Because precipitation strongly affects many aspects of our economy and general livelihood, efforts to improve warm-season quantitative precipitation forecasts (QPFs) have commanded a high priority in meteorological research. Nevertheless, despite steady improvements in forecasting precipitation amount (Fig. 1), a very low level of skill persists in summer (Fig. 2). The high societal impact of warm-season rainfall, together with the low operational forecast skill, suggests that warm-season rainfall prediction should be established as a principal focus of the United States Weather Research Program (USWRP).

Recognizing the need for improvement in warm-season QPFs, a workshop was

**Fig. 1.** Annual threat scores for the NOAA Hydrometeorological Prediction Center (HPC) for 24-h forecasts of ≥ 1.00 in. or more of precipitation.
conducted in March 2002 to develop an implementation plan for the USWRP. The organizational steps, workshop participants, and interim reports are summarized in appendices A through H. A report from each of the subgroups is provided in appendix H. These reports constitute a reservoir of specific actions, many of which clearly should be taken as part of the program implementation. An independent reading of appendix H is highly recommended, especially as planning and funding progress through the interagency process.

Based on the subgroup reports, major themes and key elements were identified. A strategy for future predictions and a framework within which to attack the QPF problem is advanced in section 2. Areas of focus, distilled from the subgroup reports, are summarized in section 3. Section 4 outlines some practical steps toward implementation of needed research and a program of advanced forecast demonstration.

**STRATEGY AND FRAMEWORK FOR RESEARCH AND DEVELOPMENT (R&D).** As an outgrowth of the subgroup reports, the overarching strategy is to provide user guidance in a probabilistic form. The selection of this strategy is based upon the following arguments.

**Risk management and probabilistic guidance.** Risk management is central to the efficient execution of operational systems, such as mitigation of impacts resulting from natural hazards. It is generally recognized that probabilistic guidance facilitates risk management in a multitude of applications.

**Convection, deterministic prediction, and probabilistic guidance.** The core of the warm-season QPF problem is how to reliably forecast deep, moist convection. In a world of nearly perfect forecasts, deterministic prediction of convective events would stand on its own. However, given the uncertainty and bias in real world predictions, skillful deterministic forecasting of moist convection will likely be limited to less than 3 hours for the foreseeable future. Beyond this time frame, skill will be manifested through the statistical properties of the forecasted convection. Therefore, deterministic prediction should be viewed as a foundation upon which probabilistic prediction is built. That is to say, probabilistic predictions can be improved through the use of ensembles and the application of statistical postprocessing to deterministic forecasts. As deterministic forecasts improve, the uncertainty will decrease and the potential for improved specificity will increase. Improving deterministic forecasts will improve probabilistic guidance by sharpening the probability distributions. The practical consequence of this circumstance is that improved deterministic prediction must be pursued principally to improve future probabilistic forecasts beyond the nowcast range.

**Representation of convection.** Owing to limited computational resources, moist convection must be parameterized in current operational models. Parameterization of moist convection has inherent limitations and, as a result, has contributed to a long history of little progress in improving QPFs. It is believed that improved representation of convection in forecast models is a necessary path through which major advances will be realized. To this end, sufficient computational resources will be available in the not too distant future for explicit representation of moist convection. It is expected that explicit representation of convection is far better suited to capturing the critical statistical properties of moist convection heretofore arbitrarily specified in convective parameterization. Therefore, the balance of this report proceeds with the understanding that explicit representation of convection should ultimately replace parameterized convection in USWRP efforts to improve QPF.

**Forecast bias and statistical postprocessing.** Statistical postprocessing can be applied to deterministic forecasts (and ensembles thereof) to generate reliable probabilistic forecasts. Given a time series of obser-
vations and forecasts with adequate duration and resolution, forecast bias can be minimized and uncertainty quantified. As the duration of time series increases and/or as statistical analyses improve, improvements in probabilistic forecast skill can be achieved, even in the absence of improved understanding of precipitation processes.

**BACKGROUND AND PROPOSED AREAS OF FOCUS.** Certain issues, ideas, and activities emerged as being particularly important for advancing QPFs. Several of the items that emerged most strongly are discussed below. The discussion begins with the use and value of warm-season QPFs; continues with process representation and observational requirements for QPFs; and then identifies certain R&D challenges, which must be overcome to provide reliable probabilistic guidance for end users.

