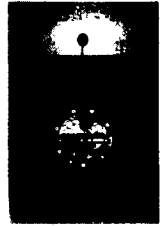


meeting summary

Quantitative Precipitation Forecasting: Report of the Eighth Prospectus Development Team, U.S. Weather Research Program



J. M. Fritsch,* R. A. Houze Jr.,+ R. Adler,* H. Bluestein,@ L. Bosart,& J. Brown,**
F. Carr,@ C. Davis,++ R. H. Johnson,** N. Junker,@@ Y.-H. Kuo,++ S. Rutledge,**
J. Smith,&& Z. Toth,*** J. W. Wilson,++ E. Zipser,+++ and D. Zrnich***

ABSTRACT

Quantitative precipitation forecasting (QPF) is the most important and significant challenge of weather forecasting. Advances in computing and observational technology combined with theoretical advances regarding the chaotic nature of the atmosphere offer the possibility of significant improvement in QPF. To achieve these improvements, this report recommends research focusing on 1) improving the accuracy and temporal and spatial resolution of the rainfall observing system; 2) performing process and climatological studies using the modernized observing system; 3) designing new data-gathering strategies for numerical model initialization; and 4) defining a probabilistic framework for precipitation forecasting and verification. Advances on the QPF problem will require development of advanced ensemble techniques that account for forecast uncertainty, stemming from sampling error and differences in model physics and numerics and development of statistical techniques for using observational data to verify probabilistic QPF in a way that is consistent with the chaotic nature of the precipitation process.

*Meteorology Department, The Pennsylvania State University, University Park, Pennsylvania.

+Department of Atmospheric Sciences, University of Washington, Seattle, Washington.

*NASA/GSFC, Greenbelt, Maryland.

@School of Meteorology, University of Oklahoma, Norman, Oklahoma.

&Department of Atmospheric Science, The University at Albany, State University of New York, Albany, New York.

**NOAA/ERL/Forecast Systems Laboratory, Boulder, Colorado.

++National Center for Atmospheric Research, Boulder, Colorado.

**Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado.

@@Hydrometeorological Prediction Center, National Centers for Environmental Prediction, Camp Springs, Maryland.

&&Department of Civil Engineering and Operations Research, Princeton University, Princeton, New Jersey.

***Environmental Modeling Center, National Centers for Environmental Prediction, Camp Springs, Maryland.

+++Department of Meteorology, University of Texas, College Station, Texas.

***National Severe Storms Laboratory, Norman, Oklahoma.

Corresponding author address: Professor Robert A. Houze Jr., Department of Atmospheric Sciences, Box 351640, University of Washington, Seattle, WA 98195-1640.

E-mail: houze@atmos.washington.edu

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1. Introduction

What people need to know most about the weather is, will it rain or snow, and if so, how much? Consequently, the most important element of the daily weather forecast is the amount of precipitation that will fall over a given area in a given period of time. Improvement in this “quantitative precipitation forecast (QPF),” is, moreover, prerequisite to improving forecasts of high-impact weather events such as damaging ice storms, snowstorms, and floods—especially flash flooding. (In an average year, the property damage owing to flash flooding exceeds that for all other weather-related natural phenomena.) Besides its relevance to citizens, QPF strongly affects daily decisions in governmental and business activities throughout the United States. For example, since rainfall amount directly affects streamflow, utility companies rely on QPF to decide whether or not hydroelectric power generation can be used instead of the more costly fossil fuel generation. Agricultural operations rely upon QPF to decide whether or not to expend increasingly limited and expensive water resources for irrigating crops. Similarly, golf courses and ski resorts depend upon QPF to guide their daily watering and

snowmaking operations, and transportation companies count upon QPF to avoid massive scheduling and delivery bottlenecks. The effect of QPF even reaches into trading in the commodities markets, where daily prices often rise and fall based upon precipitation forecasts. Thus, QPF affects the efficiency of our markets as well as the prices of the food we eat and the water we drink.

In view of the importance of QPF to citizens and to the economic health of many businesses, it was selected by the Science Advisory Committee of the U.S. Weather Research Program (USWRP) as one of the three highest priority topics for research. To develop guidance for the research, a team of scientists convened in Boston, Massachusetts, on 24–26 September 1996. The scientists were given the following charge by Dr. William Hooke, director, and Dr. Richard Carbone, chief scientist, of the USWRP:

General charge:

- 1) Identify and delineate emerging research opportunities associated with improved precipitation estimation, short-term precipitation forecasts, and the hydrological aspects thereof. Deliberations will include mesoscale phenomena that produce heavy precipitation at midlatitudes, such as fronts associated with extratropical cyclones and mesoscale convective systems.
- 2) Recommend efforts to determine what aspects of the heavy precipitation forecast problem limit our progress, given that such forecasts will be heavily dependent on observations for the very short (0–6 h) forecast period, and highly dependent on mesoscale models for the short-term (6–48 h) forecast period.
- 3) Recommend techniques to improve model initialization and verification of adaptive, cloud-resolving forecast models using WSR-88D radars, profilers, and satellite data.

Due to the breadth and complexity of the charge, the working group was divided into four subgroups, each of which focused upon a basic component of the overall problem.

- 1) Basic physics of rainstorms
- 2) Effects of synoptic processes and surface boundaries
- 3) QPF techniques
- 4) Precipitation estimates for forecast validation

Following a brief summary of the current status of QPF and a statement of emerging opportunities, re-

ports from each subgroup are presented in section 4. The reports include specific hypotheses and recommendations addressing the respective research components. A summary and list of the main recommendations are provided in section 5.

2. Status of quantitative precipitation forecasting

In spite of the importance of QPF to public safety and commercial operations, skill in forecasting precipitation amount has historically been relatively low. For example, Fig. 1 shows the average annual threat scores of the Heavy Precipitation Branch of the National Weather Service (NWS) for forecasting the area of ~1.00 in. of precipitation. It is evident that recent scores for the day 1 period (a 12–36-h forecast) are mostly in the 0.2–0.25 range. A physical interpretation of these threat score values can be obtained from a few simple manipulations of the threat score definition. Recall that threat score (T) is defined as

$$T = \frac{A_c}{A_f + A_o - A_c}, \quad (1)$$

where, for a given threshold of precipitation amount, A_c is the correctly forecast area, A_f is the total area forecast, and A_o is the observed area. Recall also that forecaster bias (B) is defined as

$$B = \frac{A_f}{A_o}. \quad (2)$$

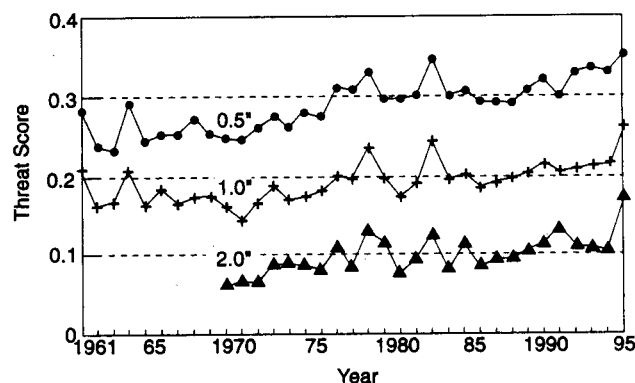


FIG. 1. Threat scores for the forecasters' 0.50-, 1.00-, and 2.00-in. forecasts for day 1 from 1961 through 1995. (Adapted from Olson et al. 1995.)

