Improving Short-Term (0–48 h) Cool-Season Quantitative Precipitation Forecasting

Recommendations from a USWRP Workshop

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A Cool-Season Quantitative Precipitation Forecasting (CSQPF) workshop was convened to advise the U.S. Weather Research Program (USWRP) on the development of an implementation plan for improving cool-season quantitative precipitation forecasting (QPF). The workshop defined critical research activities and operational tests needed to advance short-term (0–48 h) QPF in the cool season, including snow and freezing rain. The workshop considered physical process studies, numerical weather prediction (NWP) and data assimilation methods, atmospheric observing systems, and the use and value of improved forecasts.

COOL-SEASON QUANTITATIVE PRECIPITATION FORECASTING WORKSHOP

WHAT: A meeting sponsored by the U.S. Weather Research Program brought together nearly 60 federal, private, and university scientists to develop a strategy to improve short-term cool-season QPF

WHEN: 2–5 February 2004

WHERE: Boulder, Colorado

The CSQPF community recommends implementation of a national Hydrometeorological Test Bed (HMT) strategy focused on improving cool-season QPF, including two long-term regional efforts that address key regional differences. One effort should

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focus on winter storms along the East Coast of the United States, with freezing rain, coastal cyclones (e.g., nor'easters), heavy snow, and lake-effect snow as priorities, that is, HMT-East. The other should focus on the West, with orographic effects, flooding, and water resources as priorities, that is, HMT-West.

It was concluded that probabilistic forecasts specifying the size, position, orientation, timing, amount, and type of precipitation should be provided to the user communities (e.g., water resources, transportation, emergency management, utilities). Probabilistic products specifying the location of boundaries separating precipitation types, and distinguishing regions of rain, snow, and mixed precipitation, are all desirable.

The Weather Research and Forecasting (WRF) system should be the focus of modeling efforts to improve cool-season QPF. Because early implementation of the ensemble Kalman filter (EnKF) technique is risky, and a decision to embrace four-dimensional variational data assimilation (4DVAR) is expensive, the recommended course for the near term is continued enhancement of three-dimensional variational data assimilation (3DVAR) techniques, while EnKF and 4DVAR are explored further.

The socioeconomic impacts of winter weather are often underappreciated. In the populated northeast corridor of the United States, for example, winter cyclones annually shut down basic transportation and public services. The 1998 northeast ice storm produced several billion dollars in damage, with power out for more than a month in parts of Canada. A lake-effect storm produced more than 80 inches of snow locally in Buffalo, New York, in 2000. Western states face major challenges from heavy winter rain and snow, which commonly close major roadways and can cause severe flooding, such as the California floods of 1997, which produced more than 40 inches of rain, inundated large areas, and caused greater than $1 billion in damage. Nationally, nearly 7,000 deaths, 600,000 injuries, and 1.4 million accidents per year are due to adverse road weather, mostly during winter (Goodwin 2003).

Figure 1 illustrates current QPF skill of the Eta and Global Forecast System (GFS) models and the Hydrometeorological Prediction Center (HPC) as a function of month of the year, as measured by the threat score (Olson et al. 1995). The cool-season QPF skill exceeds that of the warm season by about a factor of 2, primarily due to the limited predictability of convective precipitation. However, these statistics do not tell the full story—in winter, qualitative precipitation forecasts can be as significant as quantitative forecasts. A minor freezing drizzle event can cause traffic havoc and highway disasters at rush hour in a major city. Minor ice accumulation at an airport hub can clog the air transportation system nationwide. Other factors combine with the quantity of precipitation in determining the severity of a winter event. For example, the devastation of a major ice storm is increased dramatically if strong winds follow the period of ice accumulation. Nevertheless, we should be reasonably optimistic that because of the higher skill scores in winter, incremental increases in QPF scores in the cool season driven by research, test bed experimentation, improved data assimilation techniques, and numerical weather prediction (NWP) can provide the users of these forecasts with better decision-making capability. These incremental increases have the potential to lead to significant improvements in public safety and the protection of property.

Can the impacts of winter storms be mitigated by improved forecasts? The answer is clearly yes. For example, the U.S. Army Corps of Engineers has explored using QPF to guide an experimental anticipatory release program for Folsom Dam on the American River. If reliable QPF becomes available, the dam can retain 60,000 additional acre-feet of water for summer use within the reservoir and still protect the downstream areas in the event of extreme precipitation. The Federal Highway Administration recently convened a National Research Council (NRC) panel to examine the impacts of adverse road weather and develop a strategy to reduce these impacts. Key to this NRC report was the recognition of the need for improved cool-season QPF. This report illustrates several examples where maintenance decisions could be improved through more precise (timing, location, and intensity) QPF associated with hazardous winter weather. The Federal Aviation Administration has

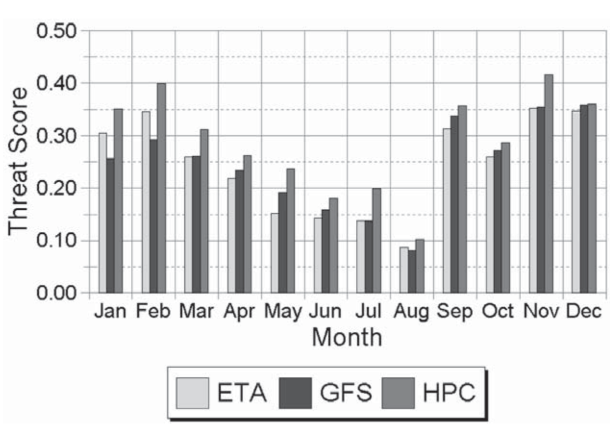


Fig. 1. Hydrometeorological Prediction Center QPF verification threat score for 1 inch of precipitation during 2003.

funded the development of a decision support system to improve safety and mitigate the impact of winter weather on aircraft delays caused by deicing. Recent studies have shown that the liquid equivalent of snow is the most critical parameter impacting safety due to the dilution of deicing fluids. Better snowfall-rate forecasts will improve decision making regarding aircraft deicing, which, in turn, will benefit both safety and airport capacity and efficiency.

The U.S. Weather Research Program (USWRP), recognizing the critical importance of short-term (0–48 h) cool-season QPF, sponsored the CSQPF workshop in February 2004 to help develop a plan for improving short-term cool-season QPF. The goals of the workshop were to define critical research activities required to advance short-term quantitative precipitation forecasts during the cool season, to consider the development of NWP and data assimilation systems relevant to the cool-season problem, to propose and assess various methods for observing the atmosphere on scales necessary to provide improvements in cool-season precipitation forecasts, and to examine the use and value of the improved

Table 1. Participants in the USWRP Cool-Season QPF workshop.

