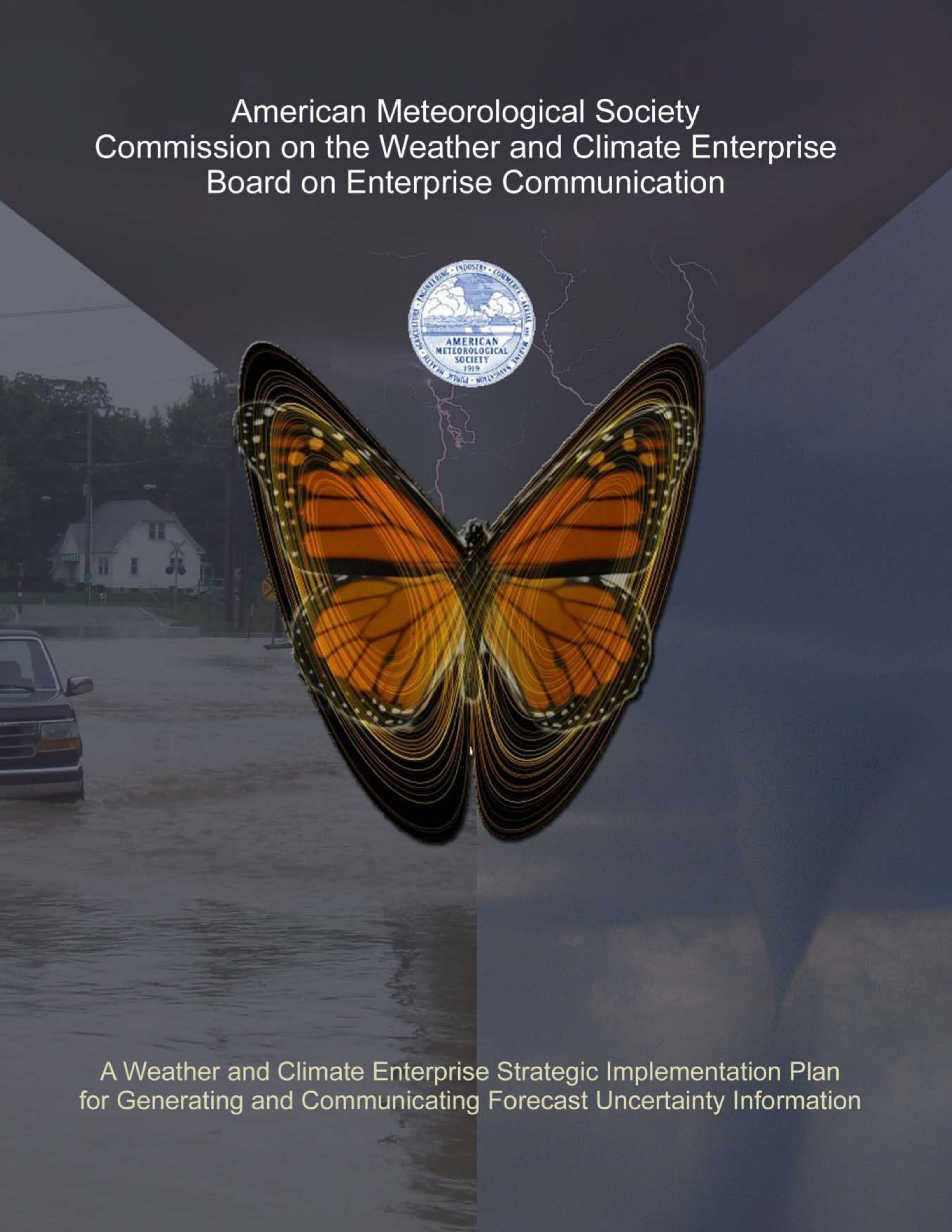
American Meteorological Society
Commission on the Weather and Climate Enterprise
Board on Enterprise Communication



A Weather and Climate Enterprise Strategic Implementation Plan for Generating and Communicating Forecast Uncertainty Information

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Generating and Communicating Forecast Uncertainty Information

Edited by

Paul A. Hirschberg and Elliot Abrams

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The cover art includes an overlay of a monarch butterfly and the so-called "Lorenz attractor" (Gleck 1988). The Lorenz attractor shows the evolution of a simple 3-dimensional nonlinear dynamical system that exhibits sensitive dependence upon initial conditions, a fundamental property of chaotic flow. If two particles were started in motion very close to one another on the attractor, their trajectories would diverge after time with both particles tracing out separate butterfly-looking paths around the two centers. This divergence in the particle trajectory paths illustrates that even if the initial conditions are known very precisely in even simple nonlinear dynamical systems, the unavoidable error in specifying the initial conditions nevertheless grows rapidly, so that after only a short time the details of the motion cannot be predicted. This effect is manifested in the atmosphere (a much more complicated nonlinear dynamic system) by the inability to predict any weather phenomena with absolute certainty and provides the impetus for generating and communicating the uncertainties in all weather, water, and climate forecasts. Although the Lorenz Attractor does look like a butterfly, the term "The Butterfly Effect" refers to initial-condition sensitivity. At the December 1972 meeting of the American Association for the Advancement of Science, Lorenz gave a talk entitled, "Predictability: Does the Flap of a Butterfly's Wings in Brazil set off a Tornado in Texas?"

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Preface

This Weather and Climate Enterprise Strategic Implementation Plan for Generating and Communicating Forecast Uncertainty (Plan) was developed by the American Meteorological Society (AMS) Ad-Hoc Committee on Uncertainty in Forecasts (ACUF). The purpose of the Plan is to define a vision, strategic goals, roles and responsibilities, and an implementation roadmap that will guide the weather and climate enterprise (Enterprise) toward routinely providing the Nation with comprehensive, skillful, reliable, and useful information about the uncertainty of weather, water, and climate forecasts. The Plan is intended for a wide audience including senior decision makers, program managers, service providers, and scientists.

The ACUF was charged by the AMS Commission on the Weather and Climate Enterprise (CWCE) Board on Enterprise Communication to formulate a cross-Enterprise plan to provide forecast uncertainty information to the nation. The ACUF was commissioned in response to a growing number of studies recognizing the scientific, socioeconomic, and ethical value of quantifying and effectively communicating information about the uncertainty inherent in all weather, water, and climate forecasts. Additionally, the CWCE recognized the ACUF's work as another opportunity to enhance public, industry, and academic partnerships[1] within the Enterprise since the plan would propose mutually beneficial roles and responsibilities for these partners to jointly plan and execute programs and projects.

The Plan is based on, and intended to provide a foundation for implementing, recent recommendations regarding forecast uncertainty by the National Research Council (NRC), AMS, and World Meteorological Organization (WMO). It leverages emerging results from scientific and socioeconomic studies, and the best practices of hydrometeorological[2] services and industry from around the world.

One NRC recommendation that was assumed axiomatic by the ACUF, is that the entire Enterprise should be involved in, and take responsibility for, transitioning to a new forecast paradigm that embraces uncertainty. Therefore, the intent is for the four sectors comprising the Enterprise (i.e., government, industry, academia, and nongovernmental organizations) to work in partnership over the next decade to execute the Plan and achieve its goals. While the implementation roadmap suggests sector roles and responsibilities for the various tasks, it is not programmatic in the sense of defining specific program plans with accompanying cost, schedule, and performance information. These important details are beyond the scope of this Plan and are the purview of decision makers throughout the Enterprise. However, leadership in organizing and motivating Enterprise resources and expertise will be necessary to reach the Plan's vision and goals, and shift successfully to a greater emphasis on forecast uncertainty; and the ACUF endorses the NRC (2006) recommendation that the National Oceanic and Atmospheric Administration and in particular, the National Weather Service as the nation's public weather service, take on this role.

Paul Hirschberg and Elliot Abrams, ACUF Co-Chairs

[1] As recommended by the National Research Council (NRC 2003).
[2] Hydrometeorological refers to hydrological- and meteorological (weather and climate)-related services.

Acknowledgments

Over sixty professionals (Appendix A) from government, industry, and academia volunteered to be members of the American Meteorological Society (AMS) Ad-Hoc Committee on Uncertainty in Forecasts (ACUF) and contributed to the development of this Plan. The number of multisector volunteers is reflective of the broad recognition by the entire Enterprise that the time is now to provide useful forecast uncertainty information in order for the nation to make better decisions. Thanks go to all of those individuals who served on the committee, as well as those who reviewed the Plan, the AMS Board on Enterprise Communication, Commission on the Weather and Climate Enterprise, and Council. Special thanks go to the ACUF Subgroup Co-leads: Bill Bua, John Gaynor, Betty Morrow, Thomas Hamill, Douglas Hilderbrand, Ross Hoffman, Brenda Philips, John Sokich, and Neil Stuart; and to Andrea Bleistein, who provided both technical expertise and logistical support. Much appreciation also goes to Bob Glahn for authoring appendices on probability theory and decision theory and the authors of the forecast uncertainty application examples: Andrea Bleistein, Luca Delle Monache, Tom Dulong, Thomas Hamill, Jim Hansen, and Douglas Hilderbrand; and also to Geoff Manikin who mined and analyzed National Center for Environmental Prediction operational model data and provided analysis and figures for the east-coast snowstorm side box. Finally, thanks to Andrea Bleistein, Thomas Hamill, Douglas Hilderbrand, and John Sokich who helped write, edit, and rewrite various portions of the many drafts leading to the final version of the Plan, and to Ken Heideman for technically editing the document.

Executive Summary

The ability to predict hurricanes, winter storms, severe weather, floods, droughts, El Niño, and other weather, water, and climate conditions has improved greatly over the last 50 years. Nevertheless, the accuracy of forecasts for these events remains far from perfect. While science and technology advances will continue to reduce forecast errors, there will always be varying degrees of uncertainty in forecasts because of the physical nature of the atmosphere, oceans, and related Earth-systems. Knowledge of this day-to-day forecast uncertainty will not only improve decisions and decision outcomes, but also decision makers' confidence in using forecast information in the first place.

This Plan defines a vision, strategic goals, roles and responsibilities, and an implementation roadmap to guide the weather and climate enterprise (Enterprise) toward routinely providing the nation with comprehensive, skillful, reliable, and useful information about the uncertainty of weather, water, and climate forecasts. The Plan is based on, and intended to provide a foundation for implementing, recent recommendations regarding forecast uncertainty by the National Research Council, American Meteorological Society, and World Meteorological Organization. It leverages emerging results from THORPEX[3], other scientific and socioeconomic studies, and the best practices of hydrometeorological[2] services and industry from around the world.

As an overview of the use and benefits of forecast uncertainty information, the Plan provides a synopsis and several scenarios of how hydrometeorological forecast uncertainty information can improve decisions and outcomes in various socioeconomic areas. For example, weather-related delays account for 70% (~$28 billion) of all U.S. aviation delays during a year. Furthermore, a study by Keith (2007) has shown that one airline alone could potentially save $50 million annually on domestic flights by relying on probabilistic terminal weather forecasts to save fuel and other associated costs. These types of savings sum to potentially large benefits when extrapolated nationally and over other sectors such as emergency management, national security, energy, ecosystem management, and public health.