**Use and value of QPFs.** Weather information has no intrinsic value to society unless there are end users of that information. In the case of warm-season QPF, current and prospective users abound and few sectors of society are spared. Water management in various agricultural and urban applications, electric power generation, and pesticide application are among a myriad of QPF applications. While aviation is not a user of QPFs per se, warm-season QPF is tantamount to accurate thunderstorm prediction, the major source of commercial air traffic delays in the United States.

Unfortunately, the economic and social impacts of warm-season rainfall and related forecast information have not been quantified. There is an inadequate understanding of how QPFs are actually used, in what form these are applied, and what decisions are made or influenced on the basis of forecast products or analyses. Furthermore, the marginal value of improved QPFs should be better understood to bolster the justification for an additional national commitment to research and development.

It was concluded that a social science research effort should be mounted, early on, to help quantify the various uses and value of warm-season QPFs. Such research should include baseline studies to quantify current practice and analyses of decision-making value in various economic sectors for the relevant ranges and scales of prediction. The findings from these studies will likely influence both the meteorological research emphasis and the envisioned forecast system properties, including the analysis and forecast product stream.

**Process representation and observational requirements.** As mentioned previously, improving warm-season QPFs is tantamount to improving forecasts of moist convection. Numerous field experiments, cloud-resolving model simulations, and sensitivity experiments clearly indicate that anticipation or replication of convective events typically requires the following:

- knowledge of the cloud-scale and mesoscale structure of the environment,
- adequate understanding and representation of cloud-scale and microphysical processes, and
- realistic treatment of certain subcloud-scale processes such as moist turbulence.

Field programs and numerical experiments have demonstrated that the timing, location, and organizational mode of convective events are often sensitive to cloud-scale planetary boundary layer (PBL) variations in temperature, moisture, and kinematic features that are, in part, related to variations in soil moisture and vegetation. Moreover, numerical sensitivity experiments, in which microphysical parameterizations are varied, produce significant changes in the phase speed of convective systems, the area of rainfall, and the magnitude and distribution of the rainfall. As resolutions are increased to the point wherein subcloud-scale turbulent eddies are resolved ($\Delta x \sim 100$ m), qualitatively similar changes are produced as a result of the increase in resolution. These immense sensitivities help to explain why expectations for skillful deterministic forecasts now appear limited to less than 3 h. They also lend support to the workshop consensus that probabilistic forecasting is the most logical path to pursue. An especially important goal, then, is for forecast systems to generate convective clouds and convective systems with statistical properties that resemble observed properties.

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2 As used here, the term "reliable" means "without bias." For example, for all forecasts for which the probability of a particular type of event is say 70%, reliability requires that the event will happen 70% of the time; for all forecasts for which the probability is 20%, the event will happen 20% of the time, etc.

3 For the purposes of this report, cloud-scale properties or processes are considered to be those resolved with grid lengths on the order of 1 km. The term "subcloud scale" refers to features or processes requiring grid lengths of the order 100 m or smaller to be resolved.
For example, it is expected that models will be able to forecast areas of convective storms—but will not be able to forecast the location, structure, and movement of the specific individual thunderstorms within the area of activity. On the other hand, it is expected that the properties of the individual storms and storm systems forecast by models will be similar to those observed. Specifically, the distribution of storm types (supercells, multicells, etc.), rain rates, cloud-top heights, phase speeds, etc., should be similar to that of the observed population of thunderstorms. Likewise, it is expected that the models would exhibit skill in forecasting the organizational mode (e.g., squall line, MCC, isolated cells, etc.) of convective events.

In order to best equip models to accurately forecast storm properties, the subgroups noted that it is most desirable to

- construct new models with more realistic representations of physical processes, especially microphysics and moist turbulence; and
- further integrate the strengths of nowcasting systems with dynamically based models by fully incorporating mesoscale and cloud-scale structure of the environment in model initialization.

Workshop participants recognized impediments to the inclusion of such detailed information in forecast operations at the present time and for the near future. This suggests that actions should be taken to increase the likelihood that the desired information (or suitable alternatives) will be available to future forecast systems for application in nowcasting and the shorter ranges of dynamically based prediction. Toward this end, several of these high-priority areas of R&D and related actions are discussed below.

**Understanding microphysical properties and processes.** The extreme sensitivities in cloud-resolving model simulations are strong testimony to the need for improved understanding of the physical properties and processes that influence the life cycle of moist convection. Although it is possible to increase forecast skill through application of statistical techniques alone, without new understanding, these improvements will be limited and will likely remain well below the practical limits of predictability. Representations of microphysical processes are of special concern. Microphysical data from previous field experiments should be reexamined, specifically to clarify critical issues for numerical experimentation and to plan further field studies as necessary. Future field studies should utilize advanced ground-based and airborne remote sensing technology such as polarimetric radars and aircraft equipped to observe cloud microphysics and environmental structure. The sensitivity to aerosol properties and concentrations in the inflow environment should also be evaluated, especially with respect to precipitation efficiency for various types of convection.