Therefore, after some manipulation of (1) and (2), the fraction (F_o) of the observed area that is correctly forecast can be obtained from

$$F_o = \frac{A_c}{A_o} = \frac{T(1+B)}{1+T}. \quad (3)$$

Similarly, the fraction (F_f) of the forecast area that is correctly forecast can be obtained from

$$F_f = \frac{A_c}{A_f} = \frac{T(1+B)}{B(1+T)}, \quad (4)$$

$$= \frac{F_o}{B}.$$

According to Olson et al. (1995), the typical bias for forecasters' 1.00 in. isohyetal forecasts for the day 1 period is approximately 1.25. Therefore, a threat score of 0.2 implies that forecasters usually forecast only slightly more than a third of the observed area correctly, even though they overforecast the total observed area by roughly 25%. If the same bias is assumed for forecasting amounts over 2 in., then using the typical threat score (from Fig. 1) of near 0.1, the fraction of observed area correctly forecast is only about 20%.

It is very important to point out that this analysis of performance is not a criticism of the efforts of the forecasters but, rather, is an indication of the extreme difficulty in making accurate forecasts of significant precipitation amounts, especially amounts in excess of 2 in. It is also important to note that, even with the benefit of vastly improved observations and numerical models during the past decade, the rate of improvement in skill has been very slow. Therefore, it is worthwhile to examine more closely the nature of the forecast problem and to try to identify those paths that provide the greatest opportunities to significantly improve QPF skill. To this end, the work of Olson et al. (1995) provides valuable insight. In particular, comparison of the average monthly distribution of observed area of ≥ 1.00 in. of precipitation to the monthly threat score distribution (Fig. 2) reveals two important points: 1) most of the significant precipitation events occur during the warm season, and 2) skill levels are the lowest at the time of year when the area of heavy precipitation is greatest. Thus, when the threat of flash flooding is the greatest, forecast skill is the poorest.

Further insight into the QPF problem comes from an analysis of the warm season precipitation over the United States. Specifically, Heideman and Fritsch (1988) found that approximately half of the significant precipitation (24-h amounts ≥ 0.50 in.) is associated with extratropical cyclones, and half is produced by mesoscale forcing mechanisms acting independently of traveling extratropical cyclones. They also found that over 80% of significant precipitation was associated with thunderstorms. These heavy rain-producing convective processes tend to be poorly resolved by the numerical models that provide the primary guidance for the 12–36-h forecast period. This agrees with the assessment of Olson et al. (1995); they attributed forecasters' lower scores to the fact that the warm season is dominated by small-scale convective processes that are poorly resolved by numerical model guidance. In particular, there is a very strong relation between the skill of model guidance and the skill of the forecaster (Fig. 3). It is evident from Fig. 3 that the overall skill of the forecasters varies in direct proportion to that of the model guidance. Thus, it is clear that to improve 24-h QPF, we must improve our understanding of convection, and in taking those steps, we will improve numerical model forecasts of convective events.

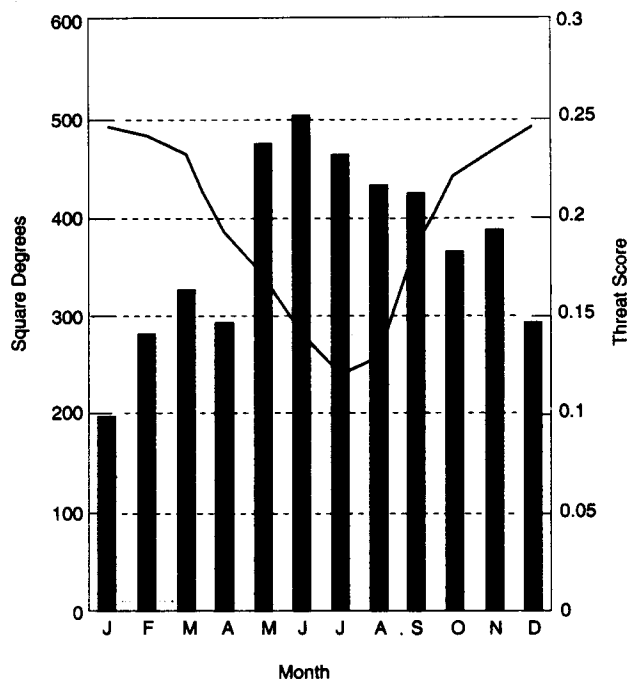


FIG. 2. Average monthly 1.00-in. area in square degrees for the period 1961–93 (bargraph). The curved solid line shows the average monthly threat score for 1.00-in. forecasts for the same period. (From Olson et al. 1995.)

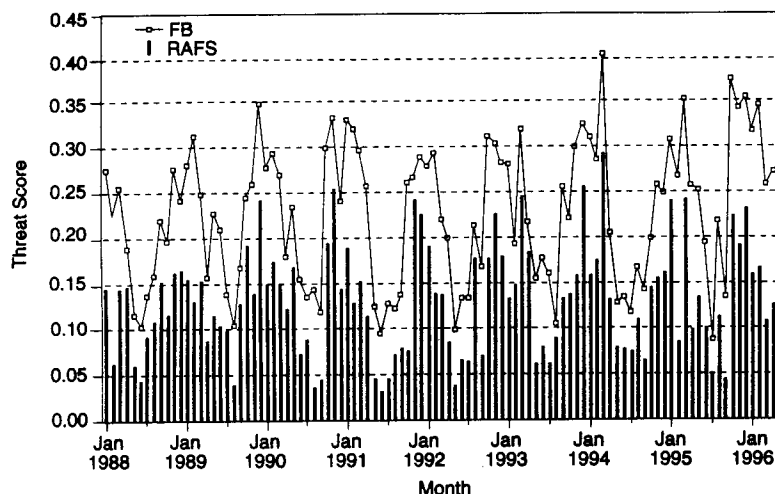


FIG. 3. Monthly threat scores that compare Forecast Branch (FB) subjective Day 1 QPF to the 12–36-h QPF of the Regional Analysis and Forecast System (RAFS) from January 1988 to April 1996. (Adapted from Olson et al. 1995 and updated to include 1995–96 data.)