In order to meet the scientific, technical, and cultural challenges associated with a greater focus on forecast uncertainty, the Enterprise must build capabilities in four key, interrelated strategic areas:

1. **Understanding** customers' needs for uncertainty information, how societal and human factors influence the communication and use of uncertainty information, the nature of forecast uncertainty and how to quantify it;

2. **Communicating** uncertainty information effectively and **collaborating** with users to assist them in interpreting and applying the information in their decision making;

3. **Generating** uncertainty data, products, services, and information needed by users; and

4. **Enabling** the development, acquisition, and operation of forecast uncertainty processing systems with necessary computational, telecommunications, and other types of infrastructure.

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[3] The Observing System Research and Predictability Experiment (THORPEX) is dedicated to accelerating the improvement of high-impact weather predictions. Improving probabilistic forecast systems is a large component of the THORPEX research agenda. See http://www.wmo.int/pages/prog/arep/wwrp/new/thorpex_new.html.

The Plan lays out a comprehensive roadmap of objectives and tasks that the four sectors comprising the Enterprise (i.e., government, industry, academia, and nongovernmental organizations) should work on in partnership over the next decade to meet the strategic goals and enable the nation to understand and use uncertainty information effectively in decision making. While the implementation roadmap suggests sector roles and responsibilities for the various tasks, it is not programmatic in the sense of defining specific program plans with accompanying cost, schedule, and performance information. These important details are beyond the scope of this Plan and are the purview of decision makers throughout the Enterprise. However, leadership in organizing and motivating Enterprise resources and expertise will be necessary to reach the Plan's vision and goals, and shift successfully to a greater emphasis on forecast uncertainty; and the ACUF endorses the NRC (2006) recommendation that the National Oceanic and Atmospheric Administration and in particular, the National Weather Service as the nation's public weather service, take on this role.

1. Purpose and Introduction

A great success of 20th century science and technology was developing the ability to forecast future weather conditions. The skill[4] and accuracy[5] of these forecasts have increased enough to improve decisions protecting life and property, health, national defense and homeland security, and socio-economic, ecosystem, and individual well-being. Particularly, over the last 50 years, forecasts have improved to the point where seven- to ten-day weather forecasts are frequently skillful (i.e., compared to climatology). Hurricanes, winter storms, severe weather, floods, and other hazardous conditions can be identified many days in advance with forecast skill and accuracy increasing as the lead time shortens. Much progress has also been made in predicting expected conditions (e.g., above or below normal temperature, precipitation, drought, and storminess) beyond the one-to-two week "weather regime" associated with seasonal to interannual climate variability (e.g., El Niño), and even longer-term, scenario-based, climate change. However, despite these successes, the accuracies of weather, water, and climate forecasts[6] are far from perfect. Errors in forecasts can not only adversely affect decisions and outcomes, but also decision makers' confidence in using the forecast information in the first place.

The purpose of this Plan is to define a vision, strategic goals, roles and responsibilities, and an implementation roadmap for routinely providing the nation with comprehensive, skillful, reliable[7], sharp[8], and useful information about the uncertainty of weather, water, and climate (collectively called hydrometeorological) forecasts. The Plan is based on, and provides a foundation for, implementing recent recommendations of the National Research Council (NRC 2006), American Meteorology Society (AMS 2008), World Meteorological Organization (WMO 2008) and others. These reference documents synthesize the emerging consensus of the scientific, socioeconomic, and ethical value of quantifying and effectively communicating information about the uncertainty inherent in all hydrometeorological forecasts.

Here and throughout this plan, the term "forecast uncertainty" or just "uncertainty" is used as a general, overarching term referring to ambiguities, indeterminateness, or lack of exactness in forecasts[9]. The cumulative result of uncertainty in a forecast is forecast error—the actual difference between what was forecasted to occur prior to an event (e.g., the amount of snow two days from now) and what actually occurred (was observed) in nature (e.g., the measured amount

[4] Skill is a measure of how well a forecast performs relative to some standard of comparison, such as climatology or persistence.
[5] Accuracy is the extent to which the forecasted value of some variable approaches the true (observed) value.
[6] Here and in the remainder of the plan, the term "forecasts" is intended to be generic and include warnings, watches, forecasts, predictions, and outlooks as appropriate.
[7] Reliability measures whether, over a large set of events, individual probability values are equivalent to the relative frequency of occurrence of the event. For example, for a large subset of Probability of Precipitation (PoP) forecasts in which the probability forecast is 0.25, precipitation would occur 25 percent of the time if the forecasts are reliable.
[8] Sharpness represents the degree to which the probability forecasts of the event approach zero or one. Desirable forecasts are those that differ as much as possible from the climatological (or mean) value and are still reliable. Although sharp forecasts are very desirable, reliability is imperative for decision making, and must not be compromised to make them sharper.
[9] NRC (2006) defines forecast uncertainty as the "condition whereby the state of a system cannot be known unambiguously".

of snow that actually fell). Fortunately, it is possible to ascertain information about forecast uncertainty before the forecasted event occurs. At its simplest, forecast uncertainty information can be used to describe and quantify the magnitude of the expected error in a forecast, while more sophisticated expressions of uncertainty may include confidence intervals, probability density functions, threshold probabilities, and so on. The bottom line is that forecast uncertainty information can provide users knowledge from which to make better decisions based on the uncertainty in a forecast and its associated risks.

The degree or size of forecast uncertainty can vary depending on many factors. Generally, forecast uncertainty increases as the forecast lead time (hereafter referred to as forecast lead or just lead) increases (i.e., the farther the forecast extends into the future). Also, forecast uncertainty increases more quickly for smaller-scale (size and duration) phenomena, such as a thunderstorm, than for larger-scale phenomena, such as a winter storm (Figure 1). Forecast uncertainty also grows more quickly in dynamically active regions around storms than in the middle of quiescent, fair-weather regimes. Typically, by two weeks uncertainty is large enough that forecast skill (predictability[10]) is lost for nearly all types of weather (Simmons 2006, Tribbia and Baumhefner 2004). Beyond two weeks and on into monthly, seasonal and longer-range forecast leads, all predictability of individual weather systems is lost and the predictability /uncertainty of climate modes or conditions (averages of weather) becomes the question.

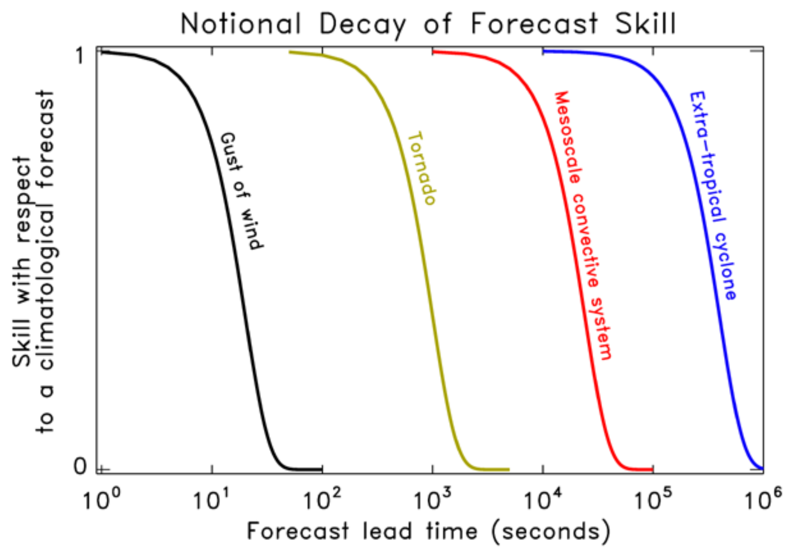


Figure 1. Notional decay of forecast skill (0 is no skill compared to climatology and 1 is perfect skill—agrees perfectly with observations) as a function of lead time in seconds. Theoretically, a perfect forecast can be produced with a perfect model and perfect initial conditions. However, the initial state cannot be known perfectly and even exceedingly small errors will grow rapidly during the forecast, eventually making the forecast no more skillful than a climatological forecast. The time scale when zero skill is reached generally depends on the scale of the phenomenon. This time scale is determined by the phenomenon, not the model. For most of these phenomena, the skill of current forecasts decreases much more rapidly than these curves with a perfect model.

Uncertainties in forecasts can be reduced to some degree through more and better observations, and improved data assimilation and numerical modeling techniques. However,

[10] The term "predictability" refers to the time limit at which a phenomenon can be predicted with skill (i.e., with more specificity than climatology). Predictability is an innate characteristic of the atmosphere, not of forecast models, and typically varies with the spatial scale of motion of the phenomenon of interest (e.g., a thunderstorm, hurricane, winter storm, etc.).

other factors causing uncertainty will never be completely eliminated no matter how much science and technology is applied to the problem. The atmosphere, like other fluid systems, is inherently chaotic. This means that its evolution in time and therefore, the ability to predict it, can be highly sensitive to very small changes (perturbations) in its current or initial state. According to chaos theory (Lorenz 1963), popularly known as the "butterfly effect", nearly perfect routine forecasts can never be achieved because of this sensitivity, which manifests itself in the exponential growth of small errors in model initial conditions and therefore forecast uncertainty.

Fortunately, through the technology of ensemble prediction[11] it is possible to quantify not only the most likely forecast but also the uncertainty of the forecast. With ensemble prediction, multiple, parallel numerical simulations of the weather or climate are generated, typically from slightly different initial conditions that are equally plausible given the uncertainty in the estimate of the initial state. Additionally, the forecast model used to predict future conditions may vary from one member to the next, perhaps incorporating different ways of representing the effects of small-scale phenomena like clouds and thunderstorms. Using ensembles, the initially small differences between forecast members tend to grow due to chaos and model uncertainty. In some situations, such as in the middle of a fair-weather high-pressure area, the differences between ensemble members may grow slowly, so that the estimate of forecast uncertainty is small. In another situation, perhaps near a developing Nor'easter, the initial differences may grow quite rapidly, and the ensemble will provide a useful estimate of the range of possible locations of the rain–snow line, or the amount of snow expected in a major metropolitan area.

Nevertheless, despite a growing theoretical understanding of forecast uncertainty and an increasing ability to quantify it, the "deterministic" paradigm of communicating forecast information is still standard[12] for most hydrometeorological applications. As the name implies, the goal of deterministic[13] forecasting is to determine a single, most accurate value (a single value) for a future hydrometeorlogical element such as tomorrow's high temperature. Although there are notable exceptions such as hurricane track and wind forecasts, and precipitation forecasts, most current operational forecast products and services are based on single-value predictions with little or no accompanying forecast error or uncertainty information. In part, deterministic forecasts likely have been the format of choice because of the public desire for easy-to-understand, nonambiguous predictions. In some cases, communication time and format restrictions have also played a significant role in the choice of presentation formats. For example, broadcasters may only have so many minutes or even seconds to deliver a weather forecast (although this limitation is less important for online presentations) and do not have the time to explain vagaries in the forecast. Moreover, determining what forecast uncertainty

[11] Other techniques have been proposed for quantifying uncertainty. For example, through the statistical relationships between past forecasts and observations, it is possible to provide an "average" estimate of the forecast uncertainty, though this estimate is not specific to the weather of the day. Other techniques like "stochastic-dynamic prediction" have also been proposed and tested with very simple dynamical systems but appear to be conceptually very difficult to apply to high-dimensional systems like the weather, which is simultaneously predicted for many variables at millions of locations.