**Predictability at the mesoscale.** Understanding the evolution of organized convection, including factors associated with propagation, dissipation, and regeneration, is central to quantifying the practical limits of QPF predictability in the warm season. It has been established that weakly forced episodes of convection occur on a daily basis in midsummer and exhibit coherence on scales of order 1000 km and 20 h. While individual clouds, storms, and mesoscale convective systems persist for only a fraction of this time, regeneration mechanisms markedly increase the likelihood that convective rainfall will persist once it is organized at the mesoscale. This statistical property of organized convection is a principal basis for optimism with respect to probabilistic prediction at ranges from 6 to 24 h since the coherence of events infers an intrinsic predictability. The future forecast system should be able to exploit this predictability once the underlying mechanisms for triggering, dissipation, and regeneration are better understood and the predictor variables are identified.

**Observations of the atmosphere.** While it is clear that forecasts of convective events would benefit from knowledge of cloud-scale and mesoscale features, it is also clear that, for the most part, observations on these scales are limited to those available from surface mesonets, profilers, geostationary and GPS satellites and radars. While these observing systems and platforms provide useful data, they do not provide certain key pieces of information required by the models. For example, the quality and vertical resolution of geosynchronous satellite data over heterogeneous continental backgrounds remains unacceptably low, distant radars overshoot the boundary layer, nearby radars leave a “cone of silence,” and surface mesonets provide no information about the free troposphere unless augmented with profiling devices.

Observations are certain to improve as new remote sensing systems with far greater capabilities are deployed during the current decade. Moreover, in situ observing systems such as Aircraft Communications Addressing and Reporting System (ACARS) and surface mesonets (that measure soil moisture availability) are likely to be greatly expanded. Polarimetric
WSR-88D radars will provide critical microphysical information such as hydrometeor type, distribution, and amount. Planning to upgrade the present radar network to include polarimetric capabilities is underway and will no doubt lead to advances in knowledge about microphysical regimes and the relationship to dynamical evolution. Another promising development is the use of atmospheric radio-refractivity information (from ground-based GPS measurements and Doppler radars) for lower-tropospheric humidity structure on scales of order 10 km.

On the other hand, there is a growing belief that knowledge of environmental aerosols may prove necessary for properly representing cloud microphysical processes, but there are no efforts underway to provide routine observations of aerosols or even to provide a systematic research assessment of the forecast sensitivity.

The current shortage of microphysical information leaves model developers in the difficult situation of having only limited and highly event-specific datasets from past field programs from which to improve microphysical parameterizations and to define “truth” for validation. Nevertheless, it appears that there is now a technological basis for measuring much of the cloud-scale and mesoscale structure that is suspected to be responsible for the characteristics of convective events.

**Data assimilation.** While the requirements in observing the atmosphere are formidable, the hurdles in data assimilation to initialize cloud-resolving models appear to be equally if not more challenging. Basically, there are two major issues that must be addressed; one is science based and the other concerns human resources. The science issue stems from the fact that, at the present time, there are no established procedures for assimilating cloud-scale observations, especially in situations involving deep, moist convection. For static initializations, there are no known balance constraints applicable to convective scales (as there are with large-scale weather systems). Therefore, other approaches are being pursued. Two particular techniques, four-dimensional variational data assimilation (4DVAR) and the ensemble Kalman filter (EKF) are under investigation. While the results from preliminary 4DVAR experiments are encouraging, much work needs to be done before truly operational systems could be implemented.

Computational requirements for implementation of 4DVAR currently exceed the capacity available for large-domain applications at convection-resolving resolution. When considered in the probabilistic framework, wherein it may be necessary to generate large ensembles for high-resolution domains, the computational capacity issue is further exacerbated. The computational demands of EKF, while large, may be somewhat less stringent. Research is needed to evaluate the relative effectiveness of this approach at convection-resolving scales, which may have other advantages related to characterization of error covariances. One way or another, it is just a matter of time before the computational capacity issue is solved. Strong external forces, unrelated to weather prediction, are at work to solve this problem.

A general conclusion drawn from the workshop is that data assimilation, in the overall process of forecasting convective precipitation, may be the most critical path through which the pace of forecast advances will be modulated.

