AN IMPLEMENTATION PLAN

FOR COOL SEASON QUANTITATIVE PRECIPITATION FORECASTING

United States Weather Research Program

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Executive Summary

The Cool Season Quantitative Precipitation Forecasting (CSQPF) workshop was convened in February 2004 to develop an implementation plan for improvement of cool season quantitative precipitation forecasting (QPF). The overall goals of the workshop were to define critical research activities required to advance short-term (0-48 h) QPF during the cool season, to consider the development of numerical weather prediction (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 value of the improved forecasts and how the improved information is ultimately used. Four working groups undertook these tasks. The working groups were charged with examining (1) research and field studies that will contribute to advances in CSQPF; (2) numerical weather prediction and data assimilation advances required to address the CSQPF problem; (3) current and future observing systems and test-beds as a means of advancing CSQPF; and 4) the CSQPF needs of users, and the roles of the public, private, and academic sectors. This document presents a detailed summary of the findings and recommendations of the workshop.

To improve 0-48 hr cool season QPF, workshop participants concluded that greater understanding is needed in five key areas: 1) 4D mesoscale structure and dynamics of weather systems, particularly above the boundary layer; 2) the structure and mesoscale dynamics of the rain-freezing rain-snow transition region; 3) regional mesoscale boundary layer forcing, particularly orographic and lake effects; 4) moisture sources and transport into winter systems; and 5) the predictability of cool season precipitation in all of its forms. The workshop recognized that many important phenomena contribute to the difficulty of cool season QPF, including snowstorms with convection, banded precipitation, freezing drizzle and rain, supercooled clouds, flooding winter rain and snowmelt, cold-air damming, lake-effect snow, and orographic precipitation. Subtle problems, such as an incorrect forecast of surface temperature, can dramatically impact wintertime forecasts. Scientific questions related to each of these key areas and phenomena were posed and test-bed approaches to addressing these questions debated. The workshop recognized in this debate that there are major regional differences in the user needs for cool season QPF and that forecasts should be tailored to those needs.

Three core recommendations emerged from the workshop. These are:

Core recommendation #1: Establish a National Hydrometeorological Test-bed Approach

Each of the working groups of the workshop considered the potential of test-beds to advance our understanding of cool season processes and take the next important step of actually achieving advances in operational cool season QPF through pilot studies. From the reports of the working groups, a general consensus emerged that a test-bed approach should be implemented that 1) addresses as many of the key scientific issues as possible, and 2) advances QPF in regions of the United States where the impacts of cool season precipitation, including winter weather, are greatest.
Based on recommendations of the Working Groups, the cool season QPF community proposes that the USWRP support the implementation of a national Hydrometeorological Test-bed (HMT) strategy focused on improving cool season QPF, including two long-term regional efforts. 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 effects as priorities, i.e., HMT-East, while the other should focus on water resource related issues in the west, with flood control, water supply, and orographic effects as priorities, i.e., HMT-West. Longer-term, continuous activities that are required to optimize operational impacts should be the focus of the HMT. The HMT infrastructure will then provide a foundation upon which to conduct episodic major field programs that are required to address certain key research and forecasting problems.

Core recommendation #2: Develop Probabilistic Methods

The workshop concluded that the most productive approach to wintertime QPF is to provide the user community with probabilistic forecasts that specify the size, position, orientation, timing, and amount of precipitation within regions of snowfall and mixed precipitation, as well as probabilistic products specifying the location of boundaries separating precipitation types.

Core recommendation #3: Advance Mesoscale Data Assimilation and Modeling

The community effort to develop 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 technique (EnKF) is risky and a decision to embrace Four-dimensional variational (4DVAR) assimilation is very expensive, the recommended course for the next two or three years is continued enhancement of 3DVAR techniques while the pros and cons of using EnKF and 4DVAR are thoroughly explored. 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.

This report addresses specific recommendations for interagency participation in the HMTs and focused field programs and provides a strawman timetable for implementation of a cool-season QPF national effort.
1. Introduction

The United States Weather Research Program (USWRP) was formed in 1992 to advance weather observing capabilities and fundamental understanding of weather and to use this understanding to improve numerical weather prediction and enhance weather services provided to the Nation. In 1996, three topics were selected as the primary foci for USWRP: hurricanes at landfall, QPF, and the optimal mix of observations. Two implementation plans were developed for these areas, one for hurricanes (Elsberry 2000) and another for data assimilation and QPF (DAQPF) (Schlatter 2001). The DAQPF plan identified specific QPF goals to be addressed (Table 1), many of which were closely linked to goals within the National Weather Service’s (NWS) five-year strategic plan. The DAQPF report highlighted three projects that were either under way or under development to address the QPF problem: the Pacific Land-falling Jets (PACJET) experiment that focused on 0-24 h cool season QPF on the U.S. West Coast, the International H2O Project (IHOP) that focused on the distribution of water vapor over the Great Plains during summer and its relationship to warm season QPF, and The Hemispheric Observations and Research on Predictability Experiment (THORPEX) that focuses on medium-to long-range forecasting on a global scale. Based on the significant differences in the phenomenological, scientific, observational, and forecasting needs of QPF for warm season versus cool season conditions (e.g., convective versus ice and snow), USWRP recognized a need for more specific plans to be developed to address these differences. From 2002-2003 a team formed through USWRP developed a detailed “Warm season QPF” implementation plan that focused on the 0-48 h forecast lead time (Carbone and Fritsch 2003, 2004) and coordinated with the IHOP experiment of 2002 (Weckwerth et al. 2004). The report developed here is its cool-season counterpart, and has benefited from experiences gained during the PACJET field projects of 2001, 2002, and 2003. In an effort to gather community input into the plan, a workshop was conducted in February 2004 in Boulder, Colorado. As recommended by the USWRP Prospectus Development Team on Societal Aspects of Weather (Pielke 1997a, b), this workshop engaged the forecast user community from the beginning of the planning process. The workshop included scientists, forecasters, and forecast users (Table 2) in an effort to examine the core elements required to advance QPF in a way that takes advantage of recent research advances, recognizes the realities of the operational forecast environment, and focuses on improvements that have the greatest potential to benefit major forecast users.

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 loss of power for over a month in parts of Canada. The 2000 lake effect storm produced over 80 inches of snow locally in Buffalo. Nationwide, nearly 7000 deaths, 600,000 injuries, and 1.4 million accidents per year are due to adverse road weather, mostly during winter (Goodwin 2003). Winter rainfall and runoff causes major flooding in the western coastal states, such as the California floods of 1997, which produced over 40 inches of rain, inundated large areas, and caused greater than 1 billion dollars in damage. In this area, The National Academy of Sciences (National Research Council 1995, 1999) had earlier identified Sacramento, CA, as a major flood risk. More recently, an interagency report (ACE 2002) determined that $5 (13) billion in damage can be expected to occur in a 115 year (500 year) flood, on the American River, which is comparable to recent landfalling U.S. hurricanes. Overall, the West Coast states
of California, Oregon, and Washington average 1 billion dollars from winter flooding annually, which is roughly half the annual average impact of earthquakes in this earthquake prone-region.

Table 1: USWRP Goals for QPF recommended in DAQPF implementation plan

1. Improve numerical model guidance over the Pacific and West Coast so it is as accurate as the rest of the country
2. Extend precipitation forecasts to 3 days and attain current Day 2 accuracy at Day 3
3. Provide weather and water forecasts in probabilistic terms
4. Increase the skill of the Day 1 operational NWP model QPFs by 50%. Examine the accuracy in six-hour increments.
5. Increase flash-flood warning lead time from 52 minutes (1998) to 65 minutes (2005).
6. Develop and implement a weather research and forecast community model.
7. Achieve the optimal mix of observing systems and data processing systems to support the NWS mission.
8. Incorporate Doppler radar data into operational mesoscale models.

Table 2: Participants in the USWRP Cool Season QPF Workshop

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
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<td>NASA/MSFC</td>
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<td>Atlas, Robert</td>
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<td>Benjamin, Stan</td>
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<td>Caldwell, Dave</td>
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<td>Elsberry, Russ</td>
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<td>Estes, Gary</td>
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Figure 1 illustrates current QPF skill of the ETA and GFS models and the 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 two, primarily due to the limited predictability of convective precipitation. We should keep in mind that these statistics do not tell the full story – in winter, qualitative precipitation forecasts can be as significant as quantitative. 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 QPF in 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 NWP will 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 these 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, 60,000 additional acre-feet of water can be retained 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 panel to examine the impacts of adverse road weather and to 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 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 dilution of deicing fluids. Improvements in the forecast of snowfall rates will improve both safety and airport capacity and efficiency due to better decision making.

The Cold Season Quantitative Precipitation Forecasting (CSQPF) workshop was convened to define critical research activities required to advance short-term (0-48 h) 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 value of the improved forecasts and how the improved information is ultimately used. To accomplish this, the workshop was structured to allow optimal time for developing detailed input on these critical issues in working groups composed of representatives of different communities (Table 2), while allowing cross fertilization between these groups during plenary sessions. Roughly half of the 2.5-day workshop was devoted to plenary sessions and half to discussions in working groups.

One of the goals charged to the CSQPF workshop was to conceive field experiments and test-beds to address the cool season QPF problem. An example of a focused field program would be PACJET (e.g., Neiman et al. 2002, 2004, Ralph et al. 2003, 2004). Lessons learned from PACJET include the need to address observing system capabilities and limitations, physical process understanding, and to develop and test prototype forecast techniques. In a planning workshop in October 2001, forecasters, scientists and users came together and recommended that a combination of episodic traditional scientific field studies be combined with a more continuous effort linking research to operations. The recommendations and experiences from PACJET led to the development of a concept now termed a test-bed. In early 2002, this approach was also recognized by the USWRP warm season QPF planning workshop as a critical recommendation for improving forecasts. More recently, the December 2003 USWRP workshop on mesoscale observing systems assigned a working group the task to further refine the concept of the test-bed with particular emphasis on observing system optimization for regional prediction. The CSQPF workshop recognized the importance of the test-bed concept, and integrated it into discussions within each working group. Based on the consensus from each working group, this report recommends the implementation of test-beds as a means to address the cool season QPF challenges. The recommended implementation built on lessons learned from the recently established Joint Hurricane Test-bed and Hydrometeorological Test-bed.