[12] Although some uncertainty information is communicated informally and in ad-hoc manners (e.g., see Demuth et al. 2009).

[13] It has become common in the Enterprise to use "deterministic" to refer to single-value forecasts. Following that practice, "deterministic" and "single value" are used interchangeably in this plan, even though the single value format is not deterministic in the sense that it can be determined without error.

information users actually need and can benefit from, and how to communicate the information (e.g., forecaster confidence, alternate scenarios, probabilities, etc.) effectively is a challenging task requiring the application of social, behavioral and economic science, outreach, and education. Nevertheless, the consequence of conveying only single-value information is that poorer decisions are made by users because they do not have the benefit of knowing and accounting for the forecast uncertainties and risks upon which their decisions are based (see Box 1).

After reviewing the societal needs and potential benefits of forecast uncertainty information, NRC (2006) and AMS (2008) conclude that there are compelling reasons for the U.S. weather, water, and climate enterprise (Enterprise) to consider uncertainty as an integral and essential component of all hydrometeorological forecasts. These reports recommend that quantifying and communicating forecast uncertainty based on the probability of possible outcomes should be emphasized in addition to the current practice of determining and communicating the single, most probable forecast.

The recommendations from NRC (2006) (see Appendix B), AMS (2008), and WMO (2008), the emerging results from THORPEX[3], and other scientific and socioeconomic studies, as well as the best practices of national and international hydrometeorological services (e.g., see Figure 3) provide the foundation for this Enterprise strategic implementation plan. In particular, NRC (2006) provides guidance on how to identify and characterize needs for uncertainty information, discusses limitations in current methods for estimating and validating forecast uncertainty, identifies sources of misunderstanding, and recommends improvements in the methods of communication.

Although NRC (2006) was commissioned by the National Oceanic and Atmospheric Administration (NOAA) and the advice in the report specifically geared toward that agency, the report recommends that the entire Enterprise should take responsibility for providing products that effectively communicate forecast uncertainty information; and moreover, that product (and service) development should be collaborative with Enterprise partners and users from the outset. Therefore, this plan details implementation strategies that the government, industry, academic and nongovernmental organization communities comprising the Enterprise should undertake in partnership to develop the capacity to generate and communicate comprehensive and reliable hydrometeorological forecast uncertainty information to the nation. While the implementation roadmap suggests sector roles and responsibilities for the various tasks, it is not programmatic in the sense of defining specific program plans with accompanying cost, schedule, and performance information. These important details are beyond the scope of this plan and are the purview of decision makers throughout the Enterprise. However, leadership in organizing and motivating Enterprise resources and expertise will be necessary to shift successfully to a greater emphasis on forecast uncertainty; and the ACUF endorses the recommendation in NRC (2006) for NOAA and in particular, the National Weather Service (NWS) as the nation's public weather service, to take on this role.

The remainder of the plan is structured as follows. Section 2 provides an overview of the *societal use and benefits* of forecast uncertainty information. Section 3 defines a *vision and strategic goals* for the Enterprise to pursue over the next decade in order to transition decision

Box 1

Three major winter storms impacted the U.S. east coast between December, 2009 and February, 2010 producing record snowfalls across the Mid-Atlantic States, including the Baltimore and Washington D.C. metro areas. As is the case with many of these so-called nor'easters (Kocin and Uccellini 2004), very strong (tight) gradients (large change over short distance) between areas that received no snow and areas that received substantial snow existed on the northern and western fringes of these storms. There is typically high uncertainty in predicting the exact location of these gradients and consequently the snow totals within the observed gradient zone. For example, the third of these major snow events (9–10 February) produced 6" of snow in Plymouth, MA, but only 1" of snow 30 miles away in Boston (see Figure 2a). Numerical model outputs from the NCEP (NCEP) during this storm are shown below. Figures 2b and 2c are deterministic model predictions of 24-hour precipitation (liquid equivalent) totals during the height of the storm over New England from the NCEP global model (GFS) and mesoscale model (NAM), respectively. Assuming a 10:1 snow-to-liquid ratio, the GFS forecasted 5–8" of snow in the Boston metro area, while the NAM predicted about 10". Figures 2d and 2e are ensemble model predictions from NCEP's Short Range Ensemble Forecast (SREF) system expressed as the probability of exceeding 0.5" liquid (5.0" of snow assuming a 10:1 snow-to-liquid ratio) and 1.0" liquid (10"of snow), respectively, for the same 24-hour period. For this time period, the SREF predicted that the probability of at least 5" of snow was ~20% and probability of 10" of snow below 10% for the Boston metro area. Nevertheless, a winter storm warning was issued during the afternoon of February 9th, calling for 6" of snow in Boston the next day. Based on this deterministic forecast, a snow emergency was declared preemptively for Boston which, as it turned out, unnecessarily closed hundreds of schools, kept state employees home, and deployed a quarter of the state's snow and ice equipment. After only 1" of snow fell, the mayor of Boston made a tongue-in-cheek comment, "You're right 25 percent of the time, and you make big bucks. It's amazing, it really is."

The SREF probability forecasts in this example show the valuable potential for providing both quantitative predictions of weather scenarios (e.g., chance of greater than X inches of snow) as well as qualitative estimates of uncertainty (e.g., forecasting a strong snow gradient within southeastern New England). In hindsight, the mayor's comments might have been tempered had he known that the exact position of the snow gradient would determine a heavy or light snow event in the Boston metro area, and that a heavy snow event was far from guaranteed.

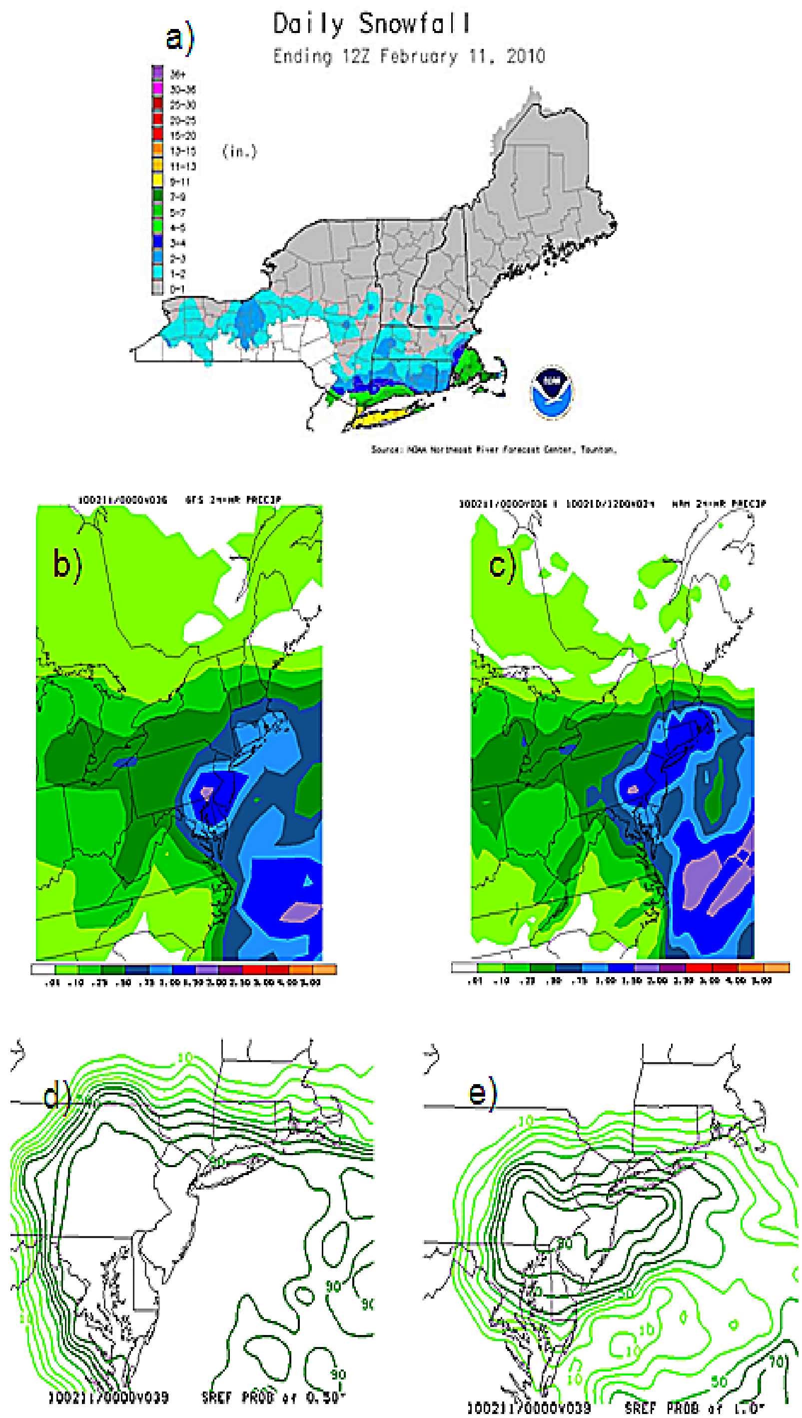
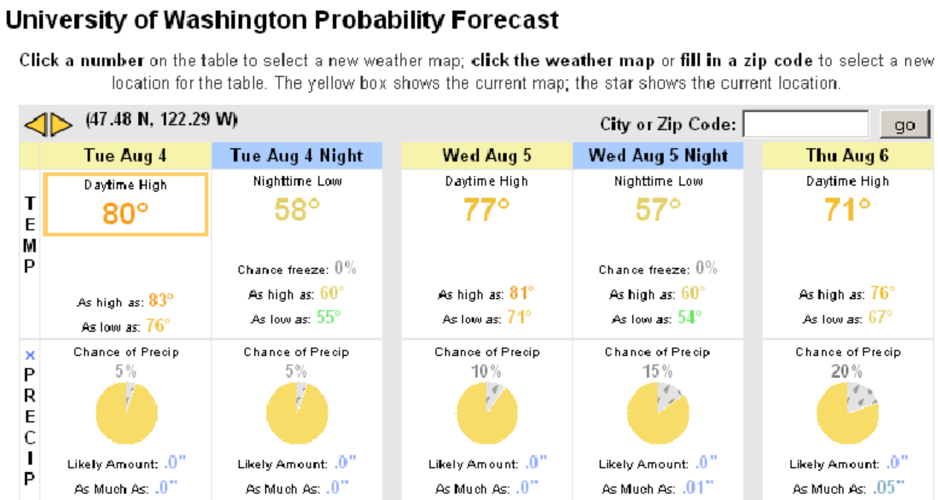


Figure 2. (a) Observed 24-h snowfall for the period 1200 UTC 10 February–1200 UTC 11 February 2010; (b) NCEP Global Forecast System (GFS) 36-h forecast of 24-hour liquid precipitation (in.) valid for 0000 UTC 10 February to 0000 UTC 11 February 2010; (c) North American Mesoscale Model (NAM) 36-h forecast of 24-hour liquid precipitation (in.) (same 24-hour valid time as in a); (d) and (e) Short Range Ensemble Forecast System (SREF) 39-h forecast (same 24-hour period as in a) of the probability of 0.5" and 1.0" of liquid precipitation, respectively. Contours are in 10% increments beginning at 10%.

