: National Weather Service Requirements for the Operational Use of Weather Radar Data (Open Systems Architecture). Inter-Office Memorandum dated 16 December 1996, 11pp.

Uccellini, L. W., 1998: Summary of the October 7-10, 1997 Collaborative Science, Technology, and Applied Research (CSTAR) workshop. Inter-Office Memorandum dated March 4, 1998, 30 pp. plus attachments.

U.S. Army Corps of Engineers, 1996: U.S. Army Corps of Engineers Annual Flood Damage Report to Congress for Fiscal Year 1995. U.S. Army, 17 pp.

U.S. Global Change Research Program, 1997: Workshop on Climate Variability and Water Resource Management in the Southeastern U.S., U.S. Global Change Research Program, 74 pp.

Van Tress, M., and P. C. Manousos, 1996: Operational QPF verification at the Ohio River Forecast Center. *Eastern Region Training and Applications Note No. 9,* 16 pp.

Vicente, G., 1996: Algorithm for rainfall rate estimation using a combination of GOES-8 11.0 and 3.9 micron measurements. Preprints, *8th Conference on Satellite Meteorology and Oceanography*, Atlanta, GA, January 29 - February 2, 1996, American Meteorological Society, Boston, pp. 274 - 278.

Vicente, G., and R.A. Scofield, 1996: Experimental GOES 8/9 derived rainfall estimates for flash flood and hydrological applications. *The 1996 Meteorological Satellite Data User's Conference*, Vienna, Austria, September 16-20, 1996, 8 pp.

Vicente, G., and R.A. Scofield, 1997: Real-time rainfall rate estimates derived from the GOES-8/9 satellites for flash flood forecasting, numerical modeling, and operational hydrology. Preprints, *13th Conference on Hydrology*, Long Beach, CA, February 2 - 7, 1997, American Meteorological Society, Boston, pp. J115 - 118.

Vicente, G., R.A. Scofield, and W.P. Menzel, 1998: The operational GOES infrared rainfall estimation technique. *Bulletin of the American Meteorological Society*, **79**, 1883-1898.

Vicente, G., and R.A. Scofield, 1998a: Satellite rainfall estimates in real time for applications to flash flood watches and warnings, heavy precipitation forecasting and assimilation into numerical weather prediction models. Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, pp. 406-408.

Vicente, G. and R.A. Scofield, 1998b: Integration of satellite rainfall estimates and radar observations for flash flood watches and warnings, heavy precipitation forecasting, model assimilation and hydrological applications. Preprints, *2nd Symposium on Integrated Observing Systems*, Phoenix, AZ, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, pp. 12-15.

Vislocky, R. L. and J. M. Fritsch, 1995a: Improved model output statistics forecasts through model consensus. *Bulletin of the American Meteorological Society*, **76**, 1157-1164.

Vislocky, R. L. and J. M. Fritsch, 1995b: Generalized Additive Models versus linear regression in generating probabilistic MOS forecasts of aviation weather parameters. *Weather and Forecasting*, **10**, 669-680.

Wernly, D. R., and L. W. Uccellini, 1998: Storm forecasting for emergency response: Current status and future directions. *Storms*, R. A. Pielke, Jr., and R. A. Pielke, Sr., Eds., Routlege, in press.

Wilson, J. W. and C. K. Mueller, 1993: Nowcast of thunderstorm initiation and evolution. *Weather and Forecasting*, **8**, 113-131.

Xue, Y., F. Zeng, K. Mitchell, and Z. Janjic, 1996: The impact of land surface processes on the prediction of the hydrological cycle over the U.S.: A study using a coupled Eta/SSiB model. Preprints, *2nd International Science Conference on the Global Energy and Water Cycle,* Washington, DC, 17-21 June 1996, 73-74.

Zeng, F., Y. Xue, K. Mitchell, Z. Janjic, and E. Rogers, 1996: The impact of land surface processes on the regional weather prediction: A case study using a coupled Eta/SSiB model. Preprints, *11th Conference on Numerical Weather Prediction*, American Meteorological Society, Norfolk, VA, 19-23 August 1996, 262-263.

Zevin, S. F., 1994: Steps toward an integrated approach to hydrometeorological forecasting services. *Bulletin of the American Meteorological Society*, **75**, 1267-1276.

Zhang, M., and R. A. Scofield, 1994: Artificial neural network techniques for estimating heavy convective rainfall and recognizing cloud mergers from satellite data. *International Journal of Remote Sensing,* **15**, pp. 3241-3261.

Zhao, Q., T. L. Black, and G. J. DiMego, 1996a: Prognostic clouds and their impact on radiation calculation in the Eta Model at NCEP. Preprints, *2nd International Scientific Conference on the Global Energy and Water Cycle*. Washington, DC, 17-21 June 1996, 396-397.

Zhao, Q., T. L. Black, G. J. DiMego, K. Mitchell, and F. Chen, 1996b: Improved clouds and their impact on radiation calculation in the Eta model at NCEP. Preprints, *11th Conference. on Numerical Weather Prediction*, American Meteorological Society, Norfolk, VA, 19-23 August 1996, 368-369.

Zhao, Q., K. Campana, S. Saha, K. Mitchell, S. Moothi, Y. Hou, and P. Caplan,1996c: Incorporation and test of a prognostic cloud scheme in the Global Spectral Model at NCEP. Preprints, *11th Conference on Numerical Weather Prediction*, American Meteorological Society, Norfolk, VA, 19-23 August 1996, 338-339.

Zhu, Y., G. Iyengar, Z. Toth, M. S. Tracton, and T. Marchok, 1996: Objective evaluation of the NCEP global ensemble forecasting system. Preprints, *15th Conference on Weather Analysis and Forecasting*, American Meteorological Society, 19-23 August 1996, Norfolk, VA, J79-82.

Zhu, Y., Z. Toth, E. Kalnay, and M. S. Tracton, 1998: Probabilistic quantitative precipitation forecasts based on the NCEP global ensemble. Preprints, *16th Conference on Weather Analysis and Forecasting*, Phoenix, AZ, Phoenix, AZ, January 11-16, American Meteorological Society, Boston, pp. J8-11.