3. Emerging opportunities

With the modernization of the National Weather Service, the United States has improved greatly its ability to *observe* the atmosphere. Of particular significance is the installation of the network of automated surface observing systems (ASOS), Doppler wind profilers, a network of weather surveillance Doppler radars (WSR-88D) covering the contiguous 48 states as well as Hawaii, Guam, and Puerto Rico, advanced GOES satellites, and lightning detection networks. Together, these observing systems provide a much more comprehensive depiction of the three-dimensional state of the atmosphere than ever before. Moreover, the data are updated on a nearly continuous basis, thereby enabling researchers and practitioners to uncover and forecast both large- and small-scale facets of the atmosphere never seen before.

Concomitant with the new observing technology has been an exponential increase in computational power. Current machines have already crossed the teraflop threshold and are providing the ability to meaningfully process the huge data streams continuously being generated by the new observing systems. Moreover, new electronic data archiving and retrieval technology promises to make possible numerical and statistical investigations that were unthinkable only a decade ago. There is every indication that Moore's law (doubling machine speed and memory every 2 yr, while the price of the machines drops by half) will remain in effect for the foreseeable future, thus ensur-

ing continuing opportunities to better understand and forecast the complex processes that result in precipitation. Over the next 5 yr, sufficient computing power will become available for operational numerical models to resolve and predict meso-g scale distributions of precipitation over large regions of the country. This will occur with the full implementation of the new observing networks. These coinciding events will facilitate more accurate identification, mapping, and forecasting of heavy precipitation events. Furthermore, they will enable multimodel ensembles to run in real time and thereby allow us to quantify more accurately the uncertainty in model forecasts. The dense network of observing systems will permit comprehensive field programs at relatively little cost, since the

“backbone” observing system will provide much of the necessary observations. Thus, there will be heretofore unparalleled opportunities to gain physical understanding of the detailed lifecycles of heavy precipitation systems and to provide meso-g scale resolution data for initializing and verifying the meso-g scale numerical models. For the first time, we will have the opportunity to forecast and verify, both numerically and statistically, the magnitudes and distributions of precipitation comparable to the extremes that are responsible for damages and casualties.

The opportunities inherent in the new databases and electronic technologies will be brought to fruition only if we aggressively pursue several areas of supporting research and development. The following section makes specific recommendations for capitalizing on the emerging technology and research opportunities.

Perhaps as important as the technological advances that portend improvement in QPF are certain theoretical advances that have occurred over the last two decades. The recognition that the atmosphere is a chaotic system (Lorenz 1963, 1993) has led to rethinking of meteorological problems of all types. Precipitation is not only the most important atmospheric variable to forecast, it is also the most intermittent in time and space and thus probably the most chaotic in its behavior. Traditionally, QPF has been treated as a deterministic problem. The lack of improvement of QPF is probably a result of this traditional view. QPF must be addressed in a probabilistic framework that accounts for the chaotic nature of the atmosphere. This

change of paradigm, combined with new technology, promises that QPF will be a productive research area in the near future.

Another theoretical advance in meteorology is the renewed emphasis on potential vorticity in solving problems of the balanced flow in the atmosphere (Hoskins et al. 1985; Haynes and MacIntyre 1987). As discussed below, this advance has led to ideas about how best to use remotely sensed fields over regions devoid of in situ data to initialize numerical models.

In cloud and precipitation physics, the last two decades have seen great advances in the integration of cloud physics with atmospheric dynamics (Cotton and Anthes 1989; Houze 1993). These advanced methods of integrating detailed microphysics and dynamics have now progressed from research-only cloud models to high-resolution operational forecast models. Such models require the detailed interactions of physics and dynamics to predict the timing, location, and amount of precipitation on all time and space scales. Though the models are technically feasible, their microphysical-dynamical aspects are still poorly calibrated, and the requisite empirical constants are poorly known, particularly in ice-phase microphysics. Focused experiments, suggested later in this report, will help bring these theoretical advances to fruition.

4. Recommendations from subgroups

a. Basic physics of rainstorms

For observations and model output to be used most effectively for QPF, a clearer understanding of the storm lifecycle, including formation, intensification, and dissipation mechanisms in a broad spectrum of heavy precipitation events must be obtained. Probably most important are studies of mesoscale convective systems, that is, systems of convective origin, which have rain areas at least 100 km in dimension (Houze 1993). Even the most ambitious field programs in meteorology in the past have not been able to address adequately the lifecycle of a mesoscale convective system. Because of technological and budgetary limitations, the full multiplicity of scales and processes in precipitation-producing storms could not be observed. We have little understanding of what terminates the lifetime of these important precipitation-producing systems.

Also needed are studies of the basic physics of isolated convection and orographically influenced pre-

cipitation, both separate from and as part of mesoscale convective systems.

Underlying the precipitation mechanisms in all these precipitation-producing storms are physical couplings between cloud dynamical and cloud microphysical processes. Much has been learned in the last 50 yr concerning these couplings. Books on cloud and precipitation processes in the 1950s concentrated on the microphysics alone (e.g., Mason 1957). Recent books (Cotton and Anthes 1989; Houze 1993) emphasize the interconnections of dynamics and microphysics of clouds. However, much of the achievement in this area remains qualitative. Key microphysics processes have been quantified only at the most rudimentary level. Yet, they determine precipitation type and amounts and govern the phase changes of water, thereby providing important feedbacks to cloud dynamics. Better understanding and quantification of the conversions between liquid and ice are therefore central needs.

A key issue related to microphysics research is that very little work has been done to verify cloud hydrometeor predictions (or simulations) with observations. The availability of polarimetric radars offers the promise of improvements in this area. However, polarimetric radars will not provide explicit measurements of the parameters that appear in microphysical equations or parameterizations. The strength of the polarimetric radar is that it will map radar-measurable variables (differential reflectivity, differential phase, etc.) with high resolution throughout the volume of a storm. However, the connection between the radar-derivable parameters and the model variables is highly empirical with unknown certainty. It is essential that focused observational programs be undertaken to obtain in situ microphysical measurements of model variables or develop procedures for relating radar observables to cloud physics quantities explicitly predicted by models. This will probably have to be done by instrumented aircraft in conjunction with polarimetric radar. Aircraft with adequate altitude and endurance capabilities exist within the meteorological community [National Atmospheric and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), and some individual universities and private operators]. However, the access of scientists working on precipitation microphysics to these aircraft is presently limited, and the instrumentation is incomplete and inadequate to solve the problems that are introducing uncertainty into QPF. Measurements from other airborne platforms (e.g., balloons) may also prove use-

ful. Instrumentation for in situ measurements must be developed and improved to measure adequately the key microphysical variables. The USWRP should support increased access of mesoscale–cloud-physics scientists to the platforms and sensors most appropriate to solving the outstanding problems of precipitation microphysics. It should also provide support for further development of cloud-physics instrumentation and observing platforms. Until this is done, it will be difficult to verify the models used in QPF. The USWRP should facilitate the design and execution of field programs using the appropriate platforms and sensors for this purpose. In these field programs, observations should be done on several scales, ranging from cumulus to synoptic scale so that model prediction of the detailed microphysical evolution of a mesoscale convective system can be verified at various stages of the lifecycle of the storm.