(a)



(b)

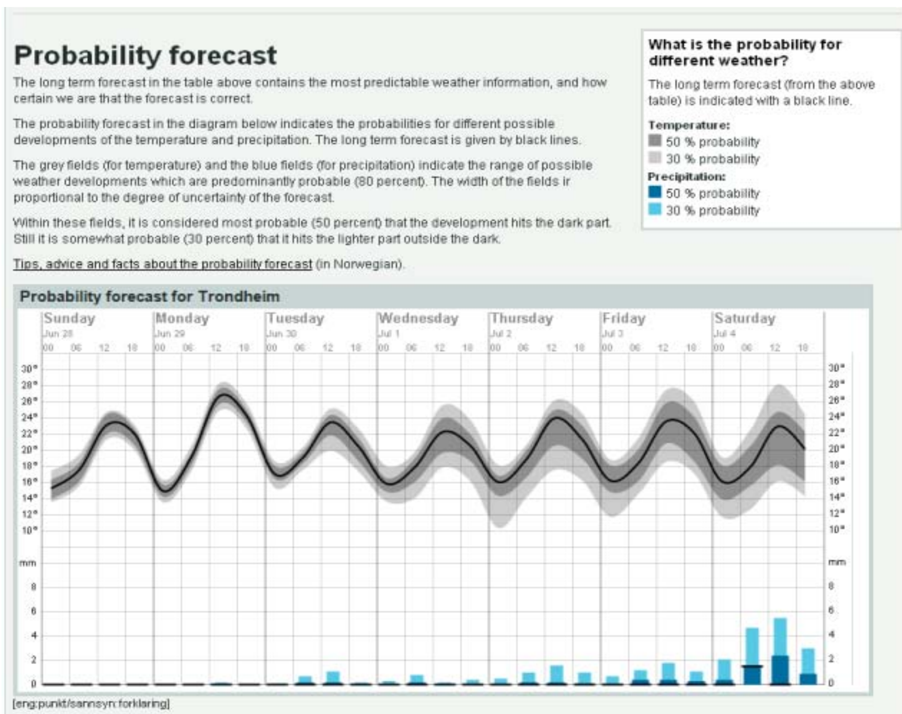


Figure 3. Two examples of efforts to express forecast uncertainty. (a) 60-hour forecast of weather parameters for Seattle, Washington (from the University of Washington, see http://probcast.washington.edu/). The temperature forecast includes a possible but unlikely upper and lower extreme referred to as 'as high as' (10% chance) or 'as low as' (10% chance) in the table. In addition, the predicted most likely precipitation forecast is accompanied by an unlikely but possible upper extreme amount referred to as 'As much as' (10% chance). (b) a weather forecast graphic for Trondheim, Norway (from the Norwegian Meteorological Institute, see http://www.yr.no/) indicating numerical probabilities for different possible temperature and precipitation occurences as a function of time.

makers, the public, and the Enterprise itself to a forecast paradigm that includes the provision and widespread use of uncertainty information. Proposed general *roles and responsibilities* of Enterprise partners are outlined in Section 4. Section 5 provides sets of *objectives* to reach the strategic goals including assessments of current and needed capabilities, performance measures and targets, and an end-to-end *roadmap of tasks* for developing and implementing Enterprise systems that generate and communicate forecast certainty information. A *summary* and considerations about *next steps* are discussed in Section 6.

2. Overview of the Use and Benefits of Forecast Uncertainty Information:

The incorporation of uncertainty information benefits decision making in fields such as medical care and insurance. Doctors and patients factor in known and unknown medical uncertainties to predict outcomes and choose treatment options. Insurance companies use a variety of data, statistical analyses, and risk models to quantify life's uncertainties and set premiums they must charge on policies in order to sustain profitability against assumed risk.

In order to deal quantitatively with future uncertainty, it is necessary to use the mathematical tools of probability theory (see Appendix C). The general concept of probability, and understanding the number scale or percentages between 0 and 100, are embedded in the lives of most people, at least to some extent. All decisions that are based on the occurrence of a future event depend on the degree of belief (i.e., the probability) that the event will or will not happen and the level of risk believed to be associated with the decision (e.g., I believe that stock will go up, but should I risk my entire savings on it?). Using single-value or yes/no deterministic information as the sole basis for decisions may be adequate for essentially riskless decisions (e.g., I think you just have a cold; go home, rest, and drink liquids). However, using single-value information alone may not be sufficient when the potential outcome is really probabilistic in nature and more is on the line (e.g., your illness responds 80% of the time to Treatment A with minimal side effects, and 95% of the time to Treatment B with larger side effects).

Likewise, it is more precise to characterize hydrometeorological forecasts in terms of some expression of probability (see Figure 4). Since weather-, flood-, and other hydrometeorologically-based decisions can be consequential (e.g., Hurricane Katrina in 2005, Red River of the North Floods in 1997 and 2009), one can imagine the benefits if reliable forecast uncertainty information is communicated effectively to sensitized customers who know how to interpret and use the information to improve their decision making and can evaluate actions based on their individual level of risk aversion. Furthermore, unlike deterministic (single-value or yes/no) forecasts, probabilistic forecasts allow flexibility in the information content communicated to users based on their specific needs and preferences. Some users may need or desire quantitative probabilistic information (e.g., "50 percent probability of afternoon temperature exceeding 90° F"), as is commonly used in decision theory and risk-management models (see Appendix D); while others may prefer the information to be conveyed in a less formal, more qualitative fashion (e.g., slight chance of rain). If nothing else, service providers[14] with customers who only want a single-value

[14] While general forecasts that include probabilistic information fall within the responsibilities of the National Weather Service, the recognition of specific user and user-segment needs and the level of customization that meeting these needs may entail falls within the primary responsibility of America's weather, water, and climate industry.

or a yes/no forecast about a potential weather event will be able to make a more informed decision about what that single value or yes/no answer should be.

As detailed in Section 5, socio-economic studies are needed to ..not only quantify the needs and benefits of using hydrometeorological forecast uncertainty information, but also to learn what users need and want, and how to increase these benefits through better communication and use of the information in decision making. However, the existing literature on the socio economic impacts of hydrometeorological forecast uncertainty information documented in NRC (2006), AMS (2008) and other published reports, already provides evidence of the needs and benefits of probabilistic forecast information.

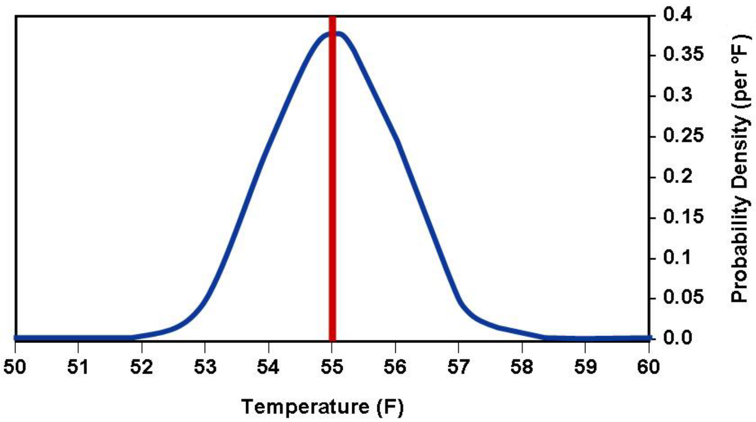


Figure 4. A temperature forecast that conveys probabilistic information. The deterministic forecast (red line) expresses only the most likely single forecast value for the temperature, which is 55°F. The extra probabilistic information is conveyed through the probability density function, or "pdf," (blue curve). This defines the relative likelihood of occurrence of each possible forecast temperature. The pdf is useful in several ways; the relative likelihood of two temperatures, say a temperature of 55°F instead of 53°F can be determined from the ratio of the pdf values at these two temperatures. Also, the probability of an event, say, the probability of a temperature less than 53°F can be evaluated by integrating the pdf from -∞ to 53°F. In these ways, the pdf "completes the forecast," implicitly providing a user with information on any possible temperature, not just an estimate of the most likely one.

A typical year brings 6 hurricanes, 1200 tornadoes, 5000 floods, 10,000 violent thunderstorms, and various other hydrometeorological and related threats (e.g., wild fires, lightning, winter weather, heat, etc.) to the United States causing on average 500 deaths, 5000 injuries, and approximately $14 billion in losses each year.[15] Shifting to probabilistic forecasts and a hazardous weather and water warning capability, which incorporates probabilistic forecasts and thresholds into the warning criteria, a “warn on forecast” (Stensrud, 2009) (or “warn on probability”) capability[16], could increase warning lead times and provide emergency managers, other decision makers and the public other valuable information by which to save lives and property (see Appendix E, Application Examples 1, 2, and 3).

Currently, weather impacts are associated with 70% of all air traffic delays within the National Air Space System (NAS) amounting to a cost of ~$28 billion per year, and about 2/3 of these delays could be avoided with better weather information (Abelman et al. 2009). These delays and costs are projected to escalate over the next 15 years as air traffic demand doubles or triples by 2025. A key goal of the Federal Aviation Administration’s Next Generation Air

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[15] See http://www.economics.noaa.gov/?goal=climate&file=users/government/nws.
[16] Any new warning capability based on probabilities will need to be developed in conjunction with social science research to elicit needs for content, format, and channels of communication.

Transportation System (NextGen)[17] is to reduce these delays by improving weather information and the use of weather information in air traffic management decision making. Documented NextGen requirements (JPDO 2007) for improved weather information already include probabilistic weather forecasts. A study by Keith (2007) showed that one airline alone could potentially save $50 million annually on domestic flights by relying on probabilistic terminal weather forecasts to save fuel and other associated costs. Another study (Steiner et al. 2008) showed how en-route weather probability information can be translated into anticipated air space capacity reductions, and consequently into shorter delay times and substantial cost savings, by enabling aircraft to fly shorter routes around weather hazards (see Appendix E, Application Example 4).

The military needs forecast uncertainty information to identify, assess, and mitigate risk owing to hydrometeorological hazards during military operations. For example, atmospheric and oceanic hazards (such as strong winds and high seas) pose risks for ships at sea, and flood and high-water hazards impact ground-based operations. Forecast probabilities (obtained by using ensemble prediction systems and/or other techniques) of these and other hazards exceeding certain thresholds (with escalating impact on the mission) can be used in so-called Operational Risk Management[18] (ORM) tools. The Navy is developing one such capability employing ORM to translate objective weather uncertainty guidance directly to piracy risk. The U.S. Department of Transportation Maritime Administration estimates that piracy around the Horn of Africa costs the U.S. maritime industry between $1 billion and $16 billion per year[19]. Pirates operate in small vessels and therefore, are particularly vulnerable to adverse wind and seas. The Navy Fleet Numerical Meteorological and Oceanic Center ensemble forecasts are used to identify the probability of various thresholds of surface winds and seas enabling an assessment of piracy risk in the domain around the Horn of Africa. Knowledge of the risk that pirates will assume by operating in a particular region at a particular time can be exploited to protect shipping through various forms of interdiction and avoidance efforts (see Appendix E, Application Example 5).