The four working groups at the CSQPF workshop were charged with examining (1) research and field studies that will contribute to advances in CSQPF; (2) numerical weather prediction and data assimilation advances required to address the CSQPF problem; (3) current and future observing systems in test-beds as a means of advancing CSQPF; and 4) the CSQPF needs of users, and the roles of the public, private, and academic sectors. This report is designed on the basis of the charges to, and inputs from the four working groups at the workshop. Sections 2-5 consist of the reports of each working group. Recommendations for an implementation plan for improvement of cool season QPF are presented in Section 6.
2. Report of Working Group 1: Research and Field Studies

Working Group 1* was concerned with the processes and phenomena associated with winter precipitation and its predictability. The charge to the working group was to define critical research activities required to advance short-term (0-48 h) QPF during the cool season primarily over the United States, with an emphasis on both the severe winter weather and hydrological aspects of the precipitation forecast problem, to identify a series of focused field campaigns and related activities spread out over a number of years that address key aspects of the cool season forecast problem, and to consider research that would lead to the integration of the results of the various activities to improve cool-season precipitation forecasts.

Key processes and phenomena associated with cool-season precipitation systems span a wide range of spatial and temporal scales. The group identified five broad categories:

- 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 are connected in some way to extratropical cyclones, which themselves originate in response to processes at longer time and space scales. This report focuses on the shorter-term (0-48 h) mesoscale processes, including the role of surface processes, with consideration of how these processes are linked to the larger scale. In addition, the working group discussed the critical issue of predictability in relation to these topics.

A. 4-D Structure of Systems in the Free Troposphere

A major challenge of cool season QPF is to determine its spatial and temporal variability within extratropical cyclones. The variability in the location and intensity of precipitation is often determined by the occurrence of precipitation banding and/or embedded convection that occurs on scales of approximately 5-200 km (Novak et al. 2004, Fig. 2).
There are several scientific questions that need to be addressed to improve the forecasts of these precipitation sub-structures such as:

- What are the predominant spatial patterns of organized precipitation features associated with free-tropospheric 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 precipitation sub-structures? 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 CSI, moist frontogenesis, gravity waves, and elevated upright convection) are controlling the generation and evolution of these precipitation substructures?

- Is instability with respect to ice a critical issue in some of these instances and is it through precipitation-related effects that instabilities can persist?

- 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 sub-structures 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 for these bands to develop?

- How does the predictability of banding depend on forcing? Are free atmosphere instabilities and gravity waves inherently less predictable than bands associated with fronts and orographic forcing?

Several activities need to be pursued to address these issues. Various radar and profiling systems could be utilized to observe and analyze the structure and evolution of these features, particularly through the use of various types of kinematic and thermodynamic retrievals. A joint radar data test-bed, analogous to the Joint Center for Satellite Data Assimilation (JCSDA), is a potential vehicle to develop and assess various processing and analysis techniques as well as to advance the assimilation of these data sets into NWP systems. This radar test-bed would also be involved in the development and evaluation of techniques that utilize data from dual-polarized radars. To complement such measurements, the utility of total lightning data should also be investigated.

A regional test-bed could also be established to evaluate the utility of various observing and NWP systems. This test-bed could utilize targeted integrated profiling systems with high temporal resolution embedded within the WSR-88D network. Mobile systems, such as the University of Alabama-Huntsville Mobile Integrated Profiling System (MIPS), should be an integral part of this test-bed. Between NOAA/ETL and NCAR, there exist as many as 20 transportable boundary layer wind profiling systems that could be deployed in targeted field projects in a test-bed array at fixed sites for several months. These could be part of a field
program similar to the recent IHOP experiment that also include aircraft data in tandem with NWP sensitivity studies, and could be leveraged off of test-bed activities recommended as an overarching element of addressing cool season QPF. Additional smaller investigative projects, such as those sponsored by the Collaborative Science, Technology, and Applied Research (CSTAR) Program, and the COMET Outreach Program would be complementary to the larger-scale field programs and test-bed activities.

B. The Form of Precipitation

An important distinction between winter and summer storms is the form of the ensuing precipitation. Except for the occasional occurrence of devastating hail, summer storms produce only rain. In contrast, winter storms typically produce a wide variety of forms of precipitation (rain, snow of varying densities, wet snow, ice pellets, freezing rain, drizzle, and freezing drizzle, see Fig. 3) and the impacts of the storms are often linked with the precise nature of this precipitation.

Figure 3. Distribution of cool-season precipitation (top left), snowfall (top right), and the average number of hours per year with freezing precipitation (bottom).

A critical region of many winter storms is the zone that separates the major types of precipitation. This transition region typically represents the transition from snow to rain, but often involves freezing precipitation. The storm scale thermal field determines the general
location of this region. An important factor in determining whether or not freezing precipitation occurs is the distribution and intensity of warm air advection into this region.

Although the storm scale thermal field and warm advection are critical, the local thermodynamic structure is often modified by smaller scale spatial variability in microphysical characteristics and associated latent heating within or near the transition zone (Stewart 1992). Snow falling on the warm side of the transition region will melt to form rain, whereas on the cold side, it remains as snow. Within the region, the particles may melt completely aloft and reach the surface as freezing rain, they may melt partially aloft and refreeze completely near the surface to form ice pellets, or they may reach the surface in a semi-melted state to produce wet snow. These possibilities lead to a wide variation of particle types at the surface, and the associated phase changes modify the initial atmospheric temperature and moisture distributions and can initiate secondary mesoscale circulations. Such thermodynamic and dynamic effects collectively modify the type, amount, and distribution of subsequent precipitation, and directly impact both quantitative and qualitative precipitation and hazard forecasts. Many of these processes are poorly understood and have not been adequately observed. The transition zone and the impact of precipitation from the zone is affected by surface conditions, including sloping terrain, whether the surface temperature is above or below freezing, whether snow cover exists, and low-level temperatures and moisture fluxes (e.g., land vs. water).

There are a number of other key precipitation-related issues that need to be addressed in regard to the form of precipitation. A key aspect is the determination of factors governing the density of snow that accumulates on the ground (Roebber et al. 2003). This is linked with the types of crystals produced aloft and how these interact with other ice particles and cloud water aloft. Other issues are also linked with the precise conditions associated with the onset of ice in clouds. This can have major impacts such as the production of freezing drizzle through warm rain processes as opposed to ice-based processes that lead to snow.

It should be noted that other hazards are closely linked with these winter weather QPF challenges. These include potentially the devastating effects of wind on ice laden structures or trees, low visibilities in blowing snow that can lead to white-out conditions, and low ceilings that can restrict aircraft operations. Because of their close connection with precipitation-related issues, these phenomena should be considered in tandem.

Several activities can be initiated to address winter precipitation-type issues. These include:

- The development of a test-bed to provide a longer-term perspective on the nature, structure, morphology, and predictability of precipitation-type transition regions.

- The mounting of comprehensive field experiments to acquire the needed detailed information on the thermodynamic, dynamic, and microphysical environment of transition regions. These experiments should include a requirement for detailed precipitation measurements at the surface and aloft, the exploitation of multi-wavelength polarization radar, moisture information in the environment of the transition zone, and very accurate (of order 10 cm/s) vertical air motion information across the transition zone.
• Some of these measurements can be acquired within small field experiments through the use of small portable systems with appropriate remote sensing and surface measurements.

• Detailed studies of snow formation and subsequent evolution down to the surface are needed to better understand the snow density issue as well as ice initiation and subsequent precipitation evolution issues.

• Development of a radar test-bed to develop and evaluate techniques utilizing dual-polarized radars.

C. Impact of Regional Mesoscale Boundary Layer/Surface Forcing Processes

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 (Sierras, Cascades), and the Appalachians are all responsible for generating heavy orographic rain and snow, but each has unique regional cool season QPF problems. The Sierras represent 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 (Figure 3).

It is recognized that such precipitation is initiated or enhanced by dynamic and thermodynamic factors that typically alter stability. For example, Neiman et al. (2002) showed that hourly variations in upslope wind speed explained >50% of the variance in hourly rain rates in California’s coastal mountains over a full winter season, and that orographic precipitation efficiency was 50% greater when a low-level jet was present than when it was not. They also showed that variations in the rain rate were most closely linked to the upslope flow at the altitude of the low-level jet (~1 km MSL), and that rainfall extended westward to the coast due to the presence of stably stratified blocked flow (Figure 4). There are many outstanding issues associated with the production of precipitation within such environments including microphysical processes (including the generation of heavy rain through warm rain processes – see White et al. 2003), gravity waves, and blocking flows associated with induced pressure perturbations (Colle 2004, among others). For example, Colle (2004) showed 2-D idealized simulations suggesting that relatively wide barriers (e.g., Sierras) may be able to seed themselves with ice aloft through generation of a deep upstream-pressure perturbation.

Smaller-scale topographic features can induce similar perturbations to precipitation amounts and types (Cortinas et al., 2004); however, these precipitation processes may be more linked to riming and warm rain processes. 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 is still uncertain, since it requires understanding both the moist dynamics and microphysics within orographic clouds.
Figure 4. Conceptual representation of orographic rainfall distribution in California’s coastal mountains, and the impact of terrain-blocked flow on this distribution: (a) plan view; and (b) cross-section perspective, with representative coastal profiles of wind velocity and correlation coefficient (based on the magnitude of the upslope flow at the coast versus the rain rate in the coastal mountains) shown on the left.
Large water bodies can have a profound impact on winter precipitation through heat and moisture fluxes into the atmosphere. This can occur 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 sub-synoptic environment (Sousounis and Fritsch 1994). Non-homogeneous conditions, such as leads within the ice or unusual water temperature gradients, can make a substantial difference in the magnitude and distribution of the moisture and heat fluxes. Currently, measurements of ice and water temperatures are typically dependant upon satellite data that require cloud-free conditions. Climatologically, there are frequently extended periods during the cold season when such measurements are not possible due to persistent cloud cover. These periods often are coincident with considerable changes in water temperatures or ice coverage. As a result, the initial conditions available to NWP systems can contain significant errors.

Several activities can be initiated to address such issues. These include:

- A comprehensive field experiment is warranted in regard to orographic precipitation. This would require appropriate observations including wind profilers upwind of the barrier or within mountain passes, GPS integrated water vapor units collocated with the profilers, precipitation gages at various locations over the barrier, and even instruments on ships and/or buoys upstream from the barrier.

- Similar experiments can be envisioned to examine other terrain-related phenomena. Some of these efforts could be smaller investigative projects that might focus on particular localized phenomena.

- Ice microphysical measurements aloft using aircraft and polarized radar.

- Flux measurements over land and water that require aircraft measurements supplemented by surface-based systems over land.

- Development of new satellite-based techniques to measure surface state (ice/snow coverage) and temperature in the presence of clouds.