From past field studies and numerical simulations, we have learned that convective organization and precipitation production are strongly coupled. For example, mesoscale convective systems are organized into convective and stratiform precipitation areas marked by distinctly different physical processes. The properties of the precipitation within these two modes of organization vary from heavy, but relatively short-lived, rain rates over a few tens of kilometers to generally light rainfall rates extending over a few hundreds of kilometers. We have also learned that the precipitation efficiency of convective storms can vary greatly; some supercells, for example, may produce copious rainfall rates with or without large hail, while others produce little, if any, rainfall (so-called low precipitation supercells). Still, other supercell storms produce large, damaging hail with little rainfall. The factors influencing precipitation efficiency and type have yet to be determined.

Recommendations:

- 1) *Use the operational WSR-88D, satellite, and profiler systems to develop a comprehensive climatology of the structure and organization of storms producing major precipitation at all stages of the storm lifecycle.*
- 2) *Utilize research radars in addition to operational radars to permit more detailed and comprehensive analysis of microphysical and kinematic processes in storms and their relation to precipitation production. Lightning observations of location, frequency, and polarity should be integrated into these analyses.*
- 3) *Continue to explore the use of polarization diversity radars in mapping the general characteristics of hydrometeors to learn more about the bulk precipitation structure and efficiency of precipitating cloud systems.* These studies should take advantage of the fact that it is now possible to examine and statistically document the structures of storms across the whole continent as they form, intensify, and decay.
- 4) *Conduct focused field observational programs that will determine the physical processes in each stage of the lifecycle of storms producing major precipitation.* These field campaigns will use observational strategies to determine the water budgets of these storms (vapor and condensate) with emphasis on the ice-phase microphysics and the processes by which the storms neutralize the stratification of moist static energy. These programs will require a mix of multiple Doppler-radar kinematic measurements, polarimetric radar measurements to document microphysical evolution, new and improved techniques for measuring the water vapor content of the air, profilers to delineate the mesoscale environmental flow, the WSR-88D network to show the broader context with finescale resolution, and evaluation of experimental results in real-time in the context of high-resolution model simulations of the storms. This capability will allow scientists in the field to perform experiments directly related to operational meteorology. For example, nowcasts can be made side by side with and without supplemental experimental input. Also, mobile observations (aircraft, soundings, radars, etc.) can be placed based on high-resolution numerical forecasts. This latter capability will be especially useful since the focus of field experiments will be on the lifecycles of storms, which last on the order of 1–3 days.
- 5) *Use new observing systems such as mobile rawinsondes, portable lidars, mobile radiometers, RASS, high-resolution satellite data, improved humidity measurements, and surface mesonetworks to quantify more accurately the environmental profiles of temperature and moisture.* Whether or not a convective event is triggered depends upon the environmental stratification of temperature and moisture and the nature of the mesoscale and synoptic-scale forcing. Our ability to predict the onset of convection is limited in part by our inability to measure the former, especially the moisture, and our lack of understanding of the latter. The

nature of the mesoscale and synoptic-scale forcing could be further understood by analysis of wind profiler data, clear-air WSR-88D data, and focused field experiments. The differing nature of vertical circulations associated with fronts, the dryline, outflow boundaries, topographic features, sea- and land-breeze fronts, and boundary layer rolls needs to be detailed. The effect of the vertical circulations on convective initiation needs to be determined. The observational studies should be supplemented by controlled experiments using mesoscale models available to the scientific community.

b. Effects of synoptic processes and surface boundaries

Significant rainstorms occur on many scales. Some are highly localized, short-lived, and primarily reflect small-scale unbalanced processes. Others are longer lasting, larger in scale, and are governed by quasi-balanced processes. The fundamental mechanisms that are responsible for the organization and intensity of convective circulations need to be better understood, especially long-lived precipitation events that may result when a balanced flow state is reached. Thus, further study is required to elucidate the interaction of the environment and storm-scale circulations that promote balanced flow states, and to find how certain types of convective organization may influence the establishment of balanced circulations. Typically, the larger-scale processes are dynamically driven deep vertical circulations whose intensity and duration are determined by lateral and vertical interactions of potential vorticity (PV) anomalies. These anomalies are usually found in the vicinity of the tropopause and within the lower troposphere. Current research suggests that many of the PV anomalies associated with important rainstorms are mesoscale in size, yet are sufficiently balanced to be relatively long lived and to behave as coherent structures as they move through large-scale flow patterns. Thus, they should be highly predictable *if* their structure can be defined well in the initial conditions of numerical models.

On 0–6-h timescales, successfully forecasting heavy precipitation depends strongly upon accurate knowledge of the mesoscale distribution of planetary boundary layer (PBL) wind, moisture, and thermal gradients. Information on land use, soil moisture, evapotranspiration, and finescale terrain variations is also essential.

A particularly difficult challenge is the measurement and prediction of orographic precipitation. It is

crucial to specify very-fine-mesh (< 10 km) physiographic features in numerical models and to parameterize mesoscale disturbances in the PBL. At issue is the extent to which observed lateral and vertical thermal, moisture, and wind gradients determine the origin points for orographically modified and controlled precipitation (convective and stratiform) and its subsequent evolution. Orographically induced air motions directly force and redistribute precipitation, and the orography organizes the runoff of the precipitation. Orographic processes can also create and modulate mesoscale gradients that are important to the prediction of the timing, intensity, amount, and areal coverage of precipitation.

An especially intriguing question is how mesoscale dynamical features are created. For example, along the eastern slopes of the Rockies, important mesoscale features such as the Denver cyclone often occur as a dynamical consequence of orography. Equally important is the challenge to understand how mesoscale precipitation areas, once organized in the vicinity of complex terrain, can induce the growth of new precipitation structures by means of propagating convergence lines and outflow boundaries that later interact with a spectrum of terrain features. Included in this category of events would be the impact of outflow from convection, itself initiated at locations governed by mountain wave-induced convergence.

Recommendations:

- 1) *Develop techniques to construct a more refined dynamical tropopause analysis and thereby more accurately define subsynoptic-scale PV anomalies over oceanic and continental regions.* The use of GOES 8/9 water vapor imagery and in situ observations from aircraft of opportunity will help define mesoscale wind fields in the upper troposphere. Satellite-derived radiances and ozone measurements, as well as aircraft temperature measurements, when combined with the derived mesoscale wind features, will enable specification of both mesoscale PV anomalies in the upper troposphere and the structure and configuration of the dynamic tropopause. Resolution of subsynoptic-scale PV anomalies and the associated configuration of the dynamical tropopause over oceanic and continental regions will have a positive impact on the prediction of synoptic- and subsynoptic-scale disturbances and their associated precipitation in the 0–48-h period, particularly when the background static stability is small.