James Arnold, NASA/Marshall Space Flight Center (MSFC)	Greg Poulos, UCAR/Atmospheric Technology Division (ATD)
Robert Atlas, NASA/Goddard Space Flight Center (GSFC)	Paul Pugner, U.S. Army Corp of Engineers
Stan Benjamin, NOAA/Forecast System Laboratory (FSL)	Marty Ralph, NOAA/ETL
Dave Caldwell, National Centers for Environmental Prediction (NCEP)	Roy Rasmussen, NCAR
Brian A. Colle, State University of New York (SUNY) at Stony Brook	Bob Rauber, University of Illinois at Urbana—Champaign
Edwin Danaher, NWS/NCEP/HPC	Pedro Restrepo, NWS Office of Hydrology
Russ Elsberry, Naval Postgraduate School	David Reynolds, NWS Forecast Office, San Francisco, CA
Gary Estes	Diana Roth, NOAA/CIRES
Bob Gall, NCAR	Steve Rutledge, Colorado State University
John Gaynor, USWRP Program Office	John Schaake, NOAA/NWS
Jim Giraytys, USWRP Integrated Program Office (IPO)	Tom Schlatter, NOAA/FSL
Rod Gonski, NWS, Raleigh, NC	David Schultz, CIMMS, and NOAA/NSSL
Jonathan Gourley, Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) National Severe Storms Laboratory (NSSL)	Paul Schultz, NOAA/FSL
Arthur Henkel, NOAA/River Forecast Center (RFC), Sacramento, CA	Mel Shapiro, NOAA
Mark Hjelmfelt, South Dakota School of Mines and Technology	Jim Steenburgh, University of Utah
Steve Hunter, U.S. Bureau of Reclamation	Andrew Stern, Mitretek Systems
Brian Jewett, University of Illinois at Urbana–Champaign	Ronald Stewart, McGill University
Pam Johnson, NCAR	Ed Szoke, NOAA/FSL, and Cooperative Institute for Research in the Atmosphere (CIRA)
David Jorgensen, NOAA/NSSL	Zoltan Toth, Environmental Modeling Center (EMC)
Matthew Kelsch, University Corporation for Atmospheric Research (UCAR)/Cooperative Program for Operational Meteorology, Education and Technology (COMET)	Steve Tracton, Office of Naval Research (ONR)
David Kingsmill, NOAA/CIRES	Jeff Trapp, Purdue University
Steven E. Koch, NOAA/FSL	Louis Uccellini, NOAA/NCEP
Ruby Leung, Pacific Northwest National Laboratory (PNNL)	Steve Vasiloff, NOAA/NSSL
Bill Mahoney, NCAR	Jeff Waldstreicher, NOAA/NWS
John Marwitz, Wyoming Weather, Inc.	Doug Wesley, UCAR/COMET
Douglas K. Miller, Naval Postgraduate School	Allen White, NOAA/ETL/CIRES
Rebecca Morss, NCAR	Gary A. Wick, NOAA/ETL
Paul J. Neiman, NOAA/Environmental Technology Laboratory (ETL)	James Wilczak, NOAA/ETL
Dave Parsons, NCAR	Milija Zupanski, Colorado State University
Paul Pisano, Federal Highway Administration	

forecasts. Roughly half of the workshop was devoted to discussions in working groups. Table 1 lists workshop participants (with full name and affiliation); working group members are footnoted within the article.

One of the goals charged to the CSQPF workshop was to conceive of test beds and focused field experiments to address the cool-season QPF problem. The USWRP and others have embraced the concept of test beds. Results from existing test beds indicate that their goal of accelerating the transition of research into improved operational prediction can be realized when a test bed focuses on a particular phenomenon and/or region. Examples are the Joint Hurricane Test Bed (JHT) started in 2001, and the HMT started in 2003. A recent workshop on Mesoscale Observing Systems held in Boulder, Colorado, in December 2003 dedicated a workshop group to define the key elements that distinguish a test bed from more traditional research programs (Dabberdt et al. 2005). The following consensus definition emerged from that workshop:

> A test bed entails a working relationship in a quasi-operational framework among forecasters, researchers, the private sector, and government agencies aimed at solving operational and practical regional problems with a strong connection to end-users. Outcomes are improved services, products, and economic/public safety benefits. It must accelerate the testing and transition of R&D to better operations, services, and decision-making. This will require long-term commitments and partnerships.

Test beds should be established in areas that can leverage existing partnerships between researchers, operations, and stakeholders, each with a vested interest in seeing that their investments translate to improved decision making. They also should be established with a baseline of observing tools designed to meet the minimum objectives of the program. Lead agencies and the stakeholders would fund the test beds. In a test bed, the baseline or "backbone" set of observing systems would need to be periodically augmented during intensive field programs that would be designed to address specific challenges that have been identified during routine test bed operations. Figure 2 is a hypothetical time line that shows how occasional focused field experiments fit into the ongoing test bed framework.

Based on the consensus from each working group, this report recommends the implementation of a National Hydrometeorological Test Bed strategy as a means to address the cool-season QPF challenges. This paper, based on the charges to and inputs from the four working groups at the workshop, summarizes the full implementation plan submitted to USWRP in May 2004 (Rauber and Ralph 2004). Following sections summarize key findings of each working group, and overarching recommendations are presented in "Possible cool-season HMT interagency field studies."

PHYSICAL PROCESSES ASSOCIATED WITH COOL-SEASON PRECIPITATION AND ITS PREDICTABILITY.

Working Group 1[1] addressed the physical processes associated with winter precipitation and its predictability. Key processes and phenomena related to cool-season precipitation systems span a wide range of spatial and temporal scales. The group identified the following five key research areas:

- 4D structure of systems above the boundary layer (i.e., in the free troposphere),
- the rain–freezing rain–snow transition region,
- regional mesoscale boundary layer forcing (particularly orographic and lake effects),
- moisture sources and transport into winter systems,
- predictability of cool-season precipitation.