In the U.S., floods kill more people (approximately 90 per year) and along with droughts cause more economic losses (approximately $10B per year) than any other type of natural disaster[20]. Population growth and economic development will continue to increase the demands on water resources, especially through climate change altering the water cycle, affecting where, when, and how much water is available[21]. Emergency managers, community planners and the general public require better information about the uncertainty in NWS hydrologic forecasts. This is especially true when the forecast horizon is weeks, months, seasons, or years. Contingency planning requires an understanding of both the most likely outcome and the full range of other possibilities. Short-term river flood warnings and longer-term flood and drought outlooks that communicate forecast uncertainty in a clear and consistent manner will help

[17] See http://www.faa.gov/about/initiatives/nextgen/.
[18] See OPNAV Instruction 3500.39B available at: www.usa-federal-forms.com/navy/3-pdf-forms_pubs/.../3500.39B.pdf
[19] Peter Chalk, senior policy analyst, Rand Corporation. Feb 4 2009 testimony to the House Committee on Transportation and Infrastructure, Subcommittee on Coast Guard and Maritime Transportation.
[20] See http://www.economics.noaa.gov/?goal=climate&file=users/government/nws.
[21] See http://www.nature.com/nature/journal/v452/n7185/full/452285a.html.

optimize water availability allocations for growing communities, support productive agriculture/aquaculture, expand industry and river commerce, increase hydropower generation and help to mitigate the impacts of floods and droughts.

The energy sector is one of the most weather and climate–sensitive sectors of the economy, and a main challenge to U.S. life and security is establishing the smart energy grid. The current grid limitations and vulnerability to failure are reported to cost the nation $80 billion to $188 billion per year in losses due to power outages and power quality issues[22]. To improve energy production and management, a probabilistic integrated renewable energy resource of variability and thresholds, such as accumulated precipitation, wind, and solar radiance, could be utilized. The transformation of probabilistic climate forecasts into probabilistic energy demand, production, and operational risk scenarios is a high priority for predicting electricity consumption and peak load.

Probabilistic hydrometeorlogical forecasts could also be used to increase business productivity and competitiveness as well as enhance public well-being, especially with respect to public health. For example, it has been estimated that in the U.S. poor air quality causes as many as 60,000 premature deaths each year, and the cost associated with air-pollution–related illness alone ranges from $100 to $150 billion per year [23] (see Appendix E, Application Example 6). Probabilistic forecasts could provide earlier notice about the risk for poor air quality to individuals and communities and help them limit exposure and reduce asthma attacks, eye, nose, and throat irritation, other respiratory and cardiovascular problems, and therefore save lives. For each 1 percent reduction in adverse health impacts that air quality forecasts could provide, up to 600 lives and over $1 billion could be saved every year. Similarly, probabilistic forecasts and warnings for potential hazardous weather events (such as winter storms when there are more accidents and injuries owing to people falling[24]), could help hospitals and other health care facilities better assess risks and prepare for patient surges and related transportation, staffing, and other issues.

Two last examples that could benefit from probabilistic information are ocean-state and ecosystem forecasts.[25] A forecast of the ocean state would include probabilistic sea surface temperature forecasts, but also as the need arises, probabilistic forecasts of elements such as oil concentration. The spring 2010 Deepwater Horizon oil leak in the Gulf of Mexico provided a general illustration of the difficulties in quantifying uncertainty as well as the potential benefits. Uncertainty estimates for the amount of oil leaking changed dramatically in the weeks and months after the spill. A more precise quantification of the uncertainty of oil flows from the wellhead may have changed the actions of both governmental and industrial officials. During future oil spills, ensemble prediction techniques applied to the ocean would provide a range of estimates of oil concentrations and how they would evolve with time[26]. These oil concentration estimates could

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[22] See www.repoweramerica.org/solutions/roadmap/energy-infrastructure
[23] See http://www.nrc.noaa.gov/plans_docs/2009/AQSOSFactSheetFinal.pdf and http://www.weather.gov/ost/air_quality/Fact%20Sheet%200208.pdf.
[24] The U.S. currently spends $41,636 per fracture or dislocation of the hip. See http://hcupnet.ahrq.gov/.
[25] Here ecosystem forecasts refer to the prediction of the impacts of physical, chemical, biological, and human-induced change on ecosystems and their components, see Committee on Environmental and Natural Resources, 2001. Ecological Forecasting, Washington, D.C., 12 pp.
[26] A rudimentary capability, consisting of several model simulations, was demonstrated at http://ocgweb.marine.usf.edu/~liu/oil_spill_ensemble_forecast.html.

then be used as inputs to models of affected ecosystems (e.g., along the Gulf coast), yielding probabilistic estimates of the range of impacts. This impact information could be used to prioritize and appropriately target cleanup resources and marshal solutions more quickly. For example, perhaps resources would be targeted to the most vulnerable ecosystems at highest risk.

3. Vision and Strategic Goals

In this section, strategic goals are defined to guide the Enterprise toward a future where societal benefits of forecast uncertainty information are fully realized – a vision in which the use of forecast uncertainty information in decision making helps to:

- Protect lives and property;
- Improve national airspace, and marine and surface transportation efficiency;
- Strengthen national defense and homeland security;
- Improve water resources management;
- Sustain ecosystem health;
- Improve energy production, safety, and management;
- Increase business and agricultural productivity and competitiveness;
- Provide a basis for sound, risk-informed planning; and
- Enhance public well-being.

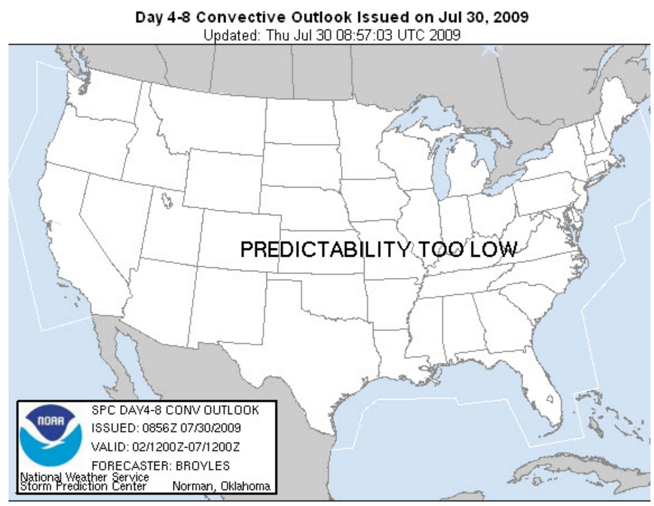

Figure 5. Sample "Day 4-8 Convective Outlook" product from the NWS Storm Prediction Center. The purpose of this product is to indicate the forecast risk of severe storms in terms of probabilities. In this example from 30 July 2009, the outlook product states, "Predictability Too Low." This term can have several meanings and can be unclear even to meteorologists indicating that more research is needed to understand how to best communicate uncertainty information.

Since the early 1990s, continuous computer power growth has permitted the development of increasingly sophisticated ensemble prediction systems for quantifying hydrometeorological forecast uncertainty. As their name implies, "ensemble" prediction systems produce a range of potential forecast outcomes using multiple predictions from the same or different numerical models initialized with slightly varying estimates of the initial state of the atmosphere. Currently, these systems are a large and growing capability at numerical forecast centers and facilities worldwide and are the basis for the day-to-day quantification of forecast uncertainty. More and more forecasters, service providers, and users are finding that improved decisions are possible when ensemble prediction-based forecast uncertainty information is included in their decision process[27].

[27] For example, NWS Storm Prediction Center forecasters have begun using output from the NCEP (NCEP) Short-Range Ensemble Forecast (SREF) system as guidance for their national Fire Weather Outlooks. The use of the SREF enhances the forecast process by quantifying the likelihood that key fire weather parameters will reach or exceed critical thresholds.

However, despite this progress, the Enterprise is not yet fully positioned to help society achieve the promising benefits of employing forecast uncertainty information described in Section 2. A comprehensive, fact-based socioeconomic understanding of what uncertainty information will benefit users' decisions is needed; along with better ways to communicate and assist users in interpreting and applying the information (Figure 5). Substantial scientific and technological challenges remain that need to be solved in order to make ensemble prediction and associated postprocessing techniques robust enough to provide highly reliable and specifically resolved probabilistic information. In particular, the probabilities estimated from current ensemble systems are not always reliable (Figure 6). For example, in situations when an ensemble system estimates a 30 percent probability of greater than 3-cm rainfall, the event may happen only 15 percent of the time. To be truly reliable the event should occur 30 percent of the time with such a prediction system. A broad program of training and education is also needed to enable forecasters and other service providers the ability to interpret, manage, and add value to ensemble prediction system output and to help users understand and apply probabilistic forecasts and other forecast uncertainty information in their decision making. Perhaps most challenging is the cultural shift that must occur within the Enterprise and user community from producing and using only the single "best" deterministic forecast, to embracing forecast uncertainty through probabilistic forecasts.

(a)

(b)

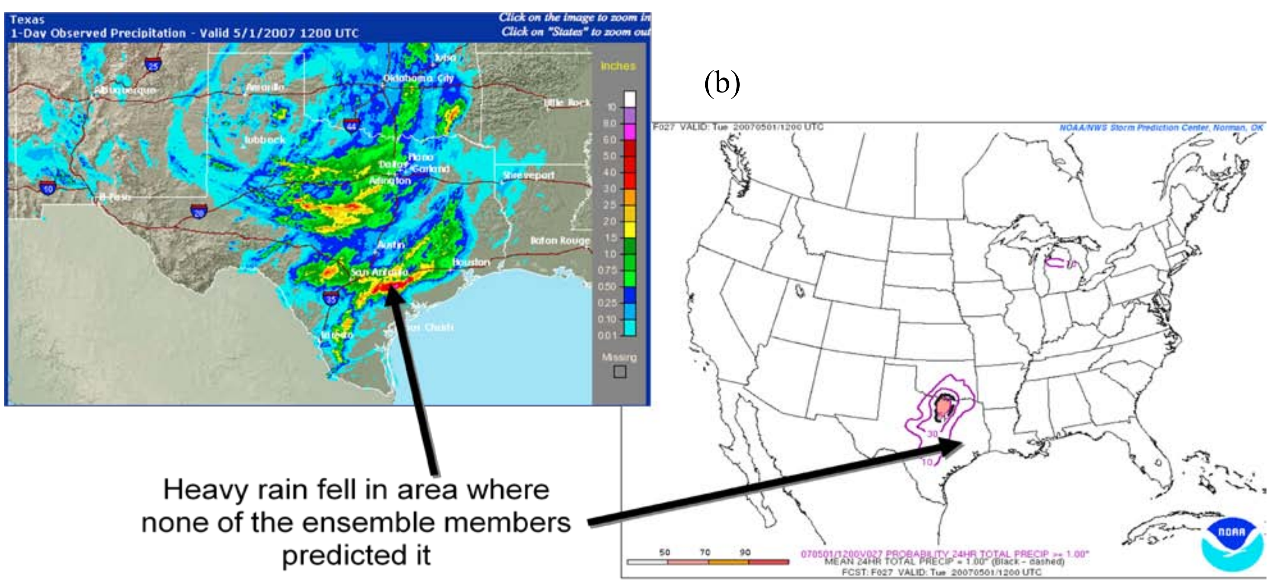

Figure 6. (a) Analyzed (from radar) 1-day precipitation estimates valid 1200 UTC 1 May 2007; and (b) NCEP Short-Range Ensemble Forecast (SREF) system forecast of the probability (contour interval 20% beginning at 10%) of 24-h (1-day) total precipitation greater than or equal to 1" valid 1200 UTC 5 May 2007. Comparison of (a) and (b) shows that the ensemble forecast did not include the possibility of precipitation >= to 1" in locations where over 3" of precipitation actually fell and was therefore unreliable. This example illustrates that current ensemble systems may be biased and/or deficient in spread resulting in misestimated probabilities.