- 2) *Make fuller use of the growing number of observations from surface mesonets, wind profilers, automated aircraft observations, satellites, and radial wind observations from WSR-88D radars.* These observations arrive at nonstandard times and must be assimilated into forecasts on an ongoing basis. This operational capability already exists and is continually being improved; however, it may not be fully utilized. The USWRP should assure that all potential data sources are used and contribute appropriately to QPF.

The assimilation of observations of opportunity into QPF is by itself insufficient. Additional observations will also be required, especially in the PBL, and these must be economical and reliable. One attractive strategy is to launch automated radiosondes on demand from key locations by experienced forecasters, who would selectively target the additional observations according to the problems of the day. This procedure would take advantage of knowledge of recurring circulations on a variety of time and space scales (e.g., southwest United States summer monsoon circulations or New England and Carolina coastal frontal circulations) to place preferential observations on demand. Objective ensemble analysis and forecasting strategies could also be used to identify favorable regions for supplementary observations. This methodology entails some risk in that it requires a forecast of what is needed to make a forecast, and the atmosphere is chaotic and therefore does not actually repeat itself. Nonetheless, preliminary tests suggest that this methodology may actually improve forecasts.

- 3) *Explore integrated data acquisition and management strategies for state and local mesonet data.* The horizontal resolution of the surface database should be improved by taking advantage of existing non-NWS data. There are many observing networks operated by the private sector and local, state, and federal agencies that are not currently available to national centers. Improved accessibility to such datasets could help establish a true mesoscale database, at least at the surface. There is thus a need for a USWRP focal point to (i) locate and encourage managers of local datasets to make their data available to the meteorological community, and in particular, to the National Weather Service; (ii) coordinate an effort to standardize the quality control and format of the data; and (iii) look into the feasibility of establishing an archive center (for observed and model data). This endeavor

will also require careful consideration of how best to process and assimilate vast volumes of mesoscale data into operational model analysis and initialization schemes.

- 4) *Use upstream data targeting methodologies to obtain additional in situ measurements of winds, temperature, and moisture (as discussed more fully in the final report from the Seventh Prospectus Development Team).* In particular, water-vapor drift winds from GOES 8/9 should be used in numerical forecast models if procedures for their assimilation can be developed and their inclusion demonstrated to be effective. We advocate such development and subsequent testing, focusing on their impact on numerical QPF. Success in making use of targeted observations will require an increased understanding of oceanic and continental heat, moisture, and momentum fluxes, radiative and convective processes, and soil moisture–evapotranspiration feedbacks. It will further necessitate the detailed (and routine) measurements of precipitation, snow cover, snow depth, and snow water equivalent.

c. *QPF techniques*

Forecasts of quantitative precipitation have shown slow but steady improvement during the last several decades (Olson et al. 1995). However, the natural disaster survey report on the great flood of 1993 concluded that “the scientific complexity in predicting rainfall from small-scale convection makes detailed positioning of high-intensity rainfall centers beyond our current scientific capabilities.” A comprehensive end-to-end approach is needed to identify problems and opportunities that need to be addressed to improve QPF (NOAA 1997). The nature of the improvements will vary with the range of the forecast. For short-term (0–6-h) forecasts, people will continue to use observation-based techniques. Longer range forecasts (6-h days) will depend more on numerical modeling improvements, especially on the improved integration of modern observations into the numerical modeling stream. The following recommendations are not made in order of priority but are in a sequence consistent with improving the end-to-end QPF process.

Recommendations:

- 1) *Improve depiction of the observed state of the atmosphere on subsynoptic scales.* The most accurate possible portrayal of the state of the atmosphere is essential to predicting mesoscale and smaller-scale

precipitation systems. Therefore, the effectiveness and relative costs of various observing systems should be assessed so that steps can be taken to optimize the total observing system. For example, the use of rawinsondes at nonconventional times could be explored. Traditionally, radiosondes have been released at 0000 and 1200 UTC, even though, for example, an 1800 UTC sounding might be much more valuable. Determination of the optimal areal distribution and location of all current and future observing systems for different synoptic and mesoscale patterns is essential to the future of improved weather prediction in general and QPF in particular.

- 2) *Develop improved empirical forecast methods for short timescales (0–6 h).* Very short-range forecasts will continue to be largely observation-based and applied by forecasters. Research on better techniques, based on better understanding of the climatology and lifecycles of mesoscale convective systems and other precipitating cloud systems, will underpin efforts to improve this type of QPF.
- 3) *Improve operational precipitation estimation by the optimal combination of rain gauge, radar, and satellite data.* Real-time rain gauge data are much too limited. Dense rain gauge networks exist, but the data are mostly not transmitted in real time. Calibrated rain gauge data need to be available and transmitted on a timely basis from a network of remote gauges around every WSR-88D radar. These gauges need not be numerous; however, there should be a sufficient number of them to use in connection with the WSR-88D data to provide real-time rain maps for assimilation and verification in QPF. The radar data in turn need to be used in connection with satellite data to map rain patterns on the larger scale. In performing this type of merged analysis, care must be taken to account properly for the widely different time and space sampling by the gauges, radars, and satellites. The USWRP must assure that this fusion of different data types is done optimally and accurately. Improved methods of using radar and satellites to estimate rain are discussed further in section 4d. Also, the report by the Second Prospectus Development Team provides an excellent summary of the observational needs for accurately defining the state of the atmosphere.
- 4) *Use better precipitation estimates in four-dimensional data assimilation (4DDA).* The avail-

ability of diverse and individually incomplete observing systems, which sample on different time and space scales, poses a challenge as to how to use this information for the initialization of high-resolution numerical models. Especially important is the use of precipitation data to introduce a diabatic initialization component into 4DDA.

- 5) *Assimilate WSR-88D data.* Assimilation of WSR-88D data into models deserves special attention. This assimilation will potentially use the entire set of radar observations in QPF. Presently, only the low-level reflectivity data are used operationally to estimate rain. This outdated procedure converts reflectivity to rain rate by various empirical methods. The WSR-88Ds obtain data over a three-dimensional volume of space, and they measure two fields: reflectivity and radial velocity. Assimilation methods will use the entire three-dimensional data fields provided by the radars and will not depend on questionable conversions of reflectivity to rain rates. This type of assimilation can be done in either meso-b or meso-g scale models. Meso-g-scale models take on special importance because they can employ detailed microphysical schemes to predict the precipitation field and have resolution more comparable to the radar data. Dual-polarization techniques offer the possibility of assimilating information that constrains the types and amounts of hydrometeors and their spatial distribution, though considerable testing and verification remains to be done.
- 6) *Improve model QPF and develop new operational forecasting techniques.* The development of new forecast techniques and guidance (especially probabilistic techniques, see section 5) is encouraged for a spectrum of different forecast projections (0–48 h) and spatial scales (meso-g to synoptic scale). Special emphasis should be placed on the very short (0–6 h) time period to produce high spatial and temporal resolution probabilistic forecasts of storm development, evolution, dissipation, and precipitation amount. These high-resolution forecasts would improve our ability to predict flash floods, and thereby mitigate their socioeconomic impact.