Most of these processes and phenomena are tied to extratropical cyclones, which themselves originate in response to processes at longer time and space scales. A major challenge of cool-season QPF is to determine the spatial and temporal variability of precipitation within extratropical cyclones. The variability in the location and intensity of precipitation is often determined by precipitation banding and/or embedded convection on scales of approximately 5–200 km (Novak et al. 2004). There are several scientific questions that need to be addressed to improve forecasts of these precipitation substructures, as follows:

- What are the predominant spatial patterns of organized precipitation features associated with free-troposphere disturbances and how do they evolve? How do frontal-scale systems above the boundary layer, such as warm fronts, trowals, and cold fronts aloft, relate to these precipita-

[1] Working Group 1 leaders: Waldstreicher and Stewart; members: Colle, Gonski, Henkel, Hjelmfelt, Koch, Luang, Marwitz, Miller, Neiman, Polous, D. Schultz, Szoke, and Tracton.

tion substructures? What are the thermodynamic and kinematic structures of these free-atmosphere frontal systems (particularly the vertical distribution of moisture and vertical motion)? What instabilities and types of mesoscale forcing [e.g., moist conditional symmetric instability (CSI), moist frontogenesis, gravity waves, and elevated upright convection] are controlling the generation and evolution of these precipitation substructures?

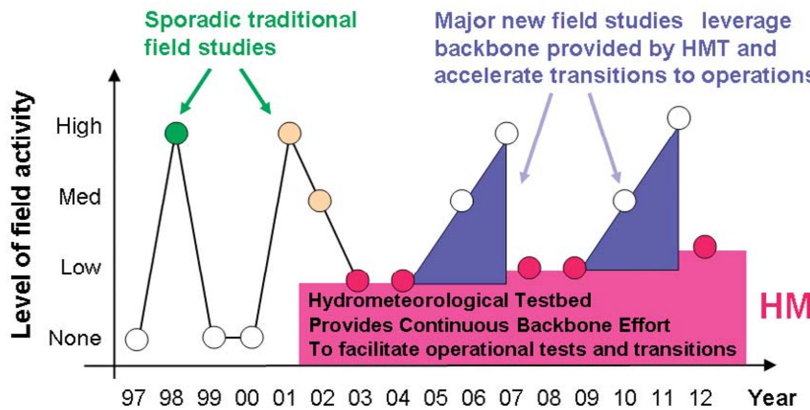


FIG. 2. Concept of how a test bed with periodic intensive field studies differs from traditional field programs.

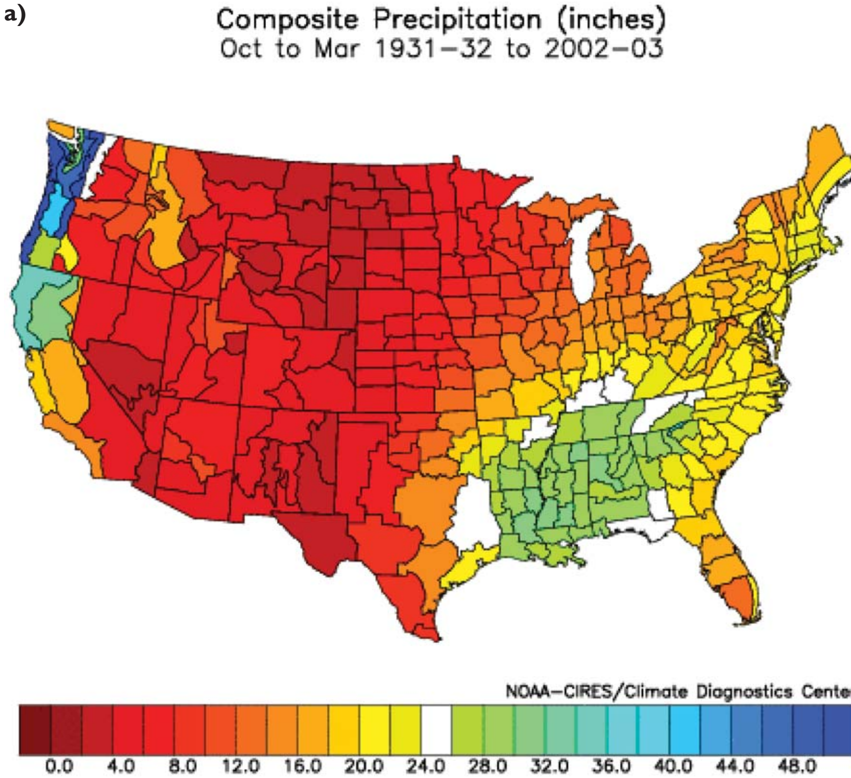
- Is instability with respect to ice a critical issue in some of these instances, and is it through precipitation-related effects that instabilities can be maintained?
- To what extent are precipitation bands predicted by the models, and are the forecasts "believable?" Are bands depicted in a model an effect of dynamical downscaling or are they dependent on initial conditions?
- How do microphysical processes vary between the different precipitation substructures and what are the consequences?
- Although the banded structures discussed here are those generated in the free atmosphere, does orography play a role in establishing the environment in which these bands can develop?
- How does the predictability of banding depend on forcing? Are atmosphere instabilities and gravity waves inherently less predictable than bands forced by fronts or mountains?

An important distinction between winter and summer storms is the form of the ensuing precipitation. Winter storms typically produce a wide variety of precipitation types (rain, snow of varying density, wet snow, ice pellets, freezing rain, drizzle, and freezing drizzle), and the impacts of the storms are often linked with the precise nature of this precipitation. The transition zones between these regions are key areas of interest, both scientifically and practically. While the storm-scale thermal field, particularly the distribution and intensity of warm-air advection, determines the general location of this region, the phase changes associated with this variety of precipitation types modifies the larger-scale atmospheric temperature and moisture distributions, which can initiate secondary mesoscale circulations. The transition zone is also strongly affected by surface conditions, including terrain slope, temperature relative to freezing, snow cover, and sensible and latent heat fluxes (e.g., land versus water). Large water bodies can impact winter precipitation through heat and moisture fluxes from open or partially ice-covered surfaces. Such fluxes can alter the intensity of systems, modify frontal and banded features, and, in the case of the Great Lakes, alter the subsynoptic environment (Sousounis and Fritsch 1994).

Some of the most profound influences on winter precipitation are associated with mountains (e.g., Cotton and Anthes 1989). The Rocky Mountains, Western Coastal Ranges (Sierra Nevada, Cascades), and the Appalachians are all responsible for generating heavy orographic rain and snow, but each has unique regional cool-season QPF problems. The Sierra Nevada represents one of the largest such barriers with respect to its height and lateral extent, and heavy rainfall and snowfall are commonly produced on their upslope side as a consequence (Fig. 3). Smaller-scale topographic features can induce similar perturbations to precipitation amounts and types. Some of these include flows over sloping terrain, in general, cold air damming along the lee slopes of ranges, such as the Appalachians (Bailey et al. 2003), that can lead to increased likelihood of freezing rain, and coastal effects on precipitation banding (Neiman et al. 2004). Small-scale topographic barriers can also have a profound impact on precipitation distributions downstream due to rain-shadowing effects (Ralph et al. 2003) and gravity waves (Koch and O'Handley 1997). Although the general nature of such factors is appreciated, the precise means through which precipitation is produced and altered under such conditions are still uncertain, because it requires understanding both the moist dynamics and microphysics within orographic clouds.