In sum, the Enterprise must build capabilities in four key, interrelated areas in order to meet the scientific and cultural challenges associated with a greater focus on probabilistic forecasting:

1) Understanding customers' needs for uncertainty information, how societal and human factors influence the communication and use of uncertainty information, and the nature of forecast uncertainty and how to quantify it;

2) Communicating uncertainty information effectively and **collaborating** with users to assist them in interpreting and applying the information in their decision making;

3) Generating uncertainty data, products, services, and information needed by users; and

4) Enabling the development, acquisition, and operation of forecast uncertainty processing systems with necessary computational, telecommunications, and other types of infrastructure.

The need to build capability in these four areas naturally leads to the following four strategic goals:

Strategic Goal 1: Understand Forecast Uncertainty

Understand the hydrometeorological forecast uncertainty needs of society, including how humans can most effectively interpret and apply uncertainty information in their decision making; the natural predictability of the coupled atmosphere, oceans, and related earth systems; and the optimal design of ensemble prediction systems.

Much of the Enterprise's customer base is accustomed to receiving and making decisions based on deterministic hydrometeorological forecast information. From a social science perspective, there is much to understand about how various types of users currently perceive, synthesize, and use uncertainty information to make decisions; how uncertainty information combines with other factors to influence decision making; what types of uncertainty information are needed; how needs for uncertainty information vary by hydrometeorlogical event; what formats will most effectively improve their decision making; how the needs for content and format vary by communication channel; and how the Enterprise can best collaborate with and assist them.

Before the pioneering works on atmospheric predictability of Lorenz (1963), Epstein (1969), Thompson (1957), and others became widely appreciated, the task of numerical weather prediction and improving weather (hydrometeorological) forecasts appeared more straightforward. Near-perfect numerical weather predictions at extended lead times were contemplated using models of sufficient complexity and resolution to support accurate deterministic forecasts. Predictability research has helped the Enterprise to understand qualitatively the chaotic nature of the atmosphere, water, and earth system. However, the limitations of hydrometeorological predictability across the range of high-impact events are still not well understood quantitatively. Before, for example, an attempt is made to generate hourly, county-by-county or individual impact tornado outlook products days in advance, there needs to be greater understanding about whether these small-scale features have any predictable signal at all. Another gap in basic understanding is what the most theoretically appropriate techniques for estimating uncertainty are. Ensemble prediction techniques are beginning to be applied to the problem, but understanding how to deal with numerical issues, such as the error introduced by the inaccuracies in the forecast model, is rudimentary.

Success Criteria: The Enterprise will have achieved this goal when product developers and service providers have an understanding of decision makers' needs and priorities for uncertainty information and how to design and communicate products and services that address these needs most effectively; when there is community consensus on theoretical predictability estimates (what phenomena are predictable out to what lead time); and when the academic and research community is actively producing new ideas for enhancing ensemble prediction systems and transitioning these ideas to operational ensemble systems.

Strategic Goal 2: Communicate and Collaborate with Users

Communicate forecast uncertainty information effectively and collaborate with users to assist them in interpreting and applying the information in their decision making.

The ultimate goal of providing forecast uncertainty information is to save lives and property, improve commerce, enable risk-informed planning, and enhance public well-being through better decision making. In principle, better decisions can be made when uncertainty information is available than when it is not. However in practice, uncertainty information may be misused or not used if it is not presented clearly, in useful ways, or if users do not know how to use the new information effectively. Therefore, the Enterprise needs to apply existing and emerging social science to develop understandable, impactful, and useful ways to communicate uncertainty information, and educate user groups and the public about the inherent nature of forecast uncertainty, and how to use uncertainty information to their best advantage.

The Enterprise also needs to listen to its customers, to understand the decisions they are making, and to work with them collaboratively to develop the most effective products and communication methods. Probabilistic forecast products and services will be driven by a wide array of end-users requiring information to be conveyed at different levels of sophistication, using multiple product formats (e.g., graphics, tabular data, text, XML, video/voice, etc.) and channels of communication (e.g., Internet, mobile devices, radio, television, webinars, etc.). Sophisticated user groups may need only digital forecast uncertainty information to interface with their decision-assistance tools, while others may want more assistance (e.g., increased personal one-on-one contact with service providers) to gain a better understanding of the forecast uncertainty, including the confidence level of the forecaster.

Success Criteria: The Enterprise will have achieved this goal when service providers express confidence in their ability to convey uncertainty information to their users and customers; when users and customers express satisfaction with the information they are receiving; and when there is quantitative and qualitative evidence that uncertainty information is resulting in better decisions.

Strategic Goal 3: Generate Forecast Uncertainty Data, Products, Services, and Information

Generate reliable, high-resolution weather, water, and climate probabilistic and other forecast uncertainty products, services, and information that meet users' emerging needs for uncertainty information.

The forecast process is shifting from focusing exclusively on disseminating accurate single-number descriptions of the forecast (deterministic paradigm) to also providing reliable uncertainty information (probabilistic paradigm), primarily through ensemble predictions. Currently, the Enterprise provides a limited set of forecast uncertainty products, including probability of precipitation forecasts (PoP), hurricane-track forecasts (e.g., the "cone of uncertainty"), convective outlooks, and climate forecasts of the probability of categorical (below, normal, above) temperature and precipitation for periods covering 6–10 and 8–14 days, 1 month and 3 months. An integrated, comprehensive, sharp and reliable suite of widely disseminated uncertainty forecast products does not yet exist. To meet current and future customer needs, the Enterprise should generate a full spectrum of hydrometeorological probabilistic information, from nowcasts to forecasts to several weeks lead and beyond. Uncertainty information should be provided in a range of convenient formats. Unprocessed ensemble guidance should be made available to customers and to America's weather and climate industry for tailoring to their particular applications and decisions tools. Derived products and postprocessed forecast information should be made available in many convenient forms, including easy-to-understand iconic and graphical representations as well as numerical representations that can be input to decision-support tools. The uncertainty information should be conveyed in different ways for different users, depending on what is most useful; for some applications users may require access to probability density functions (PDFs), while in some circumstances users may require event probabilities for "on demand" user-defined thresholds.

Success Criterion: The Enterprise will have achieved this goal when a comprehensive suite of forecast uncertainty data, products, services, and information are available, reliable, and as specific as possible, given the available computing and other enabling resources.

Strategic Goal 4: Enable forecast uncertainty research, development, and operations with supporting infrastructure

Provide the necessary supporting infrastructure to enable forecast uncertainty research, system development, testing, implementation, and operations.

Infrastructure improvements, including high-performance computing, telecommunications, processing, visualization, and archiving hardware and software, will be necessary to generate and communicate comprehensive forecast uncertainty information. Running ensemble prediction systems is a computationally intensive endeavor. As a benchmark, the European Centre for Medium Range Weather Forecasts (ECMWF) currently runs the largest and most skillful ensemble prediction system in the world, producing ensemble forecasts that provide approximately 1.5 or so days advance lead time relative to the NWS global ensemble forecast system (Hagedorn et al. 2009). That is, a 3.5-day ECMWF forecast is as skillful as a 2-day NWS forecast. The ECMWF system currently has approximately double the resolution of the NWS system (~30 km versus ~60 km), and they plan to upgrade to approximately ~15 km in 2010[28]. In addition to leveraging ECMWF and other international efforts, a comparable U.S. investment is needed[29] to implement this plan and ensure that skillful and reliable probabilistic forecast data, products, and information supporting current and future Enterprise partner and customer requirements are sustained. This will require a commensurate increase in disk storage, an archive facility to save old forecasts or preferably to store reforecasts for statistical postprocessing and model improvement research, and greatly increased bandwidth in order to communicate the information across the Enterprise and to users. At the critical end of the value chain, service provider and user processing capabilities and software tools are needed to aide interpretation, data mining, visualization, product generation, and applications.

Success Criteria: The Enterprise will have achieved this goal when the Enterprise has on a continuing basis[30] the ability to run state-of-the-art ensemble prediction systems and when the data from these advanced systems are readily available to users and developers.

4. Enterprise Partners' Roles and Responsibilities

Section 5 of this plan lays out a comprehensive roadmap of objectives and tasks for the Enterprise to complete over the next decade to meet the strategic goals and transition the nation to using forecast uncertainty information in decision-making and risk mitigation as described in Section 3. The basis for assigning Enterprise components to lead each task is provided in this section.

The Enterprise consists of four primary sectors: (1) the government sector, which includes local, state, and federal governments, (but is predominately the U.S. Federal government); (2) America's weather and climate industry, which includes two components – consulting/service companies (companies) and media; (3) academia, which includes associated research institutions; and (4) nongovernment organizations (NGOs), which includes organizations like the American Meteorological Society and National Weather Association. In order for this plan to be successful, the Enterprise will need to leverage the expertise and resources of each of these sectors to mainstream quantitative forecast uncertainty information (by using, for example, probabilistic forecasts) into decision making. Increasingly, the missions, strengths, and capabilities among these sectors can overlap, making distinct delineations difficult. Nevertheless, there are leadership roles each of these partner groups needs to fill in order to generate and communicate comprehensive forecast uncertainty information that can be used effectively by all decision makers—from the public, to emergency management, to agencies and

[28] All told, ECMWF dedicates approximately 30 times more computer resources for the computation of their ensemble predictions (including real-time reforecasting and statistical postprocessing) than does the NWS.
[29] A natural question that arises from this statement is: why is a comparable U.S. investment needed (i.e., why not simply purchase the ECMWF forecasts rather than develop a U.S. system)? There are several reasons involving national security, ensuring data access, enabling the U.S. to contribute to advancing the related science and service capabilities, and positioning U.S. leadership in this emerging area.
[30] This goal in particular requires continuous improvements in hardware capabilities, which typically double approximately every two years following Moore's law.

large corporations[31]. The challenge will be to use existing policies and propose new guiding Enterprise policies and organizational principles for developing, generating, providing and communicating forecast uncertainty products and services.

Roles and responsibilities for disseminating uncertainty information will follow current evolving responsibilities, primarily between industry and government. However, the boundary between the academia and industry for delivering information is changing and must be taken into consideration, as academia is increasingly providing services normally considered a commercial role.

Government Sector

The government sector (Government) should support interdisciplinary research efforts integrating social science and hydrometeorology to address issues associated with the provision of uncertainty information. In addition, it should support research to improve the physical understanding of predictability and the development of systems better able to quantify forecast uncertainty. A key role of the Government is to generate and sustain a foundational or baseline suite of forecast uncertainty data, products, services, and information in response to user and partner requirements. The Government should also ensure this foundational suite is available to all, including public decision makers and Enterprise partners, who can use it for their own mission needs and to add value for their specific users and customers. The Government should collaborate with Enterprise partners on new and emerging information needs and on leading edge, high-risk product development and/or resource-intensive products, as appropriate.