### D. Moisture Sources and Transport into Cool-Season Weather Systems

On the large scale, the bulk transport of moisture, particularly from tropical and sub-tropical source regions into mid-latitude storm systems, can have a substantial impact on the organization and distribution of precipitation. These source regions, which include the tropical and subtropical Pacific Ocean, the Gulf of Mexico, the Caribbean, and sub-tropical Atlantic Ocean, are not well observed three-dimensionally (Figure 5). 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. While much is known about the physical processes of convective latent heat release, what is not clear is how the vertical and horizontal distribution of latent heating relative to the phase of cyclone evolution impacts subsequent development and moisture distribution downstream. Operational NWP systems often fail to adequately capture this process, either due to problems related to initial conditions/observations, or convective parameterizations.

These scientific problems could be addressed through a targeted field project to examine the contribution and transport of moisture from the Gulf of Mexico to cool season QPF in storms over the Plains and eastern U.S. Such a study should also consider the impacts of associated deep convection over the Gulf and its influence on downstream precipitation over the eastern U.S. Such a project would have many benefits including improving conceptual understanding and assessing the impacts of various observational systems on NWP. The role of satellite data over the Gulf of Mexico could be addressed with efforts at the Joint Center for Satellite Data Assimilation (JCSDA). In addition to satellite data, aircraft, profilers and other sensors (such as relatively low-cost GPS sensors for measuring total column precipitable water) could be deployed to the region to improve observations and NWP initializations of these phenomena. A regional study of this nature could benefit from coordination with THORPEX-related field studies over the Pacific Ocean, with research emphasis placed on larger-scale processes that help set the stage for major winter storms. Other activities aimed more at climate-related water-cycle issues could also focus on monitoring the genesis and evolution of narrow filaments of enhanced water-vapor transport (i.e., atmospheric rivers, Zhu and Newell 1998) from the tropical Pacific to the West Coast of the U.S. (Ralph et al. 2004), and the impact of these filaments on both cyclogenesis and orographic precipitation enhancement in the intermountain West.
E. Predictability

Predictability of the atmosphere is fundamentally limited; even with perfect dynamical models, there are always irreducible uncertainties in the initial conditions that inevitably grow in time to the point where model solutions are indistinguishable from a random selection of all possible states. That point defines the theoretical limit of predictability (also referred to as potential predictability). Since perfect models will never exist, consideration of predictability limits must include that component attributable to deficiencies in model physics, as well as to initial conditions.

The overarching goals of predictability issues in regard to cool season QPF goals are: 1) provide realistic estimates of potential and actual predictability limits; 2) identify, describe, quantify, and understand the origin and nature of uncertainties, i.e., 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 in operational predictions for incorporation into risk analysis and decision making. Attaining these goals is meaningful to the extent that they are viewed as a function of the space and time scales of relevant phenomena, the operative physical and dynamical mechanisms, and specific sets of situations and/or circumstances of importance (e.g., location, topography, and user specific scenarios).

Some of the specific issues that must ultimately be addressed through predictability research include: i) the point of diminishing returns of increasing model resolution as related to explicit versus parameterized and/or stochastic physics; ii) design of optimal observing systems, including adaptive (targeting) strategies; iii) alternative methodologies for data assimilation; iv) alternative ensemble strategies; v) mesoscale/synoptic interaction processes; and vi) the role of air/sea and air/land surface boundary influences; and vii) optimizing the information content of forecasts.

A general approach to the above might consist of sensitivity and process studies with “simple” dynamical models, “perfect model” experiments, and with full NWP systems (similar to those discussed by Tribbia and Baumhefner 2004), and augmented by field experiment/validation studies within a test-bed framework (Figure 5).

As part of this predictability research, we envision real-time forecast activities that would combine the talents of research meteorologists and operational forecasters during the field phase of each program. During the field phase, special models and/or enhancements to existing models might be run and these would be typically used to help formulate forecasts to direct field operations. Both operational and research meteorologists could take part in this activity, but in addition there would be a set of experimental forecasts designed to test various hypotheses relating to the predictability of the phenomenon being studied. These experimental forecasts, made by a combined effort of research and operational forecasters, would utilize both operational and research models as well as new data sets that might be part of the field exercise. It has been shown (Kain et al. 2003) that such real-time activity can provide valuable insight into
predictability issues, as well as suggest important directions for follow-up research efforts that might best (and quickly) benefit operational forecasting.

**F. Summarizing Remarks of Group 1**

We have summarized some of the key scientific gaps in our understanding of winter precipitation. We recognize that this is not an all-encompassing list, but it does illustrate that there are many challenges to be faced and there are means to address them.

It should also be recognized that the final goal is better prediction. In light of some of the activities that have been proposed, it is critical that operational forecasters and users be involved along with the research and academic communities. One possible joint activity is to utilize these efforts in the development of a short-fused winter weather warning paradigm analogous to the severe convection warning program. This could involve the issuance of small-scale, short-term detailed warnings of specific winter hazards such as extreme accumulation rates, white-out visibility conditions, or rapid-onset surface freezing. These warnings could augment and complement the current larger-scale and longer-term winter storm warning system currently in place, as well as address shorter duration extreme events (e.g., brief snow squalls) that do not persist long enough to reach the longer-term warning criteria.
3. Report of Working Group 2: Data Assimilation and Modeling

Working Group 2∗ was concerned with data assimilation and modeling issues related to cool season QPF. The charge to the working group was to propose and assess advanced data assimilation systems suitable for use in high-resolution models that take advantage of existing data sources and those that are likely to become available in the next five years, with special emphasis on methods to assimilate radar and satellite data. The group was also to consider the development of NWP methods and products, as well as data assimilation systems relevant to the cool season problem.

A. Defining the Scope of the Problem

The working group limited its discussion to short-term forecasts (0-48 hours) of wintertime precipitation with a strong emphasis on mesoscale phenomena. The intent of this limitation was to avoid overlap with the extensive planning already under way for THORPEX, which deals for the most part with more extended predictions of larger-scale phenomena. The working 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.

B. Motivation for Improvements in Data Assimilation and Prediction Models

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 of each other. 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, as well as the boundaries within that separate the different precipitation types.

Other cool-season phenomena also merit consideration because they are difficult to forecast and lead to disruptions in travel and commerce. Some of these phenomena are confined to specific geographic regions within the U.S.

- Snowstorms with convection. Unanticipated convection embedded within stratiform precipitation can lead to serious errors in the predicted snow depth.
- Flooding winter rains with embedded convection, with or without snowmelt.

∗ Working Group 2 Leaders: Jewett and Schlatter; Working Group members: Atlas, Benjamin, Colle, Elsberry, Koch, Jorgensen, Schlake, Toth, Uccellini, Wilczak, Zupanski
• Cold-air damming in the lee of the Rocky Mountains or the Appalachians as it affects wintertime precipitation.

• Lake-effect snow. Cold air traverses relatively warm lake water causing the development of localized bands of heavy and sometimes persistent snow.

• Freezing drizzle. Though this type of precipitation is light, it can be very hazardous for highway and air travel. Detection and prediction of freezing drizzle are both problematic.

• Supercooled clouds. Liquid water droplets in clouds at temperatures below freezing are responsible for aircraft icing. Such clouds can produce freezing drizzle.

• Orographic precipitation. Mesoscale forecasts commonly produce too much or too little precipitation on the windward and leeward sides of mountain ranges.

• Maximum and minimum temperature forecasts within a shallow cold air mass, when the potential exists for erosion from above.

• Ground fog and advection fog.

• The diurnal cycle, especially as influenced by the state of the underlying surface.

The last two items in the above list are only indirectly related to QPF, but they do influence precipitation type at the ground.

The solutions to these wintertime forecast problems require a multi-pronged attack involving observations, because they are the basis for describing current atmospheric conditions; data assimilation, because this is the vehicle for incorporating information from the observations on a model grid, thus defining the initial conditions for a forecast; and the numerical prediction model itself, insofar as its version of atmospheric behavior is inevitably flawed. The remainder of this section addresses changes in observation networks, data assimilation methods and numerical weather forecast (NWP) procedures most likely to improve the prediction of the phenomena listed above.

C. Observations

A variety of observations may help overcome shortcomings in our analysis and prediction of high-impact winter weather. These include existing observational platforms already used for weather analysis and forecasting, observations with potentially new applications, and weather platforms planned or in development for use in the near future. Weather observations, combinations of different types of observations, and specialized observational networks have the potential to aid our current understanding of the atmosphere, improve short-term warnings, and improve numerical forecast model initialization and prediction and the evaluation of those forecasts and the key model physical parameterization schemes utilized therein.
Weather instrumentation includes both direct and remote sensors. We consider direct sensors first. The working groups identified two aspects of the Automated Surface Observing System (ASOS) of interest. First, recent research (Wade 2003) demonstrates that the ASOS Light-Emitting Diode Weather Indicator (LEDWI) sensor may be utilized not only for discriminating rain from snow but also for identifying drizzle, an important hazard to surface transportation and aviation when freezing on contact. Efforts to improve the identification of the mesoscale regions of mixed precipitation depend critically on ASOS measurements of snow, freezing rain, and freezing drizzle. In addition, the ASOS Cloud Height Indicator sensor may be used to improve cloud identification and the level of cloud base.

Among direct sensors, research aircraft observations, commercial aircraft pilot reports (PIREPS) of icing, and planned automated moisture measurements by commercial aircraft were noted by the working group as particularly important for winter hazard identification and prediction. Aircraft soundings of temperature, moisture, and wind will partly address the need for such measurements in the sub-cloud layer.

Numerous automated aircraft reports of wind and temperature (roughly 100,000 per day over the U.S. early in 2004), available through MDCRS (Meteorological Data Collection and Reporting System), have had significant positive impact on regional forecasts with the ETA and Rapid Update Cycle (RUC) models. Efforts are under way to increase the number of ascent/descent soundings and their vertical resolution. In addition, prototype moisture sensors (WVSS-2) will be tested on selected commercial flights during 2004 (AMS 2003).

Remotely-sensed measurements, whether surface- or space-based, hold great promise for winter weather assessment and prediction. Surface-based sensors already detect the melting layer, a critical region characterized by an isothermal layer at 0°C and cooling caused by the change of phase as snowflakes melt into raindrops. The melting layer is readily apparent as a bright band in radar reflectivity data, and as strong vertical velocity gradients in NOAA wind profiler vertical beam measurements. Though forecasters routinely use these observations, they have yet to be assimilated into numerical models.

Wind data from more than 60 boundary layer profilers are being collected throughout the country. Most of these operate at 915 MHz and have a vertical reach of a few kilometers. Many sites also measure virtual temperature profiles with a Radio Acoustic Sounding System (RASS). Operated by several different agencies and a few universities, they are collectively referred to as Cooperative Agency Profilers (CAPS). These observations can be made during stratiform precipitation. They provide valuable year-round sampling of the boundary layer and will soon be used in operational models at NCEP’s Environmental Modeling Center (EMC).