On the large scale, the bulk transport of moisture by midlatitude storm systems (e.g., Ralph et al. 2004) can have a substantial impact on the organization and distribution of precipitation. The source regions for this transport, which include the tropical and subtropical Pacific Ocean, the Gulf of Mexico, the Caribbean, and the subtropical Atlantic Ocean, are not well observed. The interactions of these moisture streams with developing cyclones are not fully understood and are often not simulated well by operational NWP. To what extent this is a function of the ability to accurately simulate the physical processes, or is primarily a result of inadequate initializations, is not clear. In addition, the upscale impacts of deep convection on developing systems, particularly with respect to the distribution and transport of water vapor, are a significant challenge.

a)



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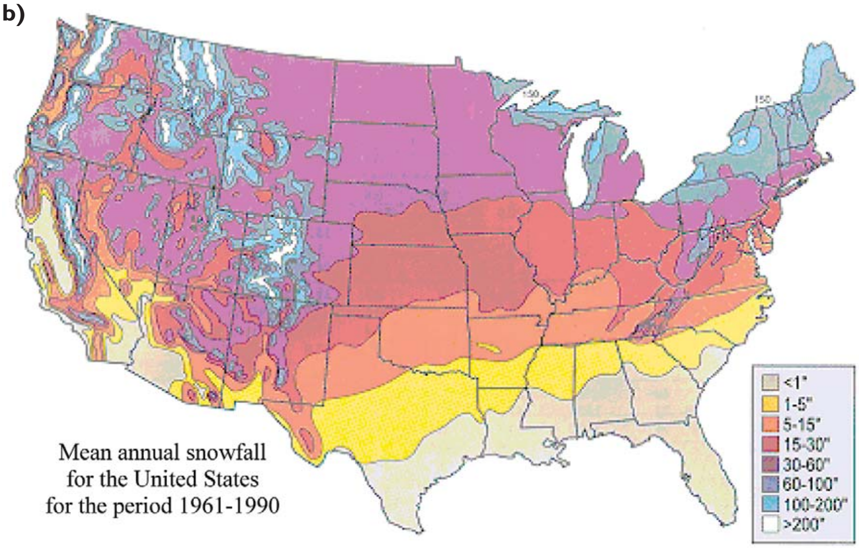

Because of the overarching nature of predictability issues, the cool-season QPF goals are to 1) provide realistic estimates of potential and actual predictability limits; 2) identify, describe, quantify, and understand the origin and nature of uncertainties, that is, forecast errors, as they evolve in time and space; 3) provide guidance for setting priorities in developing observational and modeling strategies to minimize uncertainties, and, hence, close the gap between predictability in principle and practice; and 4) communicate information on uncertainties into operational predictions for incorporation into risk analysis and decision making. Attaining these goals is meaningful to the extent they are viewed as a function of the space and time scales of relevant phenomena, the operative physical and dynamical mechanisms, and specific situations of importance (e.g., location, topography, and user-specific scenarios).

DATA ASSIMILATION AND MODELING.

Working Group 2[2] was concerned with data assimilation and modeling. The working group limited its c)

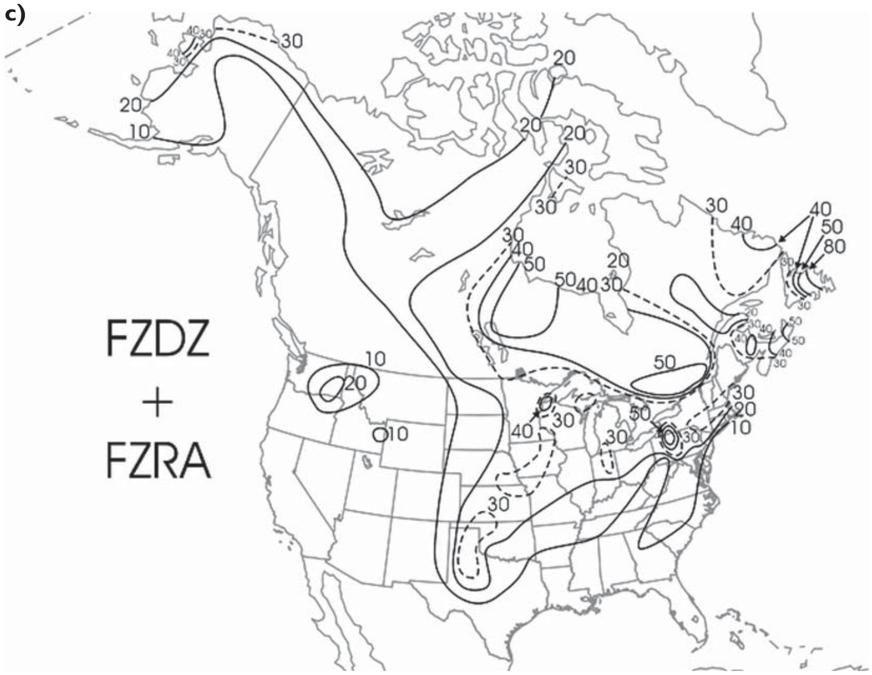

FIG. 3. Distribution of (a) cool-season precipitation (inches), (b) snowfall (inches), and (c) the average number of hours per year with freezing precipitation (FZDZ = freezing drizzle; FZRA = freezing rain). [Figures from NOAA/Cooperative Institute for Research in Environmental Sciences (CIRES), the Colorado State University Climate Center, and Cortinas et al. (2004), respectively.]

discussion to short-term forecasts of cool-season precipitation with a strong emphasis on mesocale phenomena. The group focused on improvements in short-term wintertime forecasts of precipitation type and amount, and examined the roles of observations, data assimilation, model physics, and ensemble techniques in effecting these improvements.