This conclusion leads directly to the second issue; that is, there appears to be a serious deficiency in human resources working on data assimilation. This problem is so serious that the data assimilation subgroup lists graduate student education as their number-one recommendation for how to help solve the QPF problem! Moreover, they also note that, for a variety of reasons, a large fraction of current observations are not being assimilated into today’s models. Some of these reasons are human-resource related.

Considering the multitude of new observations in the pipeline, and that many of these observations will have to be assimilated, it is clear that USWRP should promptly consider focused actions to stimulate education and training in data assimilation.

This could include the entrainment of young scholars from applied mathematics and other fields of science where there may be an ample supply of talent and relevant experience. This suggestion has precedence in the geophysical sciences associated with past programs sponsored by the National Science Foundation (unrelated to data assimilation).

**Generating probabilistic guidance.** As noted above, it is expected that both numerical models and nowcasting systems will have measurable skill forecasting the location, structure, and movement of specific individual thunderstorms to 3 h at most. Beyond this time period, the focus shifts to forecasting the properties of the individual storms and storm systems and their likelihood at a given location. This implies that there should be several different strategies deployed in generating probabilistic guidance. Three general approaches appear promising: observations-based systems, numerical model–based systems, and blended systems.
OBSERVATIONS-BASED SYSTEMS have been developed, using advection/extrapolation techniques, based primarily on the movement and trends in radar reflectivity and geosynchronous satellite image fields. Analyses of surface data, soundings, profiler data, and commercial aircraft data also factor into rule-based algorithms. Precipitation estimates are mainly retrieved from standard rainfall–reflectivity relationships and sometimes from algorithms based on satellite infrared cloud-top properties. Some predictor fields that influence trends and movement of precipitation (e.g., PBL divergence) are analyzed by means of 4DVAR in adjoint models at the cloud scale. Just as with most other forecasting systems, this approach has biases that vary with location, time of day, season, upper-air environment, etc. In a manner similar to model output statistics (MOS), it is possible to statistically remove these biases and to convert the output from advective/trend models into probabilistic form provided there exist long time series of forecasts together with adequate verification data.

These types of forecast systems have desirable properties in that they are objective, can be automated, and run quickly (in a few minutes or less) in desktop computing environments. Therefore, forecasts can be updated frequently (say, every 5 min) as new observations become available. Predictands are usually categorical (e.g., 0.01–0.10 in., 0.11–0.25 in., 0.26–0.5 in., etc.) and can be developed for a point or an area (given that high-resolution observations, such as radar-estimated precipitation, are available for verification). Moreover, techniques can be developed to provide probabilistic temporal and/or spatial distributions of precipitation instead of the mean value over an area (often not the quantity of greatest utility in end-user applications). When provided for a given watershed, this type of information is of great value to flood forecasters. Naturally, observation-based systems are most accurate for very short-range forecasts (0–3 h). Based on experiences to date, the skill of observations-based systems diminishes rapidly after 1 to 2 h and eventually becomes less skillful than guidance generated by numerical models.

NUMERICAL MODEL–BASED SYSTEMS are the main vehicle whereby current mesoscale and synoptic-scale guidance is generated. Output from these models is converted into probabilistic form in two ways: 1) performing standard statistical postprocessing (i.e., MOS), and 2) constructing ensembles, either by running the same model on perturbed initial states or by running different models on the same initial state. Since all models have biases, ensemble forecasts must also undergo some type of statistical postprocessing in order to provide reliable probabilistic categorical forecasts. When cloud-scale models eventually become operational, it is expected that ensembles will be generated and that the output will be statistically postprocessed to provide reliable, probabilistic categorical guidance. Methods of ensemble generation from any given model require further research, since the current spread of ensemble members in research systems lacks the breadth of nature in addition to having bias.

In order to fully capitalize on the capabilities of the new models, there are several avenues that should be pursued. First, multiyear archives of high-resolution radar and satellite precipitation estimates (e.g., stage III analyses) must be compiled and made readily available so that biases in model output can be statistically corrected. Second, there appears to be substantial potential for improving QPFs by constructing multimodel ensembles rather than creating ensembles simply by varying the initial state of a single model. Preliminary investigations indicate that multimodel ensembles have greater spread and therefore provide a better measure of the uncertainty and an improvement in skill relative to single-model ensembles. Further improvements in skill are likely to emerge from statistical postprocessing of the output from multimodel ensembles. Third, it is expected that cloud-scale resolution models will provide information about the “properties” of the precipitation—that is, rain rates, duration, extreme values, spatial coverage, etc. These properties will also need to be extracted from archives of the radar/satellite-estimated precipitation so that model output can be statistically corrected for bias. The longer the time series, the more likely it will be that skill in forecasting rare-category events will be increased. The resulting unbiased probabilistic distributions of precipitation should provide a source of great value to many users, especially to hydrologists.