WSR-88D radar measurements at the minimum elevation angle can detect shallow precipitating clouds, at least at close range. Polarimetric measurements, planned as an augmentation of the WSR-88D network, should be able to distinguish among hydrometeor types within and below clouds. This is important for detection of cloud supercooled water (and icing hazards to aviation) as well as the habits of crystals falling into the melting layer. Such measurements are critical to proper initialization and validation of forecast models. However, the working group identified several shortcomings, including blockage or mountain shadow
effects, lack of measurements within the critical lowest few kilometers above ground, especially for radars located on high ground, and the likelihood of multiple types of hydrometeors within the radar sampling volume at greater distances. The possible implementation of additional radars, including the existing Terminal Doppler Weather Radars-TDWR and potential future radars (e.g., phased array, polarimetric X-band, CASA systems), and reduction of the minimum WSR-88D radar elevation angle below 0.5 degrees may improve the applicability of this data.

Space-based remote sensing may hold the greatest potential for improvement of cool-season mesoscale forecasts. Visible satellite imagery is routinely used to refine daily snow cover analyses, though the working group identified significant limitations in snow analyses, including a need for more frequent updates beyond once per day, analysis of snow depth, improvements to snow cover assessment when clouds are present, and determination of the snow water content. Infrared satellite imagery may be used to identify clouds with cloud-top temperatures higher than -10°C, which are more likely to have large supercooled water content and a heightened risk to both aviation (icing) and the surface (freezing drizzle). Multiple-channel data from geostationary (GOES) and polar-orbiting satellites are used to assess precipitable water content, distinguish between fog and low clouds at night, and add or remove clouds as the images dictate. Adjusting vertical velocity fields for compatibility with the altered cloud field remains a challenge in numerical model initialization. In addition, algorithms to detect clear, cloudy, or partly cloudy regions are being used to reduce false indications of cloud icing based on data from the Advanced Very High Resolution Radiometer (AVHRR) and the upcoming second-generation Meteosat satellites (Tafferner et al. 2003). Finally, the Advanced Baseline Imager (ABI) on future GOES-R satellites is expected to improve estimates of cloud-top temperature, low-level moisture and cloud particle sizes, detection of fog and supercooled water clouds, and discrimination between clouds and surface snow or ice (Schmit et al. 2004).

The working group found that satellite data, in particular, passive microwave imagery, are currently underused, but they are becoming increasingly valuable for assessing and improving the forecast of cloud properties. Given the critical role of cloud and water vapor information in mesoscale numerical weather prediction, these data are key for improving model initialization, forecasts, and verification on the small scales at which much severe winter weather occurs.

Atmospheric scientists are addressing the inherent uncertainty in model predictions through the concept of ensemble forecasting. The concept of uncertainty in the observations has received much less attention. Part of the uncertainty in an observation stems from measurement errors. Since it is impossible to know the precise value of the parameter being measured (instrument errors are usually estimated by comparing with an adjacent measurement by a different instrument), every observation may be viewed as a stochastic variable associated with some uncertainty. Another part of the uncertainty in an observation stems from its representativeness, that is, the size of the volume sampled and the sampling time. For example, a point measurement by a mercury-in-glass thermometer on a still, clear night may not be representative of conditions within a grid volume of the model that measures tens of kilometers on a side and 20 hPa deep.

Such uncertainties in the observations must be accounted for both in the assimilation schemes that feed observations into models and in the verification schemes that measure model
accuracy with respect to observations. Precipitation observations are a case in point. Precipitation observations help to estimate the latent heat release occurring within the model clouds at the start of a forecast, and they gage the accuracy of the precipitation forecast itself. Perhaps the analysis of precipitation (utilizing radar and rain gage data) should be treated as a stochastic field, subject to a range of values. This range of values could in turn be the basis for an ensemble prediction of runoff within a hydrological model.

Test-beds bring together a collection of observational, modeling, and human resources appropriate for addressing specific problems. Having asserted that mixed precipitation is the most serious wintertime QPF problem, the group proposed a test-bed to address it. Such a test-bed would be located in an area where mixed precipitation is relatively common, for example, in the mid-Mississippi Valley or in the southern New England and Mid-Atlantic states. The size of the test-bed would depend upon the specific questions to be answered. For example, if model physics is suspected as the chief culprit in poor forecasts of precipitation type, then the test-bed might not have to be much larger than the area surveyed by a single WSR-88D radar. On the other hand, if deficient observation coverage were suspected, the test-bed might have to be considerably larger.

In either case, the test-bed must be considered a multi-year investment because it will surely take years to identify and correct the deficiencies responsible for the poor forecasts. Test-beds should serve multiple purposes where possible. Toward that end, it is desirable that the test-bed area include a River Forecast Center.

D. Data Assimilation

Which assimilation method should be chosen?

The most fundamental question for U.S. efforts in data assimilation is much broader than cool season QPF: which path to follow in the next five years or so—a continuation of three-dimensional variational (3DVAR) assimilation, which is the current operational practice, or a transition to either 4DVAR or an 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 sub-hourly. 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 a 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 lack of maturity and only very limited testing in realistic applications.

Because early implementation of EnKF is risky and 4DVAR is very expensive, the recommended course for the next two or three years is continued enhancement of 3DVAR techniques while the pros and cons of EnKF and 4DVAR are thoroughly explored. The U.S. can learn from the Meteorological Service of Canada, which has already embarked on this course. In the U.S., the Environmental Modeling Center is considering the 4DVAR approach while also testing the EnKF method in collaboration with NASA. 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.

Atmospheric data sources not fully exploited through assimilation

The group identified mixed precipitation as the most important cool season QPF problem and cloud microphysics as the most deficient model component. This section focuses on radar and satellite observations because each gives information on the properties of clouds and hydrometeors.

Experienced forecasters seem to have little trouble incorporating information from satellites and radars into their local forecasts and warnings. By contrast, it has proven very difficult to assimilate these sources into numerical prediction models. In some ways, the problem is more difficult in winter than in summer. Some of the reasons for this are as follows:

- There is more precipitation from shallow clouds in winter than in summer. WSR-88D radars shoot over the tops of many of these clouds at ranges beyond ~100 km.

- In infrared images, it can be difficult to distinguish between the tops of low clouds and snow-covered ground when both are at similar temperatures.

- The bright band (a thin layer of enhanced reflectivity where falling snow begins to melt) is more common in winter than in summer.

- Hydrometeor type is much more variable in winter than in summer.

- Crystal habits are more important in winter than in summer. For example, when solid precipitation reaches the ground, the density of snow cover depends upon crystal habit and the degree of riming the crystals experienced while they were being formed in clouds.

Satellite measurements at microwave frequencies and scanning weather radars already give at least crude indications of water and ice concentrations within clouds. Microwave satellite data have resulted in significant improvements in global forecasts, but mesoscale applications thus far are few. The promised future capability of polarimetric measurements on 88D radars will reveal more about the variety of hydrometeors within clouds.
A forward model attempts to calculate the value of an observed parameter from the variables carried explicitly in the prediction model. For example, the radiance observed by satellite for a particular wavelength interval is calculated from a model temperature and humidity profile. A radar reflectivity is calculated from the collection of hydrometeors within the model cloud. Neither models nor measurements are yet very sophisticated in describing the full complexity of atmospheric clouds, and yet we know that microphysical processes within clouds are cumulatively important in delivering a fixed amount of water to the ground in solid, liquid, or partly melted form. To make better use of satellite and radar observations, we need to invent or improve the forward models with the help of the model-prescribed physics, and be able to put error bars on the raw measurements.

Mesoscale models have marginal capability for predicting cloud heights and cloud coverage. Infrared and visible images of clouds are being used to correct the model cloud fields at analysis time, which has resulted in short-term gains in cloud prediction. This is symptomatic of a larger problem. It is common experience when assimilating cloud and moisture data that the positive impact on forecast accuracy quickly fades. It is often gone within 12 hours. We need to understand why. It seems that the insertion of clouds, deletion of clouds, and incorporation of humidity and precipitation observations into a model are necessary but not sufficient conditions for continued retention of moisture information. There are many possible causes of the fleeting impact: inadequate areal coverage of the observations, problems with assimilation, resulting model imbalances, defects in model physics, predictability, and boundary conditions. Whatever the cause, the need for more effective assimilation of all sources of moisture data (condensate and vapor) is clear.

**Land-surface observations not fully exploited through assimilation**

The assimilation of land-surface data implies that observations of precipitation, precipitation type, albedo, seasonal vegetation, snow or ice cover, soil moisture, and others are used to correct the model specification of surface conditions. This procedure is most effective when the land-surface model is fully coupled with the atmospheric model.

The group identified the snow-cover product as the one in greatest need of an upgrade. The operational snow-cover product (used in the NCEP’s ETA and GFS models) is updated once daily at 1200 UTC, but cycling of snow cover is important considerably more often than once a day. Satellite methods depend upon cloud-free views, which are not always possible. Tom Carroll ([Tom.Carroll@noaa.gov](mailto:Tom.Carroll@noaa.gov)) leads the National Weather Service’s National Operational Hydrologic Remote Sensing Center in Chanhassen, Minnesota (visit [http://www.nohrsc.nws.gov/](http://www.nohrsc.nws.gov/)) which uses multiple sources of information to derive not only nationwide snow cover but also snow depth and water equivalent depth. Even if the snow-cover product cannot be delivered until many hours after the fact, it should be possible to conduct “catch-up” cycling to bring the assimilating model up-to-date.
Short-term development of 3DVAR

Until a decision is made to embrace an advanced data assimilation system for operations (4DVAR or EnKF), many improvements can be made to 3DVAR that have broad applicability:

- We need better statistics on observational errors, especially for parameters observed that are only indirectly related to the model variables.
- We need background error covariances and dynamical constraints that are appropriate for mesoscale flows, particularly those flows disturbed by convection.
- All errors in 3DVAR are assumed to have Gaussian distributions. This is not always a safe assumption; better statistical understanding of errors needs to be addressed.

E. Numerical Prediction Models

The working group addressed numerical modeling of winter QPF within four areas of concern: (1) the effect of model resolution on forecast accuracy, (2) identifying and quantifying model errors, (3) consideration of uncertainties in ensemble prediction of winter QPF, and (4) improving forecasts of high-impact winter weather, in particular, precipitation type at the surface. Areas (1), (2), and (3) are critical to winter precipitation forecasting, and each has the potential to significantly affect (4).