The most fundamental question for U.S. efforts in data assimilation is much broader than simply regarding the cool-season QPF—which path should be followed in the next five years or so: a continuation of three-dimensional variational data assimilation (3DVAR) which is the current operational practice, or a transition to either four-dimensional variational data assimilation (4DVAR) or an ensemble Kalman filter (EnKF) technique? The 3DVAR technique is nearly independent of the assimilating model and requires only modest computing resources. It operates intermittently and could even be used subhourly. Its major drawbacks are that it does not automatically produce a balanced initial state, and the appropriate dynamical constraints are unknown for mesoscale flows. The 4DVAR technique is already operational in Europe and has resulted in significant improvement in global forecasts. The 4DVAR technique fits a model evolution to a time series of observations. It produces a state that is balanced with respect to the assimilating model. Its drawback is its huge computational load. The EnKF method is still experimental. In theory, the method can generate its own background error statistics. In 3DVAR and 4DVAR, the background error statistics must be independently specified, sometimes without sound scientific justification. EnKF does not need balance constraints. The method also leads naturally to ensemble forecasting in that it generates multiple initial states. Its drawbacks are that it still requires significant development and its testing in realistic applications has been very limited. Because early implementation of EnKF is risky and a decision to embrace 4DVAR is very expensive, the course recommended by the working group for the next two or three years is for the continued enhancement of 3DVAR techniques while the pros and cons of EnKF and 4DVAR are more thoroughly explored.

Any recommendations for improvements in data assimilation and modeling techniques specific to the cool season must first examine the most common forecast failures. The group agreed that the most serious problem associated with wintertime QPF is the accurate determination of precipitation type when the surface temperature is near freezing. Snow, partially melted snow, ice pellets, freezing rain, and rain can all fall within a short distance. This mixture of precipitation usually results in serious travel delays, if not life-threatening hazards, whenever it occurs, sometimes even when precipitation is light. Thus, it is vital to predict the size, position, orientation, and timing of the mixed-precipitation region accurately,

[2] Working Group 2 leaders: Jewett and Schlatter; members: Atlas, Benjamin, Colle, Elsberry, Koch, Jorgensen, Schaake, Toth, Uccellini, Wilczak, and Zupanski.

as well as the boundaries that separate the different precipitation types. Other cool-season phenomena, such as heavy snow and reduced visibility in blizzards, also merit consideration because they are difficult to forecast and lead to disruptions in travel and commerce.

The group agreed that the most important problem to be addressed is forecasting precipitation type. This is primarily a problem in physics rather than in dynamics. Prescriptions for the following processes should be improved in the following priority order:

- cloud microphysics: the thermodynamic conditions and presence of microscopic particulates within a cloud determine the origin and subsequent growth of hydrometeors;
- boundary layer: winds in the subcloud layer transport hydrometeors laterally, and changes of phase can strongly alter the subcloud temperature and humidity profiles;
- land surface: antecedent conditions at and near the ground affect the potential for freezing rain;
- convection: when near-surface temperature is just above freezing the intensity of precipitation can mark the difference between rain and snow.

The second most important problem to address is the lack of observations in the wintertime boundary layer, especially moisture and, to a lesser extent, winds. Together, these measurements define moisture flux convergence, which is the basis for precipitation. The assimilation of these data is not necessarily straightforward when the observed parameter is not a model variable, for example, the column water vapor, as obtained from satellite or ground-based GPS measurements, satellite cloud observations, or radar reflectivity. These observations and their assimilation are relevant to precipitation amount and, hence, bear directly on the accuracy of flood forecasts.

The group acknowledged the importance of ensemble forecasting in that it can provide a measure of uncertainty, or even error bars, on the forecast. Improvements in ensemble forecasting are being pursued vigorously. Receiving much less attention is the representation of uncertainties in the observations that are used to verify model forecasts. As an example, the distribution, amount, and timing of precipitation are still subject to large uncertainty, even with automated rain gauges and a network of Doppler radars. The uncertainties in precipitation estimates must be conveyed to hydrological models to help predict a range of probable streamflows.

One can quantify the effects on forecasts of observing systems, assimilation methods, and model improvements in the following several ways:

- Observation impact tests: Run a data assimilation and prediction system with or without a particular source of observations, and measure the effect on forecast accuracy. Such tests are applicable to observing systems undergoing field testing, but good data coverage and at least a modest number of observations are necessary to demonstrate impact.
- Observing system simulation experiments (OSSEs): Simulate a hypothetical observing system along with existing observing systems and see how the addition of the former alters the forecast. Whether conducting observation impact tests or OSSEs, one should concentrate on high-impact and difficult-to-forecast weather events.
- Better verification methods appropriate for the mesoscale, for example, feature-based verification: Choose a particular phenomenon and measure in detail over dozens of occurrences how successfully the model forecasts it. Consistent error patterns can point the way toward model improvements. Measures relating to the timing, intermittency, intensity, character, position, and spatial coverage of predicted and observed mesoscale features could also be improved.

The group identified two key areas of interest—one related to specific phenomena, the other user based. Nonstandard verification measures are needed, including those related to phenomena such as the feature tracking of cyclones or jet streaks, size and orientation of mesoscale precipitation bands, depth of a cold air mass, precipitation type, warm-frontal overrunning, depth of convective layers in lake-effect snow events, cold-air damming, erosion of stagnant cold air by strong winds above the inversion, and location of transition boundaries within areas of mixed precipitation.

OBSERVING SYSTEMS. Working Group 3[3] was charged with assessing various methods for observing the atmosphere on scales necessary to improve cool-season QPF in the 0–48-h time range.

Although it was recognized that there are significant cool-season QPF issues across much of

[3] Working Group 3 leaders: Kingsmill and Reynolds; members: Arnold, Danaher, Giratys, Gourley, Henkel, Steenburgh, Stern, Trapp, Vasiloff, White, and Wick.

Table 2. Observing systems to be applied to cool-season QPF with a test bed approach.	Nowcasting	Assimilation	Validation	Stage of development
In situ				
Precipitation gauges	✓	✓	✓	Mature
Stream gauges	✓		✓	Underway
Snow depth	✓	✓	✓	Early
Ice accretion	✓		✓	Early
Hydrometeor types	✓		✓	Early
Sondes (rawin-, drop-)	✓	✓	✓	Mature
Commercial aircraft (ACARS) (T, T_d, u, v, w)	✓	✓	✓	Underway
Unattended aerial vehicles (UAVs) (T, T_d, u, v, w)	✓	✓	✓	Early
Surface nets (T, T_d, u, v, rad, T_{surf}, $T_{subsurf}$, soil moisture)	✓	✓	✓	Mature
Buoys (T, T_d, u, v, SST)	✓	✓	✓	Mature
Remote ground based				
WSR-88D [reflectivity, wind, quantitative precipitation estimation (QPE)]	✓	✓	✓	Mature
Polarimetric upgrade to WSR-88D	✓	✓	✓	Underway
(QPE, precipitation type, refractivity)				
Multifrequency radars (QPE, precipitation type)	✓		✓	Early
Vertically pointing S-band radar (reflectivity, fall speed)	✓	✓	✓	Mature
Gap-filling radar: Terminal Doppler Weather Radar (TDWR)	✓	✓	✓	Mature
Gap-filling radar: Airport Surveillance Radar (ASR), ETL, Collaborative Adaptive Sensing of the Atmosphere (CASA)	✓	✓	✓	Early
GPS total precipitative water (TPW)	✓	✓	✓	Underway
Microwave radiometry [TPW, integrated liquid water (ILW)]	✓	✓	✓	Mature
Boundary layer profiles (land)	✓	✓	✓	Mature
Buoy mounted				Early
Remote space based				
GOES cloud drift winds	✓	✓	✓	Underway
GOES IR QPE	✓	✓	✓	Underway
GOES sounder	✓			Underway
Polar-Orbiting Operational Environmental Satellite System (POESS) microwave sounder/imager	✓	✓	✓	Underway
POESS scatterometer	✓	✓	✓	Underway
Moderate Resolution Imaging Spectrodiometer (MODIS) surface snow/ice/water mapping		✓	✓	Underway