BLENDED SYSTEMS combine the observations-based approach with the numerical model approach by offering both the observations and the model output as

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4 A multimodel ensemble can be constructed from the various operational model control runs (e.g., the Eta, NGM, AVN, ECMWF, etc.) or, alternatively, by varying the physics and/or numerics of a single-model governing system so as to, in effect, create a set of “different” models. This is in contrast to current operational techniques for creating ensembles wherein the initial state is varied but the governing system remains the same.
potential predictors in a statistical forecast system. This approach would provide the greatest benefit for forecast lead times of 3–6 h. Given the historically weak interactions among researchers engaged in these two approaches, it is expected that rapid progress could emerge from research programs and test bed environments that strongly encourage analytical interactions. The expanded use of adjoint models in formal assimilation of observations is the fertile meeting ground for these communities of investigators, since this ensures a common analysis from which both dynamical and rule-based visions of the future emerge. Since the “trajectories” of observations-based forecast systems have greater skill in the very short range, dynamical model trajectories should, somehow, be influenced by these in the course of forward integration. This influence might take the form of observations-based forecasts factoring into initial-guess fields of dynamical models during the forward integration. In other words, we can envision a phenomenon-dependent forecast period during which it would be impossible to attribute forecast products exclusively to observations-based systems or to dynamically based models.

**Verification and end-user products.** The transition to probabilistic forecasting and the ability of cloud-scale resolution models to provide information about the properties of rainfall (e.g., the spatial and statistical distributions of rain rates within a given watershed) demand that new and better verification techniques be developed. These techniques must be able to score gridded arrays of probabilistic forecast values and statistical distributions of precipitation properties. Also, quantitative pattern-recognition techniques applicable to the complex fields of convective precipitation should be developed. Since such techniques are already being used operationally in other fields (e.g., recognition of fingerprints, eye corneas, faces, etc.) it may be possible to transfer this technology so that it can be used in recognition of precipitation patterns. Quantitative measures of the “nearness of fit” of the forecast pattern to the observed would serve as a measure of the skill of a given forecast. Concomitantly, in order to score the detailed properties of statistical and cloud-scale model forecasts, new verification procedures will require upgrades in the current precipitation-observing system. Polarimetric radar is viewed as a cornerstone of the future precipitation-observing system. Use of polarimetric information and satellite-based precipitation estimates (in themselves probabilistic) in a probabilistic forecast system is an important area of applied research necessary to measure forecast skill.

The utility of a forecast is also an important factor to be considered in developing new forecast products and in designing new verification techniques to score those products. Measures of skill vary greatly based on the form and manner of QPF utilization. Verifiable and prized forecast products in one application may prove to be of relative low utility and unverifiable in another. Yet, relatively little is known about the form in which various users would prefer to receive precipitation information, or how to assign value to different forecast products. Evaluation of these issues will require contributions from diverse interest groups (social scientists, meteorologists, hydrologists, emergency managers, private sector managers, etc.). This implies the creation of a vehicle whereby these groups can interact with each other and with a broad community of QPF users to ascertain societal needs and the types of products that will best serve those needs. It further implies that user needs must be a fundamental consideration in the allocation of program resources and the conduct of QPF research. This aspect of the program has considerable potential to engage the private sector, both intellectually, and in a public–private cosponsorship capacity.

**Application to hydrologic forecasting.** For the first time, it appears that it may be possible to produce QPF in a form that hydrologists prefer—that is, categorical probability distributions with cloud-scale resolutions over mesoscale watersheds. This guidance can come from nowcasting (observations-based systems) or from statistically postprocessed numerical model output derived from individual control runs or from model ensembles. If such guidance can be produced, a major challenge is to link it to hydrologic forecast models and then to demonstrate that the QPF information actually contributes to skill in hydrologic applications. Clearly, this will require a collaborative effort in experimental prediction between meteorologists and hydrologists. It also will require high-resolution precipitation and soil moisture data for suitable watersheds on which to test the hybrid forecasting system. Since hydrological predictions, including seasonal and flash flood predictions, are among the principal societal payoffs resulting from warm-season QPF improvement, a focused and integrated applied hydrology component is vital to measures of success for the USWRP in the warm season.