Model resolution is important to winter QPF in several ways. Shallow cold air masses, such as those within valleys or left behind retreating arctic fronts, may harbor freezing drizzle and aircraft icing. Such shallow layers of cold air will be inadequately represented within the model initialization or forecast without high vertical resolution near the surface. Given that phenomena are under-resolved in numerical models if they are less than 5-10 grid points in size, it is certain that many mesoscale weather features are either unrepresented or inaccurately treated by operational numerical prediction systems. As a result, important winter weather phenomena such as narrow cold frontal rainbands, lake-effect snow, gravity waves, and banded precipitation accompanying conditional symmetric instability may be poorly forecast, if at all, if model resolution is coarse. Zhang et al. (2002) found that increased resolution led to improved representation of moist processes, greater diabatic heating and latent cooling, more accurate precipitation type forecasts, and intensified cyclogenesis. High horizontal resolution must be accompanied by sufficient vertical resolution to avoid spurious wave development within forecast models (Persson and Warner 1991). Increased horizontal and vertical resolution is therefore critical to reproduce observed mesoscale weather systems.

While poor initial or boundary condition data can lead to significant model errors (Petersen and McQueen 2001, Langland et al. 2002), so can flawed model physics. The working group addressed methods to identify and quantify these model physics errors, which are of growing importance as model resolution is increased beyond the range for which many physics schemes were designed. The model physics critical to winter QPF include convective parameterization, planetary boundary layer (PBL) treatment, physics of the lower boundary, and parameterization of cloud and precipitation processes.
The topic of convection at the workshop was considered to be important, even in the cool season. Many significant snowfall events may have weak vertical or slantwise instability present, and thus combinations of stratiform and convective precipitation. Shallow precipitating convection may also occur. In some events, deep convection may play a significant role in a developing winter storm, as in the 1993 “Storm of the Century,” when convection over the Gulf of Mexico coincided with rapid cyclogenesis (Kocin et al. 1995). While the trend toward higher resolution prompted discussion on whether convective parameterization was becoming less relevant, the consensus was that parameterizations would be needed for some time, and deserve further attention and improvement until cloud-resolving models become the norm.

The parameterization of PBL processes was also singled out for examination. Many PBL schemes produce excessive vertical mixing, resulting in errors in boundary layer erosion and growth. Thus, these schemes have difficulty maintaining shallow cold layers, whether frontal or influenced by terrain. Finally, the fluxes in the boundary layer may not be adequately modeled, which is critical for a variety of weather phenomena including lake effect snow.

Numerous critical atmospheric processes occur at the surface, and several potential limitations in current prediction systems were noted. The initial state of the surface is often inadequately known, including the soil moisture and possible presence of ice (important for runoff during heavy rainfall), and snow cover, depth, and water content. The behavior of shallow, very stable or unstable boundary layers is often poorly forecast, including the formation of fog. More accurate and long-term measurements of surface fluxes were also singled out as necessary for improved model validation, refinement, and forecasts. Finally, the separation of land-surface model (LSM) schemes from the core model microphysics has been shown to result in inaccurate forecasts of freezing rain and melting snow under certain circumstances (Lackman 2004). Fully coupled treatments in which the above-ground microphysics are fully linked with land surface processes are necessary to avoid such problems in winter QPF and the accompanying temperature biases.

Cloud and precipitation physics treatments in numerical models vary greatly. Some of the known problems include: neglect of aggregation and breakup as ice crystals fall through the melting layer (Battaglia et al. 2003), oversimplified treatment of autoconversion, problems with ice nucleation, neglect of hydrometeor wind drift, errors tied to the small number of modeled hydrometeor species, and difficulty modeling supercooled liquid water in clouds. In addition, as a greater variety of hydrometeor classes are incorporated into numerical models, refinements may be necessary to radiation schemes. Finally, the sensitivity to snow distribution slope/intercept parameters indicates a need for improved sophistication in computations of ice crystal concentration.

Several times the discussion of winter QPF gravitated toward stochastic views of the atmosphere and probabilistic prediction. As in the warm season, cool-season mesoscale prediction is limited by uncertainties in initial and lateral boundary conditions as well as model physics. The relative ranking of such uncertainties for winter QPF is not yet clear, but model physics ensemble sub-sets are considered especially important in events with significant latent heat release. The horizontal and vertical resolution used, and how best to address model biases, are also key unresolved questions when considering ensemble prediction of winter QPF. It was
concluded that physics uncertainties, including the range of “constant” parameters within such schemes, should be included as part of the model physics parameterizations. One example given was the Grell/Devenyi ensemble convection scheme (Smirnova et al. 2004). Suggestions for improving our understanding of cool-season QPF uncertainties included model sensitivity studies, and comparison of model simulation data with in-situ and remotely measured observations during field campaigns such as the Improvement of Microphysical Parameterization through Observations and Verification Experiment (IMPROVE) in the Pacific Northwest (Stoelinga et al. 2003) and the Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) in the Midwest (Davis et al. 2003).

The working group concluded that determining precipitation type at the surface was the most important winter forecast challenge at this time. The difficulty of predicting the location and timing of a mesoscale region of mixed precipitation is compounded by the significant impact of even light freezing rain on surface transportation and aviation. Suggestions to improve numerical modeling of precipitation type included: (1) sensitivity studies of how hydrometeor treatment affects sub-cloud precipitation, (2) an evaluation of precipitation type forecasting by explicit numerical prediction versus diagnosing precipitation type from model output, and (3) new observations to improve and evaluate model forecasts of winter QPF. Comprehensive field programs and/or test-bed facilities were believed important for improved precipitation type forecasts, and detailed measurement of the vertical profiles of hydrometeor species was singled out as critical to this important forecast problem.

F. Summary

Setting priorities:

Priority 1 Better Forecasts of Precipitation Type

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

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

Priority 2 Better Observations in the Wintertime Boundary Layer

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, column water vapor as obtained from satellite or ground-based GPS measurements, a satellite cloud observation, or a radar reflectivity. These observations and their assimilation are relevant to precipitation amount and hence bear directly on the accuracy of flood forecasts.

**Priority 3 Recognizing Uncertainty in the Verifying Observations**

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 used to verify model forecasts. As an obvious example, the distribution, amount, and timing of precipitation are still subject to substantial uncertainty, even with automated rain gages and a network of Doppler radars. The uncertainties in precipitation estimates must be conveyed to hydrological models so that it becomes possible to predict a range of probable streamflows.

**How to measure progress**

One can quantify the effects on forecasts of observing systems, assimilation methods, and model improvements in 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 usually applicable to observing systems undergoing field testing, but good data coverage and at least a modest number of observations are usually 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. OSSEs are more labor intensive and computationally demanding than observation impact tests, and their results are subject to interpretation.

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.
Specific metrics

The group identified two classes of metrics, one related to specific phenomena, the other user-based.

Non-standard verification measures related to phenomena:

- Feature tracking of cyclones or jet streaks
- Size, orientation, and position of mesoscale precipitation bands
- Depth of cold air mass – relevant to precipitation type, warm-frontal overrunning, depth of convective layer in lake-effect snows, cold-air damming, erosion of stagnant cold air by strong winds above the inversion
- Location of transition boundaries within areas of mixed precipitation

The group relies on Working Group 4 for user-related metrics but mentions two as especially important: the economic impact of accidents and delays avoided in air and ground transportation as a result of improved forecasts.

Vehicles for progress

- The community effort to develop the Weather Research and Forecasting (WRF) system should be the focus of work to improve cool season QPF.

- A Developmental Test Center (DTC) is being organized in Boulder, Colorado, the purpose of which is rigorous testing of promising techniques, with the eventual goal of transferring proven techniques to operations. Those who seek to effect improvements in cool-season QPF should investigate resources available at the DTC.

- Regional field studies, capitalizing on observing systems of opportunity and perhaps temporarily augmenting observing capability, should adopt a test-bed approach toward improving wintertime forecasts of particular interest to the population and businesses of the region. One of the first test-beds should be located in an area where mixed precipitation is relatively common, for example, in the mid-Mississippi Valley or in the southern New England and Mid-Atlantic states.

Working Group 3* was charged with assessing various methods for observing the atmosphere on scales necessary to provide improvements in cool season QPF in the 0-48 h time range. Specifically, the team was asked to address the following questions: What observing systems and observing system tests are needed for test-beds focused on the cool season QPF problem (0-48 hr); What types of modeling tests are required as part of the test-bed activities; and how should a test-bed be implemented?

Although it was recognized that there are significant cool season QPF issues across much of the United States, the team rather early on agreed on 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, be it heavy snow or freezing rain, along and west of the I-95 corridor of the mid-Atlantic and Northeast. By focusing on these two winter phenomena, it allowed the team to address observation platforms that would not only address the QPF issue but just as important, the topic of quantitative precipitation estimation (QPE) for validation and nowcasting, and precipitation-type forecasts.

A. Observing System Requirements

The Observing Systems and Test-beds working group considered the types of observing systems that are required to address the cool season QPF problem in a test-bed framework. It is anticipated that additional complementary observations will be required for field campaigns conducted in connection with test-bed activities and structured in the traditional sense (e.g., the Genesis of Atlantic Lows Experiment - GALE, the Experiment on Rapidly Intensifying Cyclones of the Atlantic - ERICA, the Stormscale Operational and Research Meteorology Fronts Experiment Systems Tests - STORMFEST, the Pacific Land-falling Jets Experiment - PACJET, IMPROVE).