Better conceptual models are also needed to improve the operational prediction of the scale, intensity, development, movement, and dissipation of precipitating cloud systems. The development of methods to help predict which convective systems will become quasi-stationary or will propa-

gate upstream of the mean flow should be strongly encouraged.

Assimilation methods need to be optimized to use the huge amounts of observational data now or soon-to-be available from advanced observing platforms such as *GOES 8/9*, *ASOS*, and the *WSR-88D*. These data are key to accurate short-term prediction of flash floods; however, techniques do not yet exist for the fusion of this diverse information into products targeted to help QPF and hydrological forecasts (see section 4d).

Research is needed in cloud microphysics to improve precipitation prediction using both meso- α and meso- β scale models. Such research should also result in better understanding of the knowledge of the relative importance of microphysical processes of the QPF problem. For example, improved cloud microphysics might provide insight into why some storms produce 50 mm h⁻¹ rainfall rates, while others nearby produce 200–300 mm h⁻¹. The studies may also aid in the understanding of quasi-stationary convective systems. Validation of model forecasts of QPF and of microphysical processes is needed to help improve the models.

- 7) *Develop a probabilistic framework for QPF and for QPF-related products and information.* As discussed in section 3, it is now generally recognized that the atmosphere is a chaotic system and as such it has finite predictability. The associated problems are magnified for QPF by the highly local and intermittent nature of processes generating precipitation. Despite improvements in numerical modeling, there will always be a time limit beyond which individual systems cannot be predicted; however, the likelihood of the occurrence of such systems can nonetheless be predicted. It follows then that a reasonable approach to QPF is a probabilistic one.

Users of QPF support this scientific appraisal. The natural disaster report for the great flood of 1993 (NOAA 1994) cited a need for a probabilistic approach to QPF and related hydrological forecasts to aid decision makers (i.e., emergency managers) in assessing risk. This need was reiterated by representatives from the National Hydrological Warning Council, the Tennessee Valley Authority, the Connecticut Department of Environmental Prediction, the Bureau of Reclamation and Army Corps of Engineers, and the NWS Office of Hydrology at the Fifth National Heavy Precipita-

tion Workshop in September 1996. Probabilistic QPF guidance products should be developed for use by forecasters at the national centers and regional forecast offices.

There exists a wide range of needed research on probabilistic precipitation forecasting. This is so important that we devote section 5 to a further discussion of some of the specific areas of this needed research.

d. *Precipitation estimates for forecast validation*

A basic problem in evaluating QPF performance is that there is no single way to measure and represent precipitation in space and time. The accepted “standard” of rain measurement is the rain gauge; however, rain gauges have different catchment sizes and hence are not standard among themselves. Moreover, because of local effects, there are biases that cannot readily be corrected. Thus, even point rainfall values from accepted standard instruments can have large errors.

Radar is used to fill the field of precipitation in between gauges. However, the resolution of the radar measurement (e.g., 10⁶ m²) is orders of magnitude poorer than that of even the largest rain gauge (say, 1 m²). Thus, the rain rates estimated by radar and gauge are not strictly comparable. Nonetheless, gauges must be used for removing the bias from radar rain estimates, and the accuracy of rain gauge measurements remains paramount.

Satellite data may be used to extrapolate and interpolate radar and gauge data, but this type of estimation is much more uncertain than either radar or rain gauge estimation and applies on still larger scales (a satellite resolution might be anywhere from 10⁸ to 10¹⁰ km²), making it unsuitable to relate to a gauge estimate.

Because of these limitations, the ability to verify QPF with available methods is severely hampered. Having no better alternatives, one must use the means available. In doing so, one must estimate the uncertainty of both the QPF and the quantitative precipitation estimate (QPE). The QPF validation problem is not simply a matter of having the most “accurate” QPF and QPE products at the same point in time and space. The chaotic nature of the atmosphere must be considered as well in validation. Comparisons of a statistical nature must be employed to determine if models *tend* to give the right solutions over time. One cannot rely on case-by-case gridpoint comparison as the only method of comparison. In addition, one must consider the grid resolution of a model in relation to the intrinsic

sic horizontal scale of the precipitation estimate to which the model results are being compared. As noted above, the intrinsic scale of the QPE is highly sensor dependent. This means that one must be especially cautious in interpreting hybrid QPE products that are based on a mix of gauge, radar, and satellite data.

With these caveats in mind, we present next the report of this working group.

Currently, rain gauges, radars, and satellite-borne radiometers are used for measuring and estimating precipitation; however, they operate at much different horizontal scales. Therefore, as noted above, the utility of each measurement platform is highly dependent upon the relevant scales of the phenomenon being verified. The accepted "standard" for "point" measurements is the rain gauge, but gauges are insufficient to resolve precipitation patterns. Over land, a multisensor analysis is necessary, despite the different resolutions of gauges, radars, and satellites discussed above. Currently, the hourly NWS Stage I-III and National Precipitation Analysis products integrate rainfall estimates within the WSR-88D network domain. Gauges should be used statistically to adjust the bias of the WSR-88D estimates, but then the final map has an intrinsic scale corresponding to the radar data. Radar coverage over the ocean is limited to coastal regions and extension beyond can be made by utilizing satellite radiance measurements. Measurement from space may also substitute for radar data in some regions where the radar beam is refracted above a layer of air containing precipitation. The final product of merging the gauge-calibrated radar maps with a satellite-based product results in a product with a resolution corresponding to the satellite data. Ultimately, model verification must be at the scale of the horizontal resolution of the model being verified.

Gauge-calibrated radar measurements offer the best available technique for determining areal patterns and total areal amounts of precipitation. However, some significant limitations remain. In particular, the discrimination of rain, snow, and hail is difficult and ambiguous. The bright band is a common phenomenon that requires recognition to avoid erroneous measurement. In addition, beam broadening, growth and evaporation below the beam, and orographic effects interfere with rain estimation by radar. More fundamentally, there are calibration errors, attenuation, effects of anomalous propagation (AP), ground clutter, and beam blocking. These problems cannot be completely avoided, but they can be addressed significantly if a concentrated program of applied research

on the traditional radar problems is undertaken by qualified investigators over the next decade. Up to now, there have been no routine comprehensive efforts to validate and assess the accuracy and uncertainty of multisensor rainfall estimates for a spectrum of space and timescales to maximize their operational utility.

The operational WSR-88D radars map the precipitation and radial velocity throughout a three-dimensional volume of space. Currently, only the low-elevation scans of reflectivity are used to validate model results by using the radar data for surface rain estimation. The radars are thus underutilized for forecast model evaluation. In principle, the radar data can be used to verify the three-dimensional structure and kinematics of rainstorms by comparing three-dimensional reflectivity and radial velocities computed from high-resolution model output to those observed by the WSR-88D radars. In addition, the three-dimensional radial velocity and reflectivity data (and eventually possibly polarimetric radar data) can be assimilated into high-resolution cloud models to estimate precipitation on an ongoing basis. These continually updated maps, taking maximum advantage of modeling and observational technology, may provide the best precipitation maps in the future. This approach would make it unnecessary to produce maps of rain or snow rate based on conversions of low-altitude reflectivity (or other radar parameters) to purely empirical precipitation maps.