**ROADMAP FOR IMPLEMENTATION.** Following the discussion in the section titled “background and proposed areas of focus,” the basic strat-
egy to obtain substantive improvements in QPFs is to take those steps that will facilitate forecasting deep, moist convection in a fully probabilistic manner wherein the statistical properties of the forecast convection are similar to those observed in nature. The supporting materials in appendices D, E, and H present a set of tasks necessary to execute this strategy. These tasks consist of a progression of intertwined research and development activities that proceed in a coherent and temporally logical manner over a period of 5–15 yr. Tables 1 and 2 list specific “early” and “continuing” activities, respectively, recommended for support. In several of these activities, more detailed proposals may be found in appendix H. Several specialized working groups will be needed to flesh out a detailed balance of activities in key areas.

It is readily evident from the focus areas discussed in the section titled “background and proposed areas of focus,” and the multitude of recommendations summarized in Tables 1 and 2 that making headway in improving warm-season QPFs will require a huge amount of work in widely diverse yet closely related areas of research. Unless this work is coordinated in some formal manner, it is unlikely that all of the components necessary for building a system to improve warm-season QPF will be in place at the same time. Thus, it appears that some type of management vehicle, such as a project office or laboratory that specifically focuses on the warm-season QPF problem is desirable.

As reported in section 3, five breakout groups independently arrived at the conclusion that a “test bed” was needed to pursue critical objectives in their particular application. Despite this enthusiasm, test beds are neither uniformly nor sharply defined. Each of the groups had a partially or completely independent concept. Some equated test beds essentially to live tests of experimental forecast systems. To others, “test bed” meant a coordinated chain of applied research and development, which ultimately would be tested in parallel with the operational forecast system after substantial periods of R&D. Some test bed concepts include a heavy dose of verification grounded in carefully researched socioeconomic metrics, while others proposed what might best be described as an “engineering project.”

It is important to recognize the full continuum of R&D, from basic research to live forecast demonstrations. We cannot escape the obvious fact that some fundamental understanding is lacking in almost all aspects of the warm-season QPF problem. This is evident from the climate created by warm-season precipitation predictions (from operational models), which is seriously at variance with nature’s climate. Researchers must get to the roots of this problem. From nonlinear dynamics, to microphysical processes, to data assimilation, to verification and societal definitions of most-valuable forecast information, this forecast problem demands improved understanding.

In the vernacular of the USWRP, warm-season QPFs are not “low-hanging fruit.” It is, however, the poorest performance area of today’s forecast system and a costly weakness in weather prediction services today. The United States is a most strongly affected nation. An effective attack on warm-season QPFs will require substantial resources and improved national management. We believe that management within the agencies needs to assess this reality and decide whether to attack warm-season QPFs with a critical mass of effort, or defer solutions to a later era in weather prediction. Coming to grips with this reality requires the following tightly knit program:

1) basic research for improved understanding of many issues detailed elsewhere in this report,
2) advanced development (observations, assimilation technologies, and forecast systems), and
3) experimental forecast demonstrations (with emphasis on societally grounded verification metrics).

Unless all three “legs of the stool” underpin this USWRP effort, warm-season QPFs will continue to lag other aspects of weather prediction and continue to deny hydrological prediction a similar opportunity to improve flood prediction.

Provided the agencies are prepared to exercise comprehensive and inclusive management of a tightly knit program, the following overarching recommendation is presented:

Create a program office specifically for coordinating warm-season QPF research in all of its aspects, inclusive of a test bed framework, wherein development and testing of each and all components of the forecast system can be conducted; impediments to operations can be identified and corrected; and socioeconomic value, at the margin, can be identified.

It is unclear to what extent there should be a single testbed or several, although it is evident that the nature of the problem requires the interaction of many disparate elements that, at some point, must be assembled and tested as a whole. It is also unclear whether test beds should have “bricks and mortar” associated with them or be “virtual.” It may be advisable to begin with one physical test bed that includes...
**Table 1. Early stage activities.**