A summary of recommended observing systems for cool season QPF applications is shown in Table 3. The list is composed of both individual sensors and integrated sets of sensors and is divided by 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-based or space-based. Each sensor or array of sensors is described in the context of their 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. The stage of development indicator, “mature”, indicates that the observing system requires very little if any further development and either is already contributing to QPF or can be very shortly. Examples include surface networks, sonde systems, land-based wind profilers, the WSR-88D radar network and precipitation gages. However, there was much discussion by team members that although gages

may be a mature measuring platform, the current accuracy and density of the gages falls short of what is needed for accurate QPE for many cool-season applications, especially in measuring the liquid equivalent of freezing or frozen precipitation. This will require further development such

**Table 3. Observing systems to be applied to cool season QPF with a test-bed approach.**

<table>
<thead>
<tr>
<th></th>
<th>Nowcasting</th>
<th>Assimilation</th>
<th>Validation</th>
<th>Stage of Development</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In-Situ</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation Gages</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Mature</td>
</tr>
<tr>
<td>Stream Gages</td>
<td>Y</td>
<td></td>
<td>Y</td>
<td>Under way</td>
</tr>
<tr>
<td>Snow Depth</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Early</td>
</tr>
<tr>
<td>Ice accretion</td>
<td>Y</td>
<td></td>
<td>Y</td>
<td>Early</td>
</tr>
<tr>
<td>Hydrometeor Types</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Early</td>
</tr>
<tr>
<td>Sondes (Rawin, Drop)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Mature</td>
</tr>
<tr>
<td>ACARS (T, T_d, u, v, w)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Under way</td>
</tr>
<tr>
<td>UAVs (T, T_d, u, v, w)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Early</td>
</tr>
<tr>
<td>Surface nets (T, T_d, u, v, rad, T_{surf}, T_{subsurf}, Soil Moisture)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Mature</td>
</tr>
<tr>
<td>Buoys (T, T_d, u, v, SST)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Mature</td>
</tr>
<tr>
<td><strong>Ground-Based Remote</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WSR 88D (reflectivity, wind, QPE)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Mature</td>
</tr>
<tr>
<td>Polarimetric upgrade to WSR-88D(QPE, precip-type, refractivity)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Under way</td>
</tr>
<tr>
<td>Multi-frequency radars (QPE, precip-type)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Early</td>
</tr>
<tr>
<td>Vertically pointing S-band radar (reflectivity, fallspeed)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Mature</td>
</tr>
<tr>
<td>Gap filling radar: TDWR, Gap filling radar: ASR, ETL, CASA</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Mature</td>
</tr>
<tr>
<td>GPS TPW</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Under way</td>
</tr>
<tr>
<td>Microwave Radiometery (TPW, SLW)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Mature</td>
</tr>
<tr>
<td>Boundary Layer Profilers (Land) Buoy Mounted</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Mature</td>
</tr>
<tr>
<td><strong>Remote Spaced Based</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GOES cloud drift winds</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Under way</td>
</tr>
<tr>
<td>GOES IR QPE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Under way</td>
</tr>
<tr>
<td>GOES sounder</td>
<td>Y</td>
<td></td>
<td></td>
<td>Under way</td>
</tr>
<tr>
<td>POESS microwave sounder/imager</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Under way</td>
</tr>
<tr>
<td>POESS scatterometer</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Under way</td>
</tr>
<tr>
<td>MODIS surface snow/ice/water mapping</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Under way</td>
</tr>
</tbody>
</table>
as the NCAR “hotplate” sensor which shows promise but has not been tested under a wide variety of conditions. The stage of development indicator, “under way”, suggests that an observing system 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 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. The stage of development indicator, “early”, indicates that an observing system has yet to be fully developed or tested. There are several examples such as surface hydrometeor type, snow depth and ice accretion sensors, multi-frequency and gap-filling radars, and buoy-mounted profilers.

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 critical to QPF (e.g., wind, temperature, moisture). Likewise, almost all of the recommended observing systems have perceived value to operational forecasters in their nowcasting activities. The value of these observing systems to data assimilation is not as complete, but is still substantial. This may be related to the subjective nature of the assessment and the expertise of the group. As observing systems in their early stage of development begin to mature, their perceived value to data assimilation may increase.

Most of the recommended observing systems have applicability across all regions of the U.S. However, there are some regional differences in priority. For example, identification of the rain-snow line in the eastern half of the country is principally related to horizontal temperature gradients, whereas in the west, it is related mainly to vertical temperature gradients (e.g., melt/freeze level). The optimal sensor system for mapping this feature is therefore region-dependent. In the East, horizontal mapping with scanning radars, particularly of the polarimetric variety, is critical, whereas in the West, vertical profiling systems are adequate. Radar-based QPE is another application that has regional variability in the optimal observing system that is employed. One issue deals with the choice of wavelength or combinations of wavelength, particularly when polarimetry is involved. In relatively light precipitation regimes that are often observed in the West, upper Midwest and Northeast portions of the country during the cool season, radars at K-, X- and C-band could provide added value to the existing S-band observations. Advanced polarimetric techniques at these wavelengths can overcome most traditional problems in attenuation (to the limit of complete attenuation) through use of KdP methods (e.g., Matrosov 2002). However, in heavier cool-season precipitation regimes such as the Southern Plains and the Southeast, K- and X-band observations would likely have less applicability due to signal attenuation. Another regional difference in radar-based QPE observing system optimization deals with the density of the network. The western half of the country has substantially fewer radars and much less spatial coverage, particularly in the mountainous regions, compared to the eastern half. As a result, there is certainly a need for gap-filling radars in the West to fill in areas with no radar coverage or coverage well above the low-level precipitating cloud layer. In the East, the gap radars might be of lower power and specifically focus on the boundary layer, where identification of melting and freezing is critical.
B. Cool Season QPF Test-beds

The concept of test-beds has been embraced by the USWRP and others. Results from existing test-beds indicate that their goal of accelerating the transition of research into improved operational prediction can be realized when they focus on a particular phenomenon and/or region. Examples are the Joint Hurricane Test-bed (JHT) started in 2001, and the Hydrometeorological Test-bed (HMT) started in 2003. A recent workshop on Mesoscale Observing Systems held in Boulder dedicated a working group to define the key elements that distinguish a test-bed from more traditional research programs. The following consensus definition emerged from that workshop:

“A test-bed entails a working relationship in a quasi-operational framework among forecasters, researchers, 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 on existing partnerships between researchers, operations, and stakeholders, each with a vested interest in seeing that their investments translate to improved decision making. For example, for flooding issues in the West, federal and state water agencies such as the U.S. Bureau of Reclamation, the California Department of Water Resources, and the National Weather Service’s River Forecast Center and Weather Forecast Office are all collocated in the same facility in Sacramento, CA. In addition, the Army Corps of Engineers, along with private sector interests, are already initiating a program to identify opportunities to conduct pre-releases from Folsom Reservoir, a major reservoir providing water resources and flood protection for the city of Sacramento, based on forecasts of expected heavy rain and flooding. A concept of operations for a test-bed is shown in Figure 7.
A test-bed would be established having a baseline of observing tools designed to meet the minimum objectives of the program. These would be funded by the lead agencies and the stakeholders. 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 8 is a hypothetical timeline that shows how occasional focused field experiments fit into the ongoing test-bed framework.

![Relationship of Testbed to Field Experiments](image)

Figure 8. Concept of how a test-bed with periodic intensive field studies differs from traditional field programs.

C. Observing System Tests

The group identified certain observing system tests that would need to be conducted as part of overall test-bed activities (e.g. modeling tests, forecast technique development, and physical process studies). The observing system tests would include an objective, quantitative determination of the optimal mix of observing systems. This would be achieved by oversampling, installation of redundant sensors, and intercomparison of sensors measuring common parameters. From these, a determination of the most cost-effective observing platforms can be made. In addition, it will be important to determine the error characteristics of the observing systems, including quantification of both instrument and representativeness errors required by modern data assimilation systems. For those observations considered to have large uncertainty, it is quite possible that a probabilistic approach would be taken. A prime candidate for this might be QPE. This approach would be prudent given the likelihood that large uncertainties will remain, especially as time and space scales are reduced. In addition, it would be compatible with
and a step toward developing validation techniques for probabilistic QPF. A key part of the observing system will be application of integrated observing systems, both surface based and aircraft based. Combined instrument packages have proven to be very important in previous field programs for addressing such parameters as the microphysical properties of clouds. An important issue with respect to the observing systems test will be development and testing of better techniques and algorithms for data processing and data integration. A primary outcome of the test-bed is development of decision support systems for decision makers. A primary concern is that the observations be processed in a way to maximize their utility in the decision support system.

D. Modeling Tests

Another key component of the test-bed activity will be modeling studies. Although not an exhaustive list, the following were considered by the team to be important to the cool season QPF problem.

- An optimal mix of low-resolution ensembles and high-resolution deterministic models to assess the best approach for developing probabilistic quantitative precipitation forecasts.

- Statistical post-processing of ensemble and deterministic model output for bias removal.

- Assessment of model-simulated kinematic and microphysical structures of clouds and precipitation processes.

- Assessment of the ability of models to simulate seasonal distributions of precipitation (e.g. orographic, lake, and coastal effects).

- Development and evaluation of coupled atmospheric-hydrologic land surface models.

- Verification of the model data assimilation systems (e.g., 3DVAR, 4DVAR, ETKF).

- Validation of model simulations of boundary layer processes.

- Automated forecast techniques based on observations and models (e.g., nowcast techniques).

E. Implementation

As mentioned earlier, the team concluded that the two primary cool-season foci should be winter flooding in the West and severe winter weather, specifically icing, along the I-95 corridor in the East. Establishment of the test-bed concept within these regions will require federal, state, and local government agencies, along with the private sector and university interests to partner in supporting the backbone of observing systems that will address the cool-season forecast challenge. In addition, it is anticipated that a regional modeling center would need to be established to run regional high-resolution numerical models and lower-resolution ensembles. A
dedicated staff of public, private, and academic sector researchers, working closely with forecasters and stakeholders will be necessary to assure that the decision support systems produced meet the requirements established by the decision makers, and that the appropriate agency, be it government, university, the private sector, or a combination, be willing to take over the continued costs of maintaining the infrastructure once the test-bed demonstration period has concluded. This will be a critical measure of success for the test-bed concept. In addition, it will be essential to quantify the impact of observing systems on the QPF forecast process. It was discussed that the Weather Event Simulator (WES), a simple PC running FX-net software, which is installed in each NWS forecast office, might provide a way to measure the impact on the forecast for many different forecasters. This might eliminate the need to establish parallel forecast offices, one operating without the newest observing systems, and one with full access to the test-bed data sets. In order to accomplish this, output from the observing systems will need to be tailored for viewing within the WES. This will not be a trivial effort.

It is important to consider lessons learned from the Joint Hurricane Test-bed (JHT) which has focused on testing and adoption of new forecast tools and techniques at the primary center responsible for tropical prediction in NOAA, the Tropical Prediction Center. The forecast process that yields QPF for the nation is more distributed in nature, including key roles for NCEP/HPC, the 6 River Forecast Centers (RFCs), and over 100 WFOs. In addition, the long-term nature of the test-bed approach requires focused research investment over many years, a role that is critical for national research laboratories, such as those in NOAA that are already active leaders of HMT (i.e., OAR/ETL, NSSL, FSL, and NWS/OHD/HL). Finally, advances in physical process understanding are a critical part of test-bed activities that can enhance forecaster knowledge, and which can be facilitated through grants to the academic sector. To attract the academic sector into such a long-term commitment may require three-to-five-year funding agreements to assure that resources can be maintained throughout the extended periods associated with the test-bed process.

Working Group 4* identified the users and their need for winter 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 they desire from winter QPF products. Included in that process are a number of metrics that gage the performance at each step. Three examples of this process applied to specific user groups are presented as examples.