The Government should develop, maintain, and execute the nation's baseline probabilistic forecast machinery. The Government should procure the supporting high-performance supercomputing resources necessary to perform the advanced predictability and ensemble development studies, operational ensemble predictions, advanced data assimilation, archival of forecasts and data, and statistical postprocessing necessary to disseminate skillful, reliable uncertainty guidance. The Government should develop the infrastructure to ensure the open sharing of these vast amounts of data. Government forecasters should use uncertainty guidance information for probabilistic forecasts and warnings, and to create information about the distributions of forecast variables, while America's weather and climate industry should use all available information to communicate uncertainty to their clients and incorporate the information in their clients' decision support tools. The information generated by the Government should be shared with the rest of the Enterprise through any number of possible dissemination mechanisms, including Web pages, on-line databases, and so on. The Government should also include a basic set of interpretative material; for example, a Web page containing probabilistic forecast information that also has readily accessible documentation describing the product format and how to interpret it.

The Government should continue providing education, understanding, interpretation, and decision assistance to critical decision makers, such as the emergency management community,

[31] Although this plan does not address the role of the international hydrometeorological community directly, leveraging international expertise and capabilities through Enterprise partnerships will certainly be an important contribution to the success of this plan.

in fulfilling the protection of life and property role of government. The Government should assume a shared role in educating the public about how to use uncertainty information, primarily through Web tutorials and product descriptions.

The Government should be responsible for any advanced training of its forecasters necessary to make them fully capable of interpreting, modifying (adding value to) and communicating uncertainty forecast information[32]. Any training modules developed for government forecasters should also be made available to others in the Enterprise. Web-based training offers an excellent vehicle for providing uncertainty training to the Enterprise.

Finally, the Government should also exploit the use of test beds to transition the latest uncertainty focused research activities into operations and work with the academic community to define the educational skill sets needed because of the evolving focus on uncertainty (e.g., communication skills) and to determine the socioeconomic valuation and assessment of the use of uncertainty in decision making.

Industry Sector

The weather and climate industry sector (Industry) has two components: (1) weather, water, and climate companies that provide products/information for a fee and/or through advertising revenue, and (2) the media. Each of these components has particular roles and responsibilities. Some private companies span both categories.

Weather, Water, and Climate Companies

Weather, water, and climate companies should have a critical role in providing interpretive forecast uncertainty products used by media. These services exist today with many more to be developed and used in the future. Weather, water, and climate companies should also lead in developing specific tools to interpret and understand uncertainty as well as in developing the tools to educate clients and public audiences on the best way to use the information.

Industry should extend and tailor forecast uncertainty information provided by the Government and information originated within the Industry to meet their clients' specific needs. Industry should provide interpretive support educating clients about uncertainty, its socio-economic value, and how to use it to benefit their business. Industry should also emphasize developing uncertainty decision support tools geared to individual clients' needs that leverages uncertainty products produced by the Government and from within the Industry.

Media

Today the media plays a critical role in providing forecast and warning information to the public. This role should expand to providing forecast uncertainty information. The media can

[32] NWS training to date has occurred primarily through the Cooperative Program for Operational Meteorology and Training (COMET), operated by the University Corporation for Atmospheric Research (UCAR). COMET offers both onsite and Web-based training, including a number of uncertainty-related training modules. See http://www.comet.ucar.edu/.

help determine what forecast uncertainty products and services the public wants (via marketing surveys and other methods). It can also help educate the public about how to use uncertainty products and how to incorporate uncertainty into their daily decisions and planning. This can happen not only via television and radio, but also via the Internet, which may turn out to be the best medium to convey uncertainty information. While other components of the Enterprise can be expected to contribute toward education through the Web, it is the media, arguably, that will have the largest audience and most significant impact. The reach of the media cannot be equaled by the Government or any other component of the Enterprise. Even so, for potentially life-saving decisions based on forecasts and warnings, all components of the Enterprise will need to be involved.

Academic Sector

The academic sector (Academia) will continue to provide the basic education in meteorology, hydrology, and climatology necessary to begin and develop a career in the hydrometerological sciences. As the weather, water, and climate community shifts to providing more uncertainty information to users, educational institutions should incorporate uncertainty education into standard curricula. In particular, curricula should be broadened to increasingly expose students to the concepts underlying probabilistic forecasting, including statistics and chaos theory. Hydrometeorological education will also need to provide more interdisciplinary skill sets, especially in the social sciences. There is an expanding recognition that how people respond to information and make decisions has not been fully appreciated by the traditional weather, water, and climate science community. Understanding how to apply the social sciences within the hydrometeorological community is critical to successfully integrating uncertainty information into weather, water, and climate decisions. In particular, the social sciences can bring to bear their knowledge (theories, concepts, and methods such as surveys, focus groups, interviews, observations, etc.) in partnership with hydrometeorologists to understand people's cognitions, attitudes, needs, and desires for uncertainty information; in addition to how their experience, emotion, message valence, and other human aspects would influence their behavior.

Academia will also need to provide leadership in researching and developing new cutting-edge, high-risk forecast uncertainty capabilities, products, services, and information. For example, academia's traditional role in developing new sensors and networks, advancing data assimilation and numerical models, establishing new data sets, creating new products, and so on, will now be extended to address forecast uncertainty more comprehensively, including the incorporation of social science.

Academia should be the primary source for much of the basic research needed to advance understanding and knowledge about the socioeconomic value of forecast uncertainty information, and how to best communicate forecast uncertainty and apply it in decision making. Academia will also need to provide leading-edge research in advanced ensemble and statistical techniques and also supply new talent to Enterprise research facilities and operational forecast and service providers. Ideally, academic faculty and other Enterprise scientists and operational providers will work together more closely in the future, with relevant faculty invited to spend their sabbaticals at laboratories and prediction centers.

Last, but not least, Academia should have a key role in transferring knowledge to operations and/or end-user applications, including developing, testing, and communicating new products and services to the user community. Test beds in a quasioperational environment have demonstrated the usefulness of iterative technique refinement to increase the development of new techniques before they are integrated into operations and/or provided to end users. Academia will also need to help develop educational and training material for end users and the Enterprise and moreover, better education and training methods and techniques. For example, social scientists should be employed to understand the cognitive processes of forecasters as they characterize uncertainty and generate messages with uncertainty information in order to help design effective and efficient ways to train them.

Non-Governmental Organizations Sector

Non-Governmental Organizations (NGOs), such as the American Meteorological Society (AMS), National Weather Association (NWA), American Geophysical Union (AGU), National Center for Atmospheric Research (NCAR), and the National Hydrologic Warning Council (NHWC) should have a critical role in facilitating communication among elements of the Enterprise, addressing common goals, and setting the vision for discovering and meeting the needs of the Enterprise with regard to forecast uncertainty. Annual meetings of these NGOs should provide essential venues to discuss the direction, pace, and implementation of the effort to pursue this vision. NGOs are in a unique position to represent all views within the Enterprise and provide unbiased and diverse leadership and direction to reach a consensus direction and how to implement what has been agreed upon. One of their focus areas will need to be on information exchange and consensus leadership.

NGOs should also have a critical role in education—first to educate their members and second to offer training and education to critical users as well. Critical users and decision makers (as defined in the introduction) are becoming more involved in meetings arranged by the NGOs, with special sessions dedicated to their needs. NGOs, and the AMS in particular, should also play an important role in helping the academic community define the educational requirements and skills needed for the field of meteorology. The AMS should help guide the development of curricula on ensemble modeling and other techniques to quantify uncertainty, how to integrate this information into the forecast process, and how to best communicate forecast uncertainty to users.

5. Implementation Roadmap

This section describes objectives for the Enterprise to complete over the next decade in order to meet the four strategic goals described in Section 3; and ultimately, to achieve the vision of transitioning the nation to using uncertainty information. Although each objective supports a specific strategic goal (see Table 1), it is important to point out that the objectives are also interrelated across goals, acting much like the teeth of a gear system driving the whole engine forward.

Detailed information about each of the objectives is provided in Appendix F where tables for each objective provide background information; the need; current capabilities and gaps; performance measures and targets; proposed solution strategy; and specific tasks that must be accomplished to meet the objective. In this section, shorter descriptions of each objective are provided, along with a summary roadmap of their actionable tasks. These tasks include specific actions to be taken over the next decade. They include short- (0–2 years); medium- (2–6 years), and long-term (> 6 years) tasks. Many of the short-term tasks are ongoing or may be able to be started with existing resources. Suggested Enterprise partner(s) leads[33] are also identified for each task, based on the general roles and responsibilities proposed in Section 4. What is not discussed in any detail is how each task should be performed and how their deliverables or outputs should be implemented. These execution details, which can include spiral development; "build-a-little, field-a-little development"; research-to-operations; and other development and implementation concepts and mechanisms, are very important, but considered beyond the scope of this plan and the purview of responsible project and program managers.

Implementation Roadmap for Strategic Goal 1: Understand Forecast Uncertainty

The implementation roadmap for Strategic Goal 1 is summarized in Table 2, with more supporting detail provided in Appendix F. The purpose of Strategic Goal 1 is to increase the Enterprise's understanding and knowledge about hydrometeorological forecast uncertainty, which is necessary for communicating this information effectively to users (*Strategic Goal 2*), and improving operational probabilistic prediction systems (*Strategic Goal 3*). First, understanding in several areas (*Objective 1.1*) is needed in order to determine and provide uncertainty information that is most beneficial and to effectively communicate and assist users in using the information in their decision making under Strategic Goal 2. These areas include: understanding how various types of users currently perceive, synthesize, and use uncertainty information to make decisions; how uncertainty information combines with other factors to influence decision making; what types of uncertainty information are needed; how needs for uncertainty information vary by hydrometeorological event; what formats will most effectively improve decision making; and how the needs for content and format vary by communication channel. At best, if this need is not met, the forecast uncertainty information the Enterprise provides will continue to go largely unused. At worst, uncertainty information will be misinterpreted or misused, leading to poor decisions and negative outcomes. A few preliminary studies[34] exist on effective ways for communicating probabilistic information. However, there is limited knowledge specific to the effective communication of hydrometeorological forecast uncertainty and risk to various customer and user groups. While communicating uncertainty and risk has been studied in other fields and contexts, it is not apparent how this knowledge applies to communicating hydrometeorological forecast uncertainty.

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[33] Here and in the roadmap tables, "lead" refers to the sector recommended to take leadership in performing the task, not necessarily funding it. Which sector(s) should fund tasks are beyond the scope of this plan and left for appropriate Enterprise decision makers to decide when specific programs and projects are formulated. For example, the plan may recommend academia as a lead of a research task that a government agency program would fund.

[34] See for example, WMO publication http://tinyurl.com/676dyd.