<table>
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<tr>
<th>Activity</th>
<th>Details</th>
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<tr>
<td><strong>Quantify the current use and value of warm-season quantitative precipitation estimation (QPE), nowcasts, and QPFs, and establish a baseline of user needs.</strong></td>
<td>Despite the long history of QPFs, the operational and research communities still know relatively little about their customers, the actual use of precipitation information, and the value of forecasts associated with decision making. This type of information will have a bearing on the specifics of forecast products and, therefore, will play a defining role in establishing research priorities.</td>
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<td><strong>Stimulate education and training in data assimilation.</strong></td>
<td>A critical element for improving cloud-resolving models is assimilation of high-resolution data. Without an increase in the numbers of scientists and the level of expertise in data assimilation, techniques to assimilate data from the many new observing systems now in the pipeline will not be forthcoming in a timely manner. It is essential to immediately infuse new talent into this vital area.</td>
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<td><strong>Pursue data assimilation technique development with emphasis on high-resolution observations and microphysical information.</strong></td>
<td>It is recommended that a funded Working Group of Experts in Data Assimilation develop a plan of action.</td>
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<tr>
<td><strong>Evaluate the benefit from very-high horizontal and vertical resolution observations over the continent.</strong></td>
<td>Incorporate data from advanced interferometers on GOES, polarimetric WSR-88D, and GPS-based estimates of precipitable water. Other data (e.g., aerosols) await results from basic research. Early funding of an independent (outside of meteorology) systems engineering study to evaluate options and to formulate an R&amp;D plan for systematic evaluation of candidate technologies is recommended.</td>
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<td><strong>Enhance and validate the physics of cloud-resolving models.</strong></td>
<td>The immense sensitivity of cloud-resolving models to variations in physical process formulations demands that new formulations be developed and validated, especially for cloud and precipitation microphysics, three-dimensional turbulence in convective clouds, and boundary layer processes. This presents a conundrum since microphysical and soil moisture observations to validate the models are not readily available nor are techniques to assimilate data on these scales. Therefore, initial efforts should focus on the exploitation of historical field data. Immediate formation and funding of one or two field data and parameterization working groups is recommended. These groups should include both process–observation and model parameterization specialists.</td>
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<td><strong>Compile a high-quality, high-resolution observational database of precipitation properties.</strong></td>
<td>It is necessary to know the statistical properties of convection, as they occur in nature, for verification of the cloud-resolving models and for construction of the statistical postprocessing algorithms. These data are also required to develop nowcasting and short-term observations-based forecast systems and to build new techniques to score probabilistic forecasting systems. Hydrologic models require this information to test soil moisture and runoff forecasts. Many WSR-88D databases will soon be approaching one decade in duration, thus facilitating the postprocessing objective. Confirmatory field campaigns (employing Lagrangian sampling techniques via research aircraft) on the life cycles of organized convection likely will be required to confirm and clarify findings.</td>
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<td><strong>Develop improved metrics for verifying mesoscale precipitation forecasts in both time and space, especially for guidance provided in gridded probabilistic form.</strong></td>
<td>Current methodologies are unable to provide diagnostic information about the quality of forecasts and are insensitive to some errors. Standard measures of skill are not sufficiently informative to users making decisions based on the forecasts. Threat score as a principal measure of skill for a QPF should be retired and replaced with methods that can improve predictions through statistical post-processing. Object-/entity-oriented techniques that serve to quantify spatial and temporal errors and their covariance properties (model biases) are preferred. Continued calculation of threat scores will retain continuity with historical measures of QPF performance, a highly useful and necessary set of information.</td>
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<td><strong>Combine ensemble techniques and traditional statistical postprocessing techniques to provide calibrated probabilities, ensemble fields, and unbiased ensemble statistics.</strong></td>
<td>It is likely that the most accurate guidance will emerge from this blend.</td>
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<td><strong>Construct nowcasting (0–6 h) techniques that utilize high-resolution observations and numerical model output to generate categorical probabilistic QPFs.</strong></td>
<td>Very short-term forecasts (0–2 h) will likely depend almost exclusively on observations. In the 2–6-h time period, observations and model output will need to be blended statistically to optimize forecasting skill. Observations-based systems run quickly and can aid in flash-flood warning decisions.</td>
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<td><strong>Develop and validate methods to assimilate high-resolution QPE and probabilistic QPFs into hydrologic forecast models.</strong></td>
<td>Flood forecasting will benefit from more accurate estimates of precipitation at high resolution in near–real time. Polarimetric radar augmented by geosynchronous satellite techniques offer promise for improved QPE and flash-flood prediction in the near term. A Flood Forecast Working Group including radar, satellite, and hydrological modeling expertise should be funded to flesh out the specifics of technique development and coordinated field tests.</td>
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Activate partnerships between physical and social scientists and end users to maximize the value and utility of the improvements in QPFs as they become available. In addition to meteorologists, hydrologists, and engineers, the universe of scientists must be widened to include social scientists from geography, public policy, political science, communication, public health, psychology, and others in order to quantify socioeconomic impacts. A diverse group of scientists provides different perspectives of a broad spectrum of end users thereby enabling speedier application of research findings and more complete evaluation and feedback for product improvement.