A. Users of Winter QPF Information and Determination and Validation of their Needs

Although all user groups were not represented at the workshop, the group attempted to consider as many user groups as possible in the discussion. Table 4 lists key users of winter QPF. The most important methods of determining user needs, based on the group’s experiences, are listed in Table 5. The example of the Maintenance Decision Support System (MDSS, Pisano et al. 2004), a Federal Highway Administration effort to use QPF and other information to effectively treat roads during winter weather, is used to illustrate some examples in Table 5. The MDSS project is a multi-year effort to combine advanced numerical weather prediction with computerized winter maintenance rules of practice. The result of the project is to develop a prototype interface aimed at state department’s of transportation maintenance garage supervisors. Output from the system consists of treatment recommendations optimized to minimize the application of chemicals, make most efficient use of personnel and equipment, and to maintain safe mobility conditions on roadways.

Table 4. Four prominent user groups for winter QPF

<table>
<thead>
<tr>
<th>Hydrology</th>
<th>Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Public &amp; Private water suppliers</td>
<td>• Surface</td>
</tr>
<tr>
<td>• Energy producers</td>
<td>o Highway</td>
</tr>
<tr>
<td>• Recreation</td>
<td>o Transit</td>
</tr>
<tr>
<td>• Natural resources</td>
<td>o Rail</td>
</tr>
<tr>
<td>• Flood Management</td>
<td>• Aviation</td>
</tr>
<tr>
<td></td>
<td>o Aircraft icing &amp; deicing</td>
</tr>
<tr>
<td></td>
<td>• Marine</td>
</tr>
<tr>
<td></td>
<td>• Pipeline</td>
</tr>
<tr>
<td>Emergency Managers</td>
<td>Utilities</td>
</tr>
<tr>
<td>• Natural disasters</td>
<td>• Communication infrastructure</td>
</tr>
<tr>
<td>• Man-made disasters</td>
<td>• Power suppliers</td>
</tr>
<tr>
<td>• Homeland security planning</td>
<td>• Delivery of supplies</td>
</tr>
<tr>
<td>• Public Health</td>
<td></td>
</tr>
</tbody>
</table>

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

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### Table 5. Methods to determine user needs for cool season QPF products

<table>
<thead>
<tr>
<th>Method of determining needs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surveys of stakeholder groups</strong></td>
<td>Most direct method of eliciting information on the users’ needs of QPF products. Scenarios can be used as part of the surveys to help elicit responses.</td>
</tr>
<tr>
<td><strong>Storyboards</strong></td>
<td>Educate the user on “the art of the possible.” The MDSS showed that when stakeholder groups were shown conceptual prototypes of the proposed system, users were able to identify new uses of the product that had not been identified during the survey process. The eventual development of a product using winter QPF will require that the storyboard conveys the information that will meet all the user needs. Human-factors engineers must be engaged in the design of the storyboard and the final user interface.</td>
</tr>
<tr>
<td><strong>Scenario generation</strong></td>
<td>The development process of the MDSS showed how the presentation of weather scenarios and observing user response to those scenarios can reveal new applications for the information. Important requirements such as the top ten most important weather parameters for winter maintenance or the most important times for planning maintenance operations were obtained using this method.</td>
</tr>
<tr>
<td><strong>Demonstrations of Functional Prototype/Actual use of the products</strong></td>
<td>When winter QPF products are used operationally, the customer may realize that there are further needs that may not have been previously identified. This interaction between developers and users should be an iterative process, whereby feedback from the users is implemented into new versions of the QPF product. Moreover, user inclusion from the beginning of the process guarantees that the users have a sense of ownership of the process and product, thus assuring success.</td>
</tr>
</tbody>
</table>
In order to accomplish these goals, the MDSS development team had to implement a requirements definition plan that consisted of the creation of a diverse stakeholder group, the presentation of scenarios and attendant surveys, and the use of spiral development from conceptual storyboards to functional prototypes.

B. Involving Users in Test-beds and Advancements of 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. (A natural question is how to engage the public, private, and academic sectors.) The Fair Weather Report provides an excellent example of the relationships between users and their information needs and the actions that they take. The lessons learned from this report are that collaboration should start at the beginning of planning and include all stakeholders. Task forces should attempt to bring disparate users together, developing incentives if necessary.

Decision makers and those affected by decisions should be included from the beginning of all product development. It is extremely 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 developed and provided is effective and presented in the most efficient manner.

The members of the working group acknowledged that each industry sector would have different relationships and interactions among stakeholders. For example, the needs of the hydrometeorological stakeholders differ markedly from the needs of the aviation stakeholders. The working group recognized that the interaction between diverse stakeholders and developers often necessitates a facilitator to most productively interact and define the successful path for development and eventual operational deployment. The group also recognized that it is often a challenge to successfully engage the academic sector for the duration of long-term research projects. The ultimate goal of the academic community is to educate and graduate students, which does not fit well with long-term research and development products that often take 10-15 years to complete. However, a well-managed R&D program can involve students and professors by appropriately defining sub-tasks that can lead to masters’ and doctoral theses.

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 (ROI) to be made through the use of these products. The ROI 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 risk and the private sector uncertainties related to new product development. This process is most effective when there is a partnership between the private sector and the federal government such as Small Business Innovative Research (SBIR) grants.

C. A Roadmap to Successful Development of Winter QPF Products

The working group outlined the following steps as necessary for successful development of winter QPF products:
1) Determine and validate user needs for cool season QPF products. User groups involved to determine these needs should include both users of the information and those impacted by the decisions. Include a synthesis/literature review to identify cases where needs have been documented and/or cost/benefit studies have been completed.

2) Evaluate the social, environmental and security impacts of the winter QPF product. For example, perform a cost/benefit analysis, consider impacts because of required sensor locations (the use may require the placing of a sensor in an environmentally or nationally sensitive area).

3) Develop 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 system based on user response (iterate).

7) Transfer technology to operations based on the operational concept defined earlier in the process.

Figures 9-11 present sample implementation plans for a QPF decision support system for road weather, hydrology, and aircraft ground deicing. The diagrams show that there are four key components to successful implementation: 1) accurate decision making 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 that is explained below. All four components feed back to previous components, thereby ensuring continual improvement to the implementation process.

Figure 9. Road weather implementation diagram
### Hydrology

**Highly accurate river forecast flow**

- Public & Private water suppliers
- Energy Producers
- Recreation
- Natural Resources
- Flood Management

**Measuring the value**

<table>
<thead>
<tr>
<th>System Performance (Output)</th>
<th>User Acceptance (Output)</th>
<th>Decision Effectiveness (Output)</th>
<th>Operational Improvements (Outcome)</th>
</tr>
</thead>
</table>

- When and how much water to release
- Evacuation orders
- Sandbagging
- Flood Mitigation Strategies

**Figure 10. Hydrology implementation diagram**

### Ground Deicing

**Highly accurate snow forecast**

- Aircraft Operations
- Aircraft Deicing Managers
- Air traffic Controllers and Managers
- Airline Dispatchers

**Measuring the value**

<table>
<thead>
<tr>
<th>System Performance (Output)</th>
<th>User Acceptance (Output)</th>
<th>Decision Effectiveness (Output)</th>
<th>Operational Improvements (Outcome)</th>
</tr>
</thead>
</table>

- When and what type of deicing fluid to use
- Flight Cancellations
- Air traffic gate holds
- Runway Plowing

**Figure 11. Aircraft ground deicing implementation diagram**
D. Other Activities to Advance Long-term Goals

There is considerable QPF information already available of which users are not necessarily aware. The group identified a number of one-to-two-year projects that could take advantage of this information and provide users advanced forecasting capability in the short term. The identified projects are:

*Develop storyboards based on existing capabilities*

An efficient way to convey integrated operational concepts to users is through the use of storyboards. This project would develop a storyboard of current available QPF technologies, including the emerging NWS capability to provide probabilistic forecasting into reservoir management systems.

*Identify and interview forward thinkers (end users) in each industry to help define initial operational concepts*

To expedite input to QPF product developers, interviews with key forward-thinking end users could facilitate rapid transfer of operational concepts. This process has been used in a number of previous winter product developments with good success (Weather Support to De-icing Decision Making, WSDDM, Rasmussen et al. 2001).

*Baseline current winter weather impacts on infrastructure*

In order to determine the benefits of any new winter weather QPF product, one must take inventory of the current capabilities. For example, we know that approximately 7000 highway deaths occur annually during adverse weather (Goodwin 2003). However, it is not known whether these are truly caused by weather or by some unrelated factor. Therefore, a more detailed analysis is needed. Other sectors have similar needs (pipeline damage due to floods that could be better managed by improved QPF forecasting, transmission line damage due to ice accretion, etc).

*Document benefits and costs of improved QPF products*

A number of current studies have addressed the costs and benefits of the use of improved QPF products. One example is a recently completed study on the American River in California. This study reveals that improved 72-hour probabilistic QPF forecast using ensembles can improve the level of protection to Sacramento such that the increased average annual damages prevented is about $19M (USACOE 2002). These already completed studies can provide guidance for the direction of future research and development regarding QPF products.

*Develop culture-change training material on the use of probabilistic products*

Existing QPF products are deterministic, even though some existing decision support tools use a probabilistic approach. There is a need to train forecasters and users on the approach and methodology of probabilistic ensemble forecasting. If they do not understand the probabilistic
methodology and results, it is highly unlikely that they will have confidence in them. This task would be well suited for the University Corporation for Atmospheric Research COMET program, for example. Another mechanism for conducting this training is engaging community colleges to perform relevant workshops and training.

E. Measures of Success

To assess the development of an appropriate QPF product, it is necessary to establish performance metrics for each of the four implementation components mentioned above. For example, some measures of success for each of the four components in hydrology are:

Information: accuracy of river flow forecast from probabilistic space-time-quantity-type precipitation.

Users: degree of understanding and acceptance of the product by water resource and emergency managers.

Decisions: decision ease and increased level of confidence in the decision making process.

Results: improved safety, flood damage reductions, increased economic benefits in agriculture, energy production, water supply, protection of the environment, and public health.
6. **Summary: Implementing the Cool season QPF component of USWRP**

This section synthesizes input from the Workshop into three core recommendations that can be addressed through a nationally coordinated Hydrometeorological Test-bed approach. Implementation of these recommendations includes conducting two major interagency field studies over the next several years, as described in section 6b. Section 6c outlines approximate roles for several agencies and timelines based on the types of work that each agency traditionally undertakes. Although it is important to understand what costs each agency might incur to implement this plan, the level of participation from each agency is not estimated here. Essentially, the amount of progress is related to the investments that are made and how well they are coordinated. It is the degree to which each agency can bring existing or new resources to bear on this important problem that will determine the scope and rate of progress.