the United States, the team agreed rather early on to two main areas that constituted the most significant impacts from cool-season precipitation events, specifically and historically in dollar amount and human impact. The first was severe flooding from winter rains along the mountains of the West Coast. The second was severe icing, from either heavy snow or freezing rain, along and west of the I-95 corridor of the mid-Atlantic states and the Northeast.

The list of recommended observing systems for cool-season QPF applications (Table 2) is composed of both individual sensors and integrated sets of sensors and is divided by the sensing approach, either in situ or remote. Remote sensors are further divided by the nature of the platforms upon which they are deployed, either ground or space based. Each sensor or array of sensors is described in the context of its applicability to the QPF problem, which is stratified into nowcasting, data assimilation, and verification categories. The perceived stage of development for the various observing systems is also listed. A "mature" system requires very little, if any, further development and either is already contributing to QPF or can be very shortly, as in the case of boundary layer wind profilers with their snow-level detection capability (White et al. 2002). A system "underway" has been developed, but its applicability to QPF issues has not been tested adequately. Polarimetric radars, particularly in the context of the planned upgrade to the Weather Surveillance Radar-1988 Doppler (WSR-88D) network, are good examples of this category. The technology associated with polarimetric radars is relatively mature, but the algorithms used to extract valuable information from their data need further testing and systematic evaluation. An observing system at an "early" stage has yet to be fully developed or tested.

The results of this survey suggest that most of the recommended observing systems have broad applicability to the cool-season QPF problem. All of the sensors or sensor systems can be used for direct QPF validation or for validation of simulated variables that are critical to QPF (e.g., wind, temperature, moisture). Likewise, almost all of the recommended observing systems have a perceived value to operational nowcasting. The value of these observing systems to data assimilation is not as complete, but is still substantial.

The group identified certain observing system tests that would need to be conducted as part of the overall test bed activities (e.g. modeling tests, forecast technique development, and physical process studies). The observing system tests should include an objective, quantitative determination of the optimal mix of observing systems. This would be achieved by oversampling, installation of redundant sensors, and comparing sensors measuring common parameters. In addition, it will be important to determine the error characteristics of the observing systems, including the quantification of both instrument and representation errors that are required by modern data assimilation systems.

USER NEEDS. Working Group 4[4] identified the users and their need for cool-season QPF, and examined the process whereby winter QPF products are effectively developed and conveyed to those users. This group also suggested a process to guarantee that the users will obtain the results and benefits that they desire from winter QPF products. Table 3 lists key users of winter QPF. The working group emphasized that end users must be involved from the very beginning in planning and developing test beds to improve cool-season QPF. Decision makers and those affected by decisions should be included from the beginning of all product development. It is important to collaborate with all stakeholders from the beginning of the concept and product development cycles. This ensures that all the stakeholders' needs are met and the information that is developed and provided is effective and presented in the most efficient manner.

[4] Working Group 4 leaders: Rasmussen, Pugner, and Pisano; members: Estes, Gaynor, Hunter, Leung, Mahoney, Morss, Restrepo, Roth, P. Schultz, Stern, and Wesley.

Table 3. Four prominent user groups for winter QPF.

Hydrology	Transportation
Public and private water suppliers	Surface
Energy producers	Highway
Recreation	Transit
Natural resources	Rail
Flood management	Aviation
	Aircraft icing and deicing
	Marine
	Pipeline
Emergency managers	**Utilities**
Natural disasters	Communication infrastructure
Man-made disasters	Power suppliers
Homeland security planning	Delivery of supplies
Public health	

Each industry sector has different relationships and interactions between stakeholders. For example, the needs of the hydrometeorological stakeholders differ considerably from the needs of the aviation stakeholders. The interaction between the diverse groups of stakeholders and developers often necessitates a facilitator to most productively interact and define a successful path for the development and eventual operational deployment. In order to ensure the participation of the private sector in the development of cool-season QPF products, it is necessary to ensure that there is a suitable return on investment to be made through the use of these products. The return can be increased if the federal government takes an active role in the development of the product, allowing the private sector to focus on the commercialization of the product. This can also reduce risks for the private sector.

The following steps were considered to be necessary for the successful development of cool-season QPF products:

1) Determine and validate user needs for cool-season QPF products.
2) Evaluate the social, environmental, and security impacts of the winter QPF product.
3) Develop an operational concept and prototype(s) based on needs.
4) Define science needs, and conduct research to meet them.
5) Test and evaluate prototypes through the use of test beds and demonstration projects.
6) Revise a system based on user response (iterate).
7) Transfer technology to operations based on the operational concept.

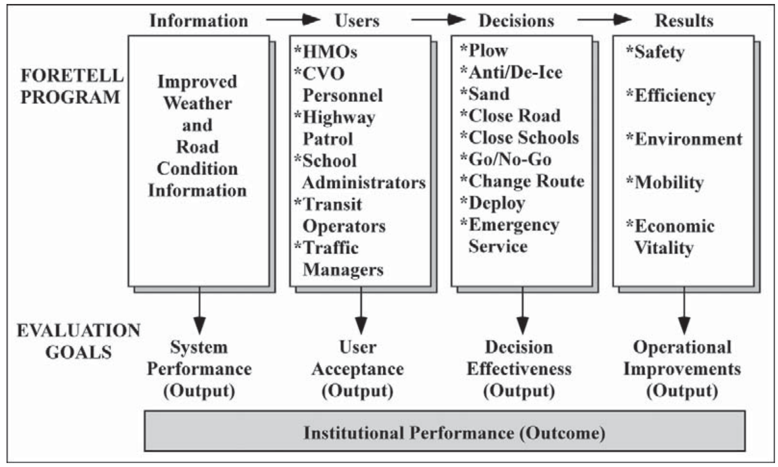

Fig. 4. Road weather implementation diagram.