Integrate cloud-resolving model advancements with emerging new data assimilation systems. Early stages of model and data assimilation development will likely proceed in a somewhat decoupled manner as various options are explored. However, the advanced forecast system requires an intimate coupling of these activities at the appropriate stage. Facilitating this coupling would be most efficient and effective in a “test bed” environment.

Assess the feasibility of periodically producing a retrospective archive of the high-resolution operational (control run) model output and the output from ensemble runs of that model. This assessment would evaluate the benefits of the archive relative to benefits arising from NWP model changes, and consider the benefits of retrospective runs of the full-resolution NWP model, “partial” ensembles, and “full” ensembles.

Develop an “optimal” design of forecast-model ensembles. Effective methods are needed to adjust the mean and spread of high-resolution ensembles and to provide calibrated probabilities, ensemble fields, and ensemble statistics. The number and make-up of ensembles should be examined to determine the benefits of adding runs with different initial conditions, different physics packages, and different numerics.

Determine critical environmental factors and variations thereof that affect the evolution, structure, and propagation of moist convection. There is major uncertainty about the relative roles of processes internal to convective systems and external “forcing” that makes convection deviate from its modal character. A unifying understanding of the critical external processes would benefit forecasters and facilitate examination of the skill of models in representing environmental structure. Understanding must be improved to the extent that representations of physical processes in cloud-resolving models yield a physically realistic result. The evolution of ice, the dependence of QPFs on environmental aerosols, and microphysical factors in negative buoyancy production and precipitation efficiency are all of concern. In the PBL, land–atmosphere exchanges of sensible and latent heat in convectively disturbed flow regimes; aerosol concentration, composition, and activity spectrum; and the dynamics of convectively disturbed nocturnal boundary layers (in relation to dissipation/regeneration of deep, moist convection) are all significant issues.

Determine appropriate methodologies to evaluate case-dependent uncertainty for precipitation events. Nonlinear methods, such as logistic regression, neural networks, and generalized additive models should be examined for inclusion into the model output statistics (MOS) approach. These techniques are, in principle, far more powerful tools than classical multiple regression schemes. The MOS approach itself should be modified to incorporate ensemble information.

Conduct forecast demonstrations for urban catchments and develop methods for QPF-driven real-time flood forecasting. Regional and seasonal demonstrations of flood prediction should be conducted in well-instrumented and previously characterized watersheds of small to medium size. The demonstrations should be based on previously explored methodologies for hydrologic model utilization of gridded, high-resolution PQPF.

Develop a baseline of forecast quality and predictive skill. Current baselines and measures of predictive skill for mesoscale QPF nowcasts and forecasts do not exist.

Develop techniques to integrate ensemble precipitation forecasts from different forecast systems ranging from nowcasts to regional (1–2 days) to medium range (< 2 weeks) to climate (> 10 days) into a seamless and consistent set of ensemble forcing. Longer ranges of prediction will be possible when fully probabilistic and unbiased QPF products can be produced at a high spatial and temporal resolution. It will take time for the atmospheric forecast systems to approach this state. Hydrologists should work collaboratively with cloud-resolving forecast model developers to design QPF products that best meet hydrological prediction requirements for flash floods, regional main-stem floods, and hydrological predictions of a seasonal nature.
development of training tools for forecasters and other users of the future forecast system.

CONCLUDING REMARKS. Warm-season QPFs are, certifiably, the poorest performance area of forecast systems worldwide. They have stubbornly fallen even farther behind other aspects of weather prediction in the past 20 yr. Warm-season QPFs are certain to remain the Achilles’ heel of weather prediction, at a progressively greater cost to society, unless a major effort is mounted to overcome the impediments to improved prediction. A cursory examination of the activities listed in Tables 1 and 2 makes clear that the challenge of improving warm-season QPFs requires a substantial and sustained commitment of resources focusing on a complex suite of issues. It is an exceedingly challenging undertaking that must garner meaningful contributions from many disparate scientific specialists. Nevertheless, the need is great, the potential benefits are many, and the technologies to meet the challenge are finally at hand. Once improved understanding is achieved, once the new observational databases are available, once cloud-resolving models have generated sufficiently large time series of forecasts, and once postprocessing tools are mature and ready for application, a substantial payoff in forecast skill is anticipated.

REFERENCES