Through its role in advocacy, interagency coordination, and direct sponsorship of the HMT approach and associated field studies, the USWRP would be better able to demonstrably achieve its goal of fostering research that improves QPF.

**a. Core recommendations**

The Cool Season QPF workshop focused on short-term (0-48 h) forecasts of cool-season precipitation with a strong emphasis on mesoscale phenomena. The workshop recognized that many important phenomena contribute to the difficulty of cool season QPF in the United States, including snowstorms with convection, banded precipitation, freezing drizzle and rain, supercooled clouds, flooding winter rains compounded by snowmelt, cold-air damming in the lee of the Rocky Mountains and Appalachians, lake-effect snow, and orographic precipitation. While the warm-season counterpart to this report (Carbone and Fritsch 2003, 2004) included an in-depth examination of issues related to deep convection, this cool-season report places less emphasis on convection, and instead focuses on issues related to snow and other forms of frozen precipitation at the surface. Nonetheless, both reports reached a similar conclusion regarding the adoption of a Hydrometeorological Test-bed approach to enhance linkages between research and operational QPF. A successful initial implementation of HMT in NOAA was established in 2003 through a joint project between NOAA Research Labs, NCEP/HPC, and River Forecast Centers focused on cool season QPF. Lessons from this experience helped inform this report. Additionally, the recent Workshop on Mesoscale Observations also identified a test-bed approach as an effective method to improve the operational observing system.

**Core recommendation #1: Establish a National Hydrometeorological Test-bed Approach**

Each of the working groups of the workshop considered the potential of test-beds to advance our understanding of cool-season processes and take the next important step of actually achieving advances in operational cool season QPF through pilot studies. From the reports of the working groups, a consensus emerged 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, including winter weather, are greatest.
Based on recommendations of the Working Groups, the cool season QPF community proposes that the USWRP support the implementation of a national Hydrometeorological Test-bed (HMT) strategy focused on improving cool season QPF, including two long-term regional efforts. One 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 effects as priorities, i.e., HMT-East, while the other should focus on water resource related issues in the West, with flood control, water supply, and orographic effects as priorities, i.e., HMT-West (Figure 12). Longer-term, continuous activities that are required to optimize operational impacts are the focus of HMT. The HMT infrastructure then provides a foundation upon which to conduct episodic major field programs that are required to address certain key research and forecasting problems.

**Overarching Recommendation:**

**Use a National Hydrometeorological Testbed (HMT) approach to improve cool season QPF**

Fig. 12. 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, i.e., 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.
Core recommendation #2: Develop Probabilistic Methods

Subtle problems, such as small errors in near-surface temperature predictions or small changes in wind direction, can dramatically impact the accuracy of cool-season forecasts. Scientific questions related to each of these key areas and phenomena were posed and test-bed approaches to addressing these questions debated. The workshop recognized in this debate that there are major regional differences in the user needs for cool season QPF, that forecasts should be tailored to those needs, and that there are important regional differences to address in terms of both the physical processes and observing systems.

The workshop concluded that the most productive approach to wintertime QPF is to provide the user community with probabilistic forecasts that specify the size, position, orientation, timing, and amount of precipitation within regions of snowfall and mixed precipitation, as well as probabilistic products specifying the location of boundaries separating precipitation types.

Core recommendation #3: Advance mesoscale data assimilation and modeling

Because early implementation of EnKF is risky, and utilizing 4DVAR would be very expensive, the recommended course for the next two or three years is continued enhancement of 3DVAR techniques while the pros and cons of EnKF and 4DVAR are thoroughly explored. 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.

b. Cool Season HMT Interagency Field Studies

i. HMT-West

The first realization of HMT was established in the western United States in 2003 through a pilot study on the flood-prone Russian River of Northern California. This study, jointly led by NOAA Research and NWS, has laid the groundwork for improving cool season QPF in an area where researchers and forecasters have been working with key forecast users. This collaboration has focused on mitigating flood risks through better flood warnings and orographic QPF, and on improving forecasts of snow level for a critical east-west bound highway (I-80). Because significant adverse effects will ensue if these user groups take action based on inaccurate forecasts, it is critical that the forecasts be of the highest possible accuracy. The enhanced predictability of major precipitation events created by orographic forcing makes this area and season the most tractable to demonstrate improved user decision making. Lessons learned on the Russian River in 2003 and 2004 are being applied to the planning of a more comprehensive study on the American River in the western Sierra Nevada focused on the winters of 2005/06 and 2006/07.
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 NOAA Research and 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 been committed already, and requests for NOAA aircraft and ship facilities have been submitted for FY06. Research on satellite-based techniques using QuickScat and the Tropical Rainfall Measuring Mission (TRMM) in this area have been sponsored by 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 Measurement (GPM) data. The opportunity that this project represents has also led to recognition in the university research community that 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 the efforts of the Army Corps of Engineers and local flood-control agencies that have created unique tools for use of QPFs in reservoir operations. Finally, the impact of unexpected snow events on highway transportation across the Sierra presents a clear opportunity to address ground transportation issues.

**ii. HMT-East**

Winter storms along the U.S. 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 2004a,b). 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 southeastern 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 shown by Zhu and Newell (1998), based on numerical model simulations, and by Ralph et al. (2004), based on experimental and satellite observations, narrow filaments known as atmospheric rivers are responsible for >90% of the meridional water vapor transport at mid-latitudes. This suggests use of a “picket fence” approach along both the northern Gulf Coast and the southern Atlantic Coast. 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 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 U.S. Additionally, wind profilers could be mounted on one or more oil platforms in place in the Gulf of Mexico. As many as 20 transportable 915 MHz wind profilers are currently available from NOAA/ETL (15) and NCAR (5). Additionally, a mobile integrated sounding system (MIPS) is available from the University of Alabama at Huntsville, and additional platforms could be developed at ETL. There is also some potential value in deeper-tropospheric wind profiling systems to monitor the subtropical jet that often comes across the Yucatan in major events. Lower-frequency wind profilers, such as 449 MHz, are capable of making continuous observations to much higher altitudes than boundary layer profilers and could be deployed in Mexico for this purpose. One such radar is being deployed by ETL in Mexico during summer 2004 as part of the North American Monsoon Experiment (NAME).

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 involved would be amenable to deployment of NOAA’s P-3 and G-IV research aircraft from their home base in Tampa, Florida, and for deployment of the NASA ER2 aircraft. The Air Force C-130s are based in Mississippi and also could be used (as they already are on occasion) for dropsonde deployment. Experience gained during the PACJET and Winter Storms reconnaissance projects in the Pacific can be used to help in the development of this project, from flight strategies for observing atmospheric rivers to dropsonde targeted observations and key boundary layer process studies. It is likely that the verification area for the experiment would include regions within reach of the 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 precipitation. The convenient locations of the experimental areas with respect to aircraft home bases could save enormous operational costs normally associated with travel and more remote deployments. It is also likely that university and 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 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 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/ETL, NCEP/Hydrometeorological Prediction Center, RFCs and WFOs.

HMT-East addresses most of the major issues identified by workshop participants as key to the cool season QPF problem in the eastern U.S. There are also substantial Canadian interests in East Coast storms and it is expected that cooperative efforts with the Canadian Atmospheric Environmental Service, Canadian universities, and other Canadian meteorological institutions would 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.
c. Interagency roles for implementing the CSQPF Core Recommendations

The following chart (Fig. 13) illustrates a sequential approach to implementing CSQPF’s goals from FY2005-2014 through a coordinated interagency effort that builds on each agency’s expertise and traditional roles. Both the sequencing and duration of key directions for each agency are highlighted schematically. In this scenario, every three years the agencies coordinate on a major interagency field study. These are identified here schematically for FY06, FY09, and FY12. Each study focuses on a different primary CSQPF objective as described above.

- **NOAA**: For NOAA, which is responsible for providing forecast and warning services as well as long-term research capabilities, there is the initial development of an HMT National Infrastructure that brings together, focuses, and strengthens elements in NCEP/HPC, NWS/OHD, NOAA’s Research Laboratories and JCSDA. In addition, NOAA invests in longer-term regionally focused efforts lasting roughly five years each. NOAA’s activities are shown from the first year of this chart since it has already conducted HMT-2004.

- **NSF**: Bringing the depth of knowledge and research skills found in the university community is critical to advancing research on CSQPF. NSF can play an important role by sponsoring targeted field studies in the regions addressed by HMT. Each field study year is followed by a three-year analysis phase, as is traditionally done in NSF. This is shown for three cycles covering orographic effects, mesoscale aspects of East Coast cyclones, and icing research.

- **NASA**: As one of the key research-focused agencies, NASA has significant facilities that have been brought to bear on key problems such as hurricanes (e.g., CAMEX I-IV) that could be targeted at cool season QPF issues, including the winter-season version of hurricanes (i.e., Nor’Easters and eastern Pacific Cyclones). In addition, expertise on satellite evaluations can contribute substantially to improving QPF, partly through JCSDA, but also through developing tools to use data from the GPM for which launch is expected in 2010.

- **FHWA**: As a major and sophisticated user of CSQPF, the FHWA plays a role through development of targeted applications and their supporting tools. Testing and evaluation of prototype tools can be accomplished efficiently through the long-term HMT-focused regional activities. The strategy described addresses the major cool-season issues for ground transportation sequentially, starting with issues in the mountainous West (HMT-West) such as snow level and snow depth along interstates (e.g., I-5 and I-80), and following with issues in the east (HMT-East) focused on icing and heavy metropolitan snow. Each targeted highway corridor is the focus of a two-year effort in this scenario.

- **FAA**: With a long history of active participation in weather research for aviation purposes, the FAA has much to contribute to this effort and many benefits to reap. Of particular importance are better predictions of icing conditions and heavy snowfall, which are the focus of HMT-East.
• **Army Corps of Engineers**: The Corps is responsible for operating many of the nation’s reservoirs, and must balance many competing needs, e.g., flood control vs. water supply vs. endangered species. Because reservoir operational procedures were developed when reliable QPF was not available, use of CSQPF requires major revisions to existing procedures. The Corps has made the most progress on this with respect to flood-control procedures for the Folsom Dam on the American River of California. For this reason, the focus of Corps activities for CSQPF are most sensibly aligned with HMT-West, for which planning is already under way. Key activities include collection of high-resolution precipitation data, development of better forecast tools, and estimates of forecast uncertainties. The challenge of these problems requires relatively long-term investments. Future efforts in the East could focus on snowmelt flooding and ice jams.

![Figure 13. Schematic summary of multi-agency involvement in achieving improved CSQPF through strong interagency coordination.](image)
References


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