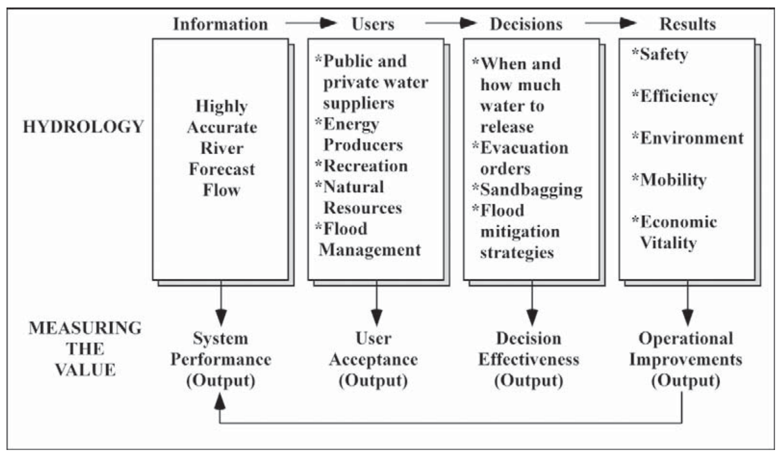

Fig. 5. Hydrology implementation diagram.

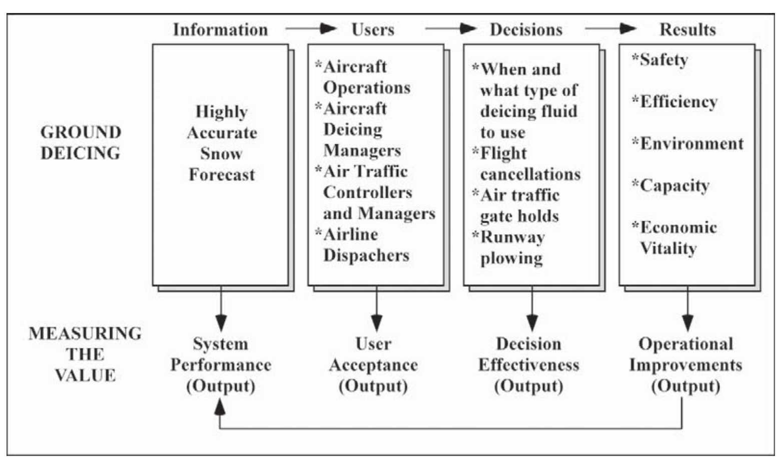

Fig. 6. Aircraft ground-deicing implementation diagram.

Figures 4–6 present example implementation plans for a QPF decision support system for road weather, hydrology, and aircraft ground deicing, respectively. The diagrams show that there are four key components to successful implementation: 1) accurate information based on a QPF forecast (system performance), 2) user understanding and acceptance of the information, 3) application of that information to make effective decisions, and 4) overall benefit to the sector and society. Each of the four components has its own performance metric. All four components feed back to previous components, thereby ensuring continual improvement to the implementation process.

IMPLEMENTING THE COOL-SEASON QPF COMPONENT OF USWRP. *Recommendations.* A general consensus emerged from the workshop that a test bed approach should be implemented that 1) addresses as many as possible of the key scientific issues described above, and 2) advances QPF in regions of the United States where the impacts of cool-season precipitation are greatest. Based on the recommendations of the working groups, the CSQPF community, as represented by 59 workshop participants, recommends implementation of a national HMT strategy focused on improving cool-season QPF, including two long-term regional efforts that address key regional differences. One effort should focus on winter storms along the East Coast of the United States, with freezing rain, coastal cyclones (e.g., nor'easters), heavy snow, and lake-effect snow as priorities, that is, HMT-East. The other should focus on the West, with orographic effects, flooding, and water resources, in general, as priorities, that is, HMT-West. (Fig. 7). Longer-term, continuous activities that are required to optimize operational impacts are the focus of HMT. The HMT infrastructure then provides a foundation for episodic major field programs that are required to address certain key research and forecasting problems.

It was concluded that a key to cool-season QPF is to provide the user community (e.g., water resources, transportation, emergency management, utilities) with probabilistic forecasts that specify the size, position, orientation, timing, amount, and type of precipitation. This includes distinguishing regions of rain, snow, and mixed precipitation, as well as probabilistic products specifying the location of boundaries separating precipitation types.

It must be kept in mind that the results of assimilation experiments may be strongly scale-dependent. Methods that work well in global models may not work well in mesoscale models with more sophisticated physics. The community effort to develop the Weather Research and Forecasting (WRF) system should be the focus of work to improve cool-season QPF.

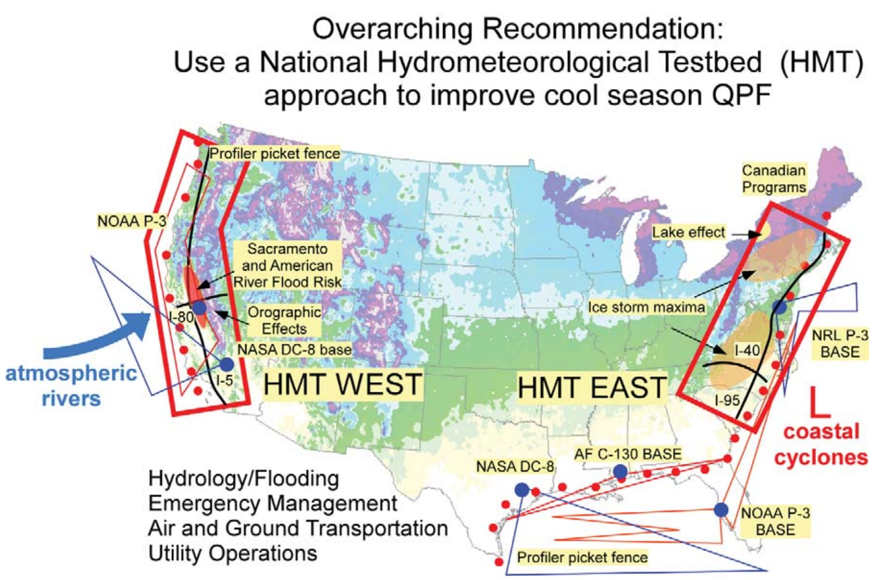

Fig. 7. Schematic summary of the primary strategy to improve cool-season QPF through establishment of a Hydrometeorological Test Bed approach that will foster both the research needed as well as its testing and transition to operations. Successful implementation requires addressing an appropriate range of phenomena that are critical to the forecast users who depend on cool-season QPF. Accomplishing this requires development of two major regional efforts, that is, HMT-East and HMT-West, which focus on differing phenomena, forecast issues, and user needs. This implementation involves developing both a long-term core infrastructure for HMT that supports efforts nationally, and conducting episodic intensive regional field studies needed to address certain key research and forecasting challenges.