Recommendations:

- 1) *Validate and improve the existing operational radar, satellite, and gauge precipitation product. Consideration should be given to data quality, including calibration, anomalous propagation, ground clutter, and scanning strategies and to the intrinsic resolutions of the different sensors.*
- 2) *Test radar polarimetric algorithms to estimate precipitation amount and to determine precipitation type. Conduct comprehensive experiments to validate these algorithms and the benefits that may arise if the WSR-88D network were converted to multiple polarization. Verification of the precipitation amount and physical validation of type should be conducted in diverse climatic locations for all seasons.*
- 3) *Refine operational radar precipitation estimates using satellite data, in situ observations, conceptual and numerical models, and mesoscale data networks when available. Evolve this method toward a scheme whereby these observational data*

are assimilated into a numerical cloud model, which in turn provides QPE and serves as input to short-term QPF.

- 4) *Develop scanning strategies for the WSR-88D that will depict the full three-dimensional distribution of radar reflectivity, radial velocity, and eventually polarimetric parameters. Use these strategies to verify QPF in a variety of regions such as in mountainous terrain and in situations where particles grow and fall from low-level shallow layers.*
- 5) *Develop and evaluate satellite-based methods of precipitation estimation that will complement radar/rain gauge analyses. Efforts should focus on mountainous areas with radar blockage problems, shallow raining systems where radars have difficulties at longer ranges, and offshore areas where radar data are lacking.*

5. Needed research on the probabilistic nature of QPF and its verification

In section 3, and in recommendation 7 of section 4c, we have noted the importance of addressing QPF and its verification in a probabilistic framework. In the following sections, we highlight some specific areas that need attention.

a. Predictability at the meso- and convective scales

How long can a mesoscale convective complex, a squall line, or a supercell be predicted into the future? The answer would provide much needed guidance for modelers, who at this point cannot be sure if a “failed” forecast is due to model deficiency, a poor initial analysis, lateral boundary conditions, or intrinsic atmospheric instabilities. Such instabilities would prevent any single prediction from being reliable (even if initial errors were small).

b. Optimal parameterizations of convection and precipitation microphysics in numerical weather prediction circa 2010

Another important research topic is how to account for the uncertainty that subgrid-scale parameterizations (such as cumulus or microphysical parameterization) introduce into forecasts. Typically, there is no stochastic forcing to represent the effects of subgrid-scale processes, and therefore, current operational packages do not account for this additional uncertainty. Thus, there is a tacit assumption that subgrid-scale processes are deterministic from grid-scale conditions,

that is, that subgrid-scale processes are not chaotic—a strikingly peculiar assumption. According to this reasoning, the atmosphere stops being chaotic at subgrid scale. In other words, the assumption that deterministic parameterization is indeed possible is not questioned. By facing this problem, it may be possible to assess the true variance of models and bring the model variance closer to the observed variance.

c. Methodology for probabilistic QPF

Case-dependent probabilistic guidance through the generation of an ensemble of forecasts is already being applied successfully to synoptic and mesoscale forecasts by major operational forecast centers worldwide (Toth et al. 1997). The applicability of the different initial perturbation methods that are used on larger scales for the smaller scales should be investigated and, if needed, the methods should be refined or new methodologies explored. The use of equally good but different physical parameterizations should also be explored. This research can easily feed back to model development by pointing out weak or uncertain points in the model formulation (Houtekamer et al. 1996).

Studies are needed to determine the relative value of high-resolution forecasts versus lower-resolution ensemble runs. For example, will the lower resolution of the ensemble runs lead to characteristic biases in precipitation forecasts? Assuming each method (higher resolution versus ensemble techniques) has strengths and weaknesses, research into combining aspects from both methods into a forecast strategy for predicting precipitation should be encouraged. The need for increased spatial resolution in the models and for increased resolution in the probability space provided by a larger ensemble will always have to be weighed against each other. The ideal choice for these two parameters will probably depend on the scales considered and can be a topic of future research.

d. Verification of probabilistic QPF

Traditional methods designed for verifying single forecasts, like the “equitable threat score” (Shaefer 1990), may be misleading to model developers. For example, if a model predicts perfectly the development of a storm but displaces it either in time or space, the equitable threat score would show zero skill. Therefore, for a true evaluation of a forecast system, the verification has to be done in a probabilistic fashion. An ensemble of forecasts must be run from initial conditions that reflect the true uncertainty in the

control analysis and the ensemble-generated probabilities evaluated over a number of forecast episodes. There is therefore a great need for the development and genuine use of probabilistic QPF verification measures for all forecast applications.

Precipitation is so highly localized and intermittent that it needs to be presented probabilistically from the point of view of measurement and sampling as well as numerical modeling. The forecast products will not be meaningful unless they are related in a statistically correct manner to the validation products. As noted in section 4d, the validation products are subject to a variety of uncertainties, related to the intrinsic scale of the sensor, to the sampling of the intermittent precipitation process, and to sensor accuracy. In addition, since the intrinsic scale of the QPE is highly sensor-dependent, one must be especially cautious validating QPE with hybrid QPE products that are based on a mix of gauge, radar, and satellite data. One must consider the grid resolution of a model in relation to the intrinsic horizontal scale of the QPE. To address these problems, research on the statistics of rain measurement must be undertaken in parallel with research on ensemble modeling in order to develop useful guidance.

e. Measurement of skill relative to climatology

Probabilistic forecasts for extreme rainfall events are not feasible without an understanding of their climatological frequency. Therefore, considerable research is needed to determine the distributions of their scale, intensity, and duration. The feasibility of developing conditional probabilities for various heavy rainfall-producing patterns should also be addressed. For example, historical data from hurricanes could provide a conditional climatology for various precipitation, or basin average precipitation amounts assuming the path of the hurricane is well forecast. Climatological studies of mesoscale convective systems could also be done to assess the potential for extreme events for a given set of similar initial conditions. The full network of WSR-88D radars now in place provide a rich data source for the development of a climatology of storm structure. However, to make full use of this resource, two additional changes are essential: (i) the level II radar data must be made more immediately available to researchers without unreasonable cost; and (ii) the scanning strategies of the WSR-88D system must be modified and adapted to regional and seasonal conditions. Applying scanning strategies appropriate for thunderstorm conditions over the central United States, for example, poorly documents the structure of

flood-producing storms on the west coast and is inadequate for snowstorm conditions in the northeastern United States. Accounting for regional effects is one of the most significant problems for QPF and one of the least expensive to solve. The USWRP needs to give special attention to this problem, since the WSR-88D network is both a vital research resource and an operational system. To accomplish the long-term research goals of the USWRP, especially those related to QPF, the procedures for distributing research-level data and for optimizing the scanning of the radars must be designed in a manner that simultaneously provides for operational needs for the present and for research needs for the future improvement of QPF.