Possible cool-season HMT interagency field studies. HMT-West. The implementation of an effective strategy to address cool-season QPF can begin immediately through coordination with and support of plans that are already in progress for a significant HMT-focused field study in the Sierra Nevada Mountains. These plans include investment by both the National Oceanic and Atmospheric Administration (NOAA) research and National Weather Service (NWS) in a core data collection and analysis effort focused on the American River watershed. In addition, a climate-related study involving the global water cycle and extreme precipitation events will focus on diagnosing the water budget in atmospheric rivers as they approach the coast, cross the coastal mountains, and impact the Sierra Nevada. NOAA research radars and other facilities have already been committed, and requests for NOAA aircraft have been submitted for the 2006 fiscal year. Research on satellite-based techniques using Quick Scatterometer (QuikSCAT) and the Tropical Rainfall Measuring Mission (TRMM) in this area have been sponsored by the National Aeronautics and Space Administration (NASA) in the past and could form the foundation for significant participation in the future study, which could also play a role in planning for applications of Global Precipitation Mission (GPM) data. The opportunity that this project represents has also led to recognition in the university research community that National Science Foundation (NSF)–type investigations of terrain effects could be built around the core activities described above. The user community is also uniquely prepared for a major QPF study in this region through efforts of the Army Corps of Engineers and local flood-control agencies that have created unique tools to use QPF in reservoir operations. Finally, the impact of unexpected snow events on major highways across the Sierra Nevada presents a clear opportunity to address ground transportation issues.

HMT-East. Winter storms along the East Coast possess several of the mesoscale features that confound QPF, and it is well known that the mesoscale details of these events are critical determinants of societal impact (Kocin and Uccellini 2004). A 100–200-km error in the forecast position of the rain–snow line, major precipitation bands, or the cyclone track itself can have significant economic and social consequences. Upstream effects of deep convection and latent heating during cyclogenesis can influence the detailed evolution of precipitation over the East Coast. Current limitations in the observing system over and around the Gulf and southeast coastlines, limitations in data assimilation techniques that use existing satellite and other data, and limitations in parameterizations of convection and air–sea fluxes in models contribute to key quantitative (precipitation type, amount, intensity, duration) forecast errors 6–48 h later as cyclones form and move up the U.S. East Coast and/or as ice storms develop over the region.

The current observing network is limited in its ability to monitor the key regions of meridional water vapor transport into East Coast storms. As Zhu and Newell (1998) showed with numerical model simulations, and Ralph et al. (2004) showed with experimental and satellite observations, narrow filaments known as atmospheric rivers are responsible for more than 90% of the meridional water vapor transport at midlatitudes. This suggests the use of a picket fence approach along both the northern Gulf and the south Atlantic coasts, building on lessons learned from the picket fence approach tested earlier on the West Coast (Hirschberg et al. 2001). This could be accomplished partly through the deployment of a combination of additional rawinsondes at existing and temporary sites, the deployment of an array of boundary layer wind profilers, and the use of GPS receivers for monitoring integrated water vapor at these sites. The picket fence should be deployed in a way that complements the existing WSR-88D and sounding network, as well as the National Wind Profiler Network in the central United States. Additionally, wind profilers could be mounted on one or more oil platforms in place in the Gulf of Mexico. There is also some potential value in deeper-tropospheric wind profiling to monitor the subtropical jet that often comes across the Yucatan Peninsula in major events.

Aircraft observations over the Gulf of Mexico could document conditions prior to and during the development of large precipitation areas and embedded deep convection. The spatial scales that are involved would be amenable to the deployment of NOAA's P-3 and G-IV research aircraft from their home base in Tampa, Florida, and for deployment of the NASA Earth Resources 2 (ER2). The Air Force C-130s are based in Mississippi and also could be used (because they already have been, on occasion) for dropsonde deployment. It is likely that the verification area for the experiment would include regions within reach of the Naval Research Laboratory (NRL) P-3 from its home base in the mid-Atlantic. The NOAA P-3s, with their radar capabilities and other sensors (e.g., fluxes and microphysics), could provide in-depth three-dimensional observations in critical areas, such as the boundary layer, and where precipitation is falling. The convenient locations of the experimental areas with respect to aircraft home bases could save on significant operational costs that are normally associated with travel and more remote deployments. It is also likely that university and National Center for Atmospheric Research (NCAR) scientists would participate and involve NSF deployment pool facilities for targeted field studies.

A key area of research involves improving the ability to assimilate satellite observations from Geostationary Operational Environmental Satellite (GOES) and polar-orbiting satellites. These studies could be undertaken with the help of NASA and its ER-2 and P-3 research aircraft, with microwave and other remote sensors for satellite validation studies. The Joint Center for Satellite Data Assimilation (JCSDA) would be an important partner in developing the data assimilation strategies. Connections to NOAA's operational QPF centers could be accomplished through the HMT and its elements at NOAA/Environmental Technology Laboratory (ETL), NCEP/Hydrometeorological Prediction Center, River Forecast Centers (RFCs) and Weather Forecast Offices (WFOs).

HMT-East addresses most of the major issues identified by workshop participants as key to the cool-season QPF problem in the eastern United States. There are also substantial Canadian interests in East Coast storms, and it is expected that cooperative efforts with the Meteorological Service of Canada, Canadian universities, and other Canadian meteorological institutions could be developed. Early involvement of the end users of QPF—decision makers in transportation, government, and business—will be essential to evaluate the success of any improvements in QPF.

This report has briefly summarized a strategy for improving cool-season QPF through a focused effort engaging both the research, operational, and forecast-user communities. The effort includes field studies, observing system development and the testing and evaluation of new methods in the context of a test bed approach. The successful experience with the JHT and the recent establishment of a Hydrometeorological Test Bed have provided lessons that can be applied to the challenge of improving precipitation forecasts and the associated societal impacts over the coming years. The challenge is significant, the payoffs are great, and the need for interagency cooperation is central.

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