f. Hybrid forecast systems

As mentioned above, beyond the ensemble methods, there are other approaches for generating probabilistic forecasts, for example, the traditional model output statistics (MOS)-based techniques, which relate analogs from historic datasets to either a single or an ensemble of forecasts. Such techniques might aid in a climatological assessment of the predictability of the system and might provide an estimate of a system's potential to produce extreme rainfall events. A combination of the traditional MOS-based technique with ensemble forecasts could provide a powerful hybrid system that would account for uncertainty arising from both sampling error and deficiencies in model physics while simultaneously removing model bias. It is imperative that the benefits and limitations of each of these approaches be evaluated objectively.

g. Application of probabilistic QPF to hydrological forecasting

The uncertainty in rainfall forecasts must be transmitted to hydrologic models in order to assess the uncertainty in basin runoff. For example, how do the ensemble variations in the temporal and spatial distribution of the precipitation within the basin change the stream flow? The technology is now available to construct hydrologic model ensembles, driven by atmospheric ensembles, but suitably modified to allow for the additional uncertainty introduced by the hydrologic models themselves. Studies need to be undertaken to determine how to optimize the use of probabilistic QPF and ensemble forecasts in hydrological models.

A related question is how the amount of rain computed through a parameterization procedure in the QPF should be distributed on time- and spatial scales that are not resolved by the model. This step, loosely

termed "deparameterization," is a very important one, especially for hydrologic applications such as probabilistically estimating basin rainfall amounts. This problem may be addressed by a combination of empirical and modeling approaches by using WSR-88D data in connection with meso-g-scale models.

6. Conclusions

The new observing systems, advances in computational power and theoretical advances, present the opportunity to make significant improvements in quantitative precipitation forecasting. On the meso- and synoptic scales, recent advances in potential vorticity theory combined with observations of upper-tropospheric winds derived from *GOES 8/9* water vapor imagery could be used in conjunction with satellite-derived radiances to define dynamically important mesoscale PV anomalies through a more refined dynamical tropopause analysis. This combination of new dynamical understanding and observing-system technology offers promise to significantly improve the initialization of important mesoscale features in data-sparse regions such as the eastern Pacific. Such improvements are vital to upgrading the accuracy of 12–48-h forecasts over the western United States.

The WSR-88D radar network, still in its infancy, offers the opportunity to improve quantitative precipitation estimates and forecasts. At the present time, the WSR-88D scan strategies and algorithms applied to the radar data emphasize the lowest elevation angle information only; they do not take advantage of the adaptable three-dimensional scanning capability of these radars. The scan strategies and rain estimation algorithms are designed primarily for thunderstorms over flat land. Moreover, the scan strategies and algorithms do not take into account the problems of precipitation measurement over complex terrain or of shallow layers of precipitation, even though the radars have the capacity to deal with the diversity of weather and topographical situations in the United States. Over the next decade, a vigorous applied research effort should be undertaken to address the current underutilization of the WSR-88D network.

Polarimetric radar technology constitutes an additional opportunity to refine verification of QPF and precipitation type and to provide a database for studying issues of cloud microphysical parameterization; however, this technology is currently not available on

the WSR-88D radars. The next few years should see a vigorous effort of testing and validation to determine the potential utility of a polarimetric upgrade of the WSR-88D radars.

Much of the advance in understanding precipitation-producing storms has come from field experiments in which research instrumentation is used to augment operational meteorological data. Field experiments in the past have, however, been limited by the fact that assessment of the experimental results had to await many years of post-experimental analysis. Advances in high-resolution numerical weather prediction and in data processing technology will permit field experiments in the coming years to include near-real-time intercomparisons with high-resolution numerical forecasts. This real-time approach to field analysis should increase the overall efficiency of future field experiments and allow the results of the field experiments to have an immediate feedback into operational utility.

The greatest need for field work in the upcoming years is to improve the understanding of the lifecycles of precipitation-producing storms. Past field work has been limited spatially so that long-lived mesoscale systems did not go through their lifecycles in the experimental domain. With the WSR-88D radar network, it will be possible to trace storms in their full mesoscale precipitation structure from one area of the country to another. The enhanced capability for high-resolution numerical modeling will allow investigators in the field to anticipate better the movement of the systems from one area to the next. The existence of aircraft and mobile ground-based observational platforms within NOAA, NASA, and National Center for Atmospheric Research will allow investigators to move experimental domains with the storms. Thus, the operational and research technology of the country can meet the longstanding need to understand the lifecycle characteristics of the storms producing the most precipitation over the country.

Large advances in computational capabilities coupled with the recognition of the inherently chaotic nature of the atmosphere (especially for precipitation processes) have changed the approach to QPF from deterministic to probabilistic. Probabilistic form provides a measure of the uncertainty in forecasts, therefore making forecasts of far greater value to users of weather-sensitive information. Within this new framework, it is essential to take advantage of all of the new observational information that helps reduce uncertainty by better defining the mesoscale structure needed for high-resolution numerical and statistical

forecasts. Techniques for assimilating these new data types are still in their early stages of development. The new data assimilation techniques can provide a powerful basis for determining what observations are required to capture essential mesoscale structure for accurate QPF.

After considering the discussion, hypotheses, and specific recommendations (sections 4 and 5), the following main recommendations are as follows:

- 1) *Improve the accuracy and temporal and spatial resolution of the rainfall observing system.* Optimally blend precipitation data from all relevant sensors. This will require taking into account all the sampling problems peculiar to precipitation and the widely varying time and space resolutions of the sensors. Implicit within this recommendation is improvement of the National Precipitation Analysis and optimization of the three-dimensional observational capability of the WSR-88D radars and other new sensors.
- 2) *Perform case and climatological studies using the modernized observing system.* Conduct focused field programs to understand better the microphysics and dynamics of precipitation processes during the full lifecycle of precipitation-producing cloud systems, especially mesoscale convective systems. Conduct climatological studies of the detailed structures of precipitation-producing storms to provide a basis for determining the skill of high-resolution precipitation forecasts.
- 3) *Design new data-gathering strategies for numerical model initialization.* Explore targeted/adaptive observing procedures, insertion of upstream data derived from balanced flow relationships, and initialization of the precipitation systems themselves.
- 4) *Define a probabilistic framework for precipitation forecasting and verification.* Develop advanced ensemble techniques that account for forecast uncertainty stemming from sampling error and differences in model physics and numerics. Develop statistical techniques for using observational data to verify the probabilistic QPF. Use model output and observation-based statistical techniques to provide probabilistic QPF for input to short-term hydrological forecasts.

In our opinion, there has never been a better opportunity to improve quantitative precipitation fore-

casting. Finally, the observational database is capable of resolving the scale of the precipitation features themselves and the requisite numerical processing capability is available—all that remains is for the scientific community to rise to the challenge.

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