Table 1. Objectives supporting each Strategic Goal

Strategic Goal 1 **Understand forecast uncertainty**	Strategic Goal 2 **Communicate forecast uncertainty information effectively, and collaborate with users to assist them in interpreting and applying the information in their decision making**	Strategic Goal 3 **Generate Forecast Uncertainty Data, Products, Services, and Information**	Strategic Goal 4 **Enable forecast uncertainty research, development, operations, and communications with supporting infrastructure**
Obj. 1.1 Identify societal needs and best methods for communicating forecast uncertainty. Obj. 1.2 Understand and quantify predictability. Obj. 1.3 Develop the theoretical basis for and optimal design of uncertainty prediction systems.	Obj. 2.1 Reach out, inform, educate, and learn from users. Obj. 2.2 Prepare the next generation for using uncertainty forecasts through enhanced K–12 education. Obj. 2.3 Revise undergraduate and graduate education to include uncertainty training. Obj. 2.4 Improve the presentation of government-supplied uncertainty forecast products and services. Obj. 2.5 Tailor data, products, services, and information for private-sector customers. Obj. 2.6 Develop and provide decision support tools and services.	Obj. 3.1 Improve the initialization of ensemble prediction systems. Obj. 3.2 Improve forecasts from operational ensemble prediction systems. Obj. 3.3 Develop probabilistic nowcasting systems. Obj. 3.4 Improve statistical postprocessing techniques. Obj. 3.5 Develop non-statistical postprocessing techniques. Obj. 3.6 Develop probabilistic forecast preparation and management systems. Obj. 3.7 Train forecasters. Obj. 3.8 Develop probabilistic verification systems. Obj. 3.9 Include digital probabilistic forecasts in the Weather Information Database.	Obj 4.1 Acquire necessary high performance computing. Obj 4.2 Establish a comprehensive archive. Obj 4.3 Ensure easy data access. Obj 4.4 Establish forecast uncertainty test bed(s). Obj 4.5 Work with users to define their infrastructure needs.

Second, in order to improve operational probabilistic prediction systems (which produce the uncertainty information) an increased understanding of the nature of atmospheric predictability is needed (*Objective 1.2*) to set reasonable forecast accuracy and reliability goals and to help prioritize the development of forecast uncertainty products and services. A more complete understanding of predictability will also provide insights about forecast model errors and help assess and improve data assimilation and other techniques to quantify forecast uncertainty. Although some rough quantification exists[35] (predictability usually increases with the scale of

[35] See for example, http://tinyurl.com/dfegwl

motion) knowledge about the predictability of specific phenomena is lacking. For example, is a 3-day tornado outlook at the county scale more or less predictable than a 10-day hurricane track and intensity forecast? Current understanding does not allow quantification of the relative gap between the ability to forecast a phenomenon and the phenomenon's intrinsic predictability. Quantifying how this gap changes for various phenomena may help determine which aspects of forecast models are in greatest need of improvement.

Third, a fuller understanding of the sources of forecast uncertainty as well as efficient numerical methods for estimating uncertainty in prediction systems *(Objective 1.3)* are also needed. The two primary effects that contribute to uncertainty in a forecast are uncertainty in the model initial conditions and forecast model error (i.e., model uncertainty). Progress in understanding and estimating the former source of uncertainty is relatively more mature than the latter. Ensemble Kalman filtering and other optimal estimation techniques are being developed to improve estimates of initial condition uncertainty and the initialization of ensembles. Ongoing challenges include how to improve analysis uncertainty estimates, especially for nonnormally distributed variables such as cloud liquid water. In comparison, efforts to better understand and develop techniques to quantify model uncertainty are only in their relative infancy. While some model errors can be reduced through the regular model development process (i.e., improving model dynamics and traditional parameterizations, increasing resolution, etc.), there will always be errors associated with hydrometeorological processes occurring below the resolution (the "grid scale") of the model. For example, the common assumption in meteorological models has been that the effects of subgrid scale processes could be "parameterized." That is, given the grid-scale conditions, the average effects of subgrid scale motions could be estimated deterministically (i.e., for every time grid scale condition X occurs, the feedback from subgrid scale effects is exactly Y). As the grid resolution is refined, this deterministic assumption is increasingly invalid; a wider and wider range of subgridscale effects Y are all plausible given the same forcing X (Plant and Craig 2008). If a range of effects Y are plausible but a single Y is consistently used, this may contribute to a lack of spread in ensemble forecasts. The implication for ensemble prediction is the need to better understand the random (stochastic) nature of hydrometeorological processes that are parameterized in models and to reformulate the parameterizations to be stochastic.

Implementation Roadmap for Strategic Goal 2: Communicate forecast uncertainty information effectively and Collaborate with users to assist them in interpreting and applying the information in their decision making

The implementation roadmap for Strategic Goal 2 is summarized in Table 3 and detailed in Appendix F. Simply generating forecast uncertainty information (Strategic Goal 3) is not enough. Users must see the value of the information, collaborate with developers to determine what information is needed and learn how to use the information to help them in their decision making. The following set of objectives support Strategic Goal 2 by applying existing and emerging understanding from the research community under Strategic Goal 1 to: reach out, educate and work with users about uncertainty information and probability; sensitize and educate students (including hydrometeorological students) about the underlying physical theory and social science aspects of uncertainty; improve the general presentation of forecast uncertainty information and tailoring it for users based on social science and user feedback; and provide decision support tools and services to assist users interpret and apply forecast uncertainty

Table 2. Summary of the implementation roadmap for Strategic Goal 1, consisting of objectives, solution strategies, and specific tasks to be performed over the short (0–2 years)-, medium (2–6 years)-, and long- (>6 years) term periods of the next decade. See Appendix F for details. Italicized and capitalized abbreviations in parenthesis refer to sector(s) recommended to take leadership in performing the task, not necessarily funding it (See Footnote 32). *GOV, ACA, COM*, and *NGO* stand for the government, academia, commercial and nongovernmental organization sectors, respectively.

Objective	Solution Strategy	Tasks		
		Short-term (0–2 years)	*Medium-term (2–6 years)*	*Long-term (> 6 years)*
(1.1) Identify societal needs and best methods for communicating forecast uncertainty	Conduct social science research to determine the best methods of conveying hydrometeorological forecast uncertainty guidance to the public.	•Host forums for social scientists to interact with hydrometeorological forecasters and service providers. *(NGO)* •Hold workshop(s) to entrain new social science and interdisciplinary researchers into study of hydrometeorological forecast uncertainty. *(NGO)* •Hold workshop(s) to prioritize social science needs and include in calls for research. (*Gov*) •Begin grants-driven projects to perform social science research on communicating uncertainty. *(ACA)*	•Fund social science proposals to examine most effective ways to communicate forecast uncertainty to different audiences in different contexts. *(GOV)* •Deliver research findings to Enterprise on how users prefer to receive uncertainty information for a spectrum of products (rainfall, severe weather, daily temperatures, etc.). *(ACA)* •Facilitate building public/private consortiums for funding research on communication of forecast uncertainty. *(NGO, ACA)*	•Sustain research based on 2-6 year results. *(GOV, NGO, ACA)*
(1.2) Understand and quantify predictability	Perform research to determine quantitatively the limits of predictability.	•Synthesize and publish results of previous studies to document current understanding of the limits of predictability. *(ACA)* •Sustain current funding of ensemble and predictability research through programs such as THORPEX. *(ACA, GOV)* •Develop funding programs/requests for proposals focusing on quantifying estimates of the limits of predictability. *(GOV)*	•Perform research with higher-resolution models that better quantify estimates of the limits of predictability. Studies should be prioritized based on the largest combined scientific and societal impact, e.g., predictability of the position and intensity of land-falling hurricanes. *(ACA)*	•Sustain predictability studies using improved, higher-resolution models that increasingly incorporate stochastic elements. *(ACA)*
(1.3) Develop the theoretical basis for and optimal design of uncertainty prediction systems	Perform research on the underlying theory and optimal design of probabilistic prediction systems.	•Continue research supported by existing research grants programs. *(ACA)*	•Expand research program on improved numerical techniques for estimating analysis and forecast uncertainty, especially at the mesoscale and for techniques that estimate the uncertainty contributions from model errors *(ACA)* •Work with operational model developers (see Obj. 3.2) to implement proven superior research techniques. *(ACA)*	•Sustain uncertainty prediction system research. *(ACA)*

information in their decision making.

Generations of hydrometeorological users and the general public have grown accustomed to single-value deterministic forecasts. Inaccurate weather forecasts are disparaged and are often satirized. New information and products that include forecast uncertainty could be viewed as a hedge against poor science and forecasts, although some social scientists argue that acknowledging uncertainties and unknowns builds credibility (Morrow 2009). Regardless, outreach, education, and public information campaigns are needed to inform users and the public that forecast uncertainty is an inherent component of hydrometerological prediction, and that comprehending and using uncertainty information will improve their decision making (*Objective 2.1*). Moreover, users will also need to collaborate with the hydrometeorological and social science community on an ongoing basis about what data and products they want and need, and how they should be formatted so they can better use the information.

More exposure to the basic concepts of probability and statistics in K–12 (especially with salient weather examples) will help children grow into the next generation of adults who are more sensitized about uncertainty and the need for probabilistic forecasts, and more liable to use the information in their decision making. Currently, the topic of uncertainty and use of probabilities in weather information only arises if math students happen to be given a probability example that has to do with weather. A more structured, systematic, and reinforcing approach is needed (*Objective 2.2*) to illustrate and embed the concepts of probability and statistics in meteorology and hydrology in our nation's youth.

Undergraduate and graduate students in hydrometeorological science need to have a better basic understanding of chaos theory, the fundamentals of ensemble predication, probabilistic forecasting, and the use of uncertainty guidance for decision making. They also need a broad understanding in the social sciences and effective communication techniques (*Objective 2.3*).

Improving the effectiveness of the day-to-day communication of forecast uncertainty information will involve both improving the presentation (e.g., formats) of government-supplied uncertainty forecast products and services (*Objective 2.4*) and tailoring uncertainty information by the commercial sector for specific customers (*Objective 2.5).* Many, if not most, users of forecast uncertainty information will not encounter it in a purely digital form from such sources as the Weather Information Database (see Objective 3.8), but rather through regularly available products. By leveraging social science research results and user feedback (see Objectives 1.1, 2.1, and 4.4), these products will need to be in formats that do the best possible job of conveying the breadth of uncertainty information iconically, graphically, textually, and/or numerically. Although there are no established Enterprise standards for graphical uncertainty products, there are some ideas for preferable ways of displaying data. NRC (2006) and WMO (2008) provide some ideas about how probabilistic information could be conveyed effectively and are a good starting point for a complex process of designing appealing new Web pages and Web services for uncertainty products.

Finally, decision support tools and services are needed (*Objective 2.6*) to provide a link between forecast uncertainty information and direct user impacts and risk tolerance. Single-value deterministic forecasts severely limit the utility of weather, water, and climate forecast

Table 3. Summary of the implementation roadmap for Strategic Goal 3 consisting of objectives, solution strategies, and specific tasks to be performed over the short (0–2 years)-, medium (2–6 years)-, and long- (>6 years) term periods of the next decade. See Appendix F for details. *Lead* refers to sector(s) recommended to take leadership in performing the task, not necessarily funding it (See Footnote 32). *GOV*, *ACA*, *COM*, and *NGO* stand for the government, academia, commercial and nongovernmental organization sectors, respectively.

Objective	Solution Strategy	Tasks		
		Short-term (0–2 years)	*Medium-term (2–6 years)*	*Long-term (> 6 years)*
(2.1) **Reach out, inform, educate, and learn from users**	Educate users about forecast uncertainty and probabilistic forecast products through information campaigns, broadcast meteorologists, and other educational information and feedback mechanisms (e.g., Web sites); find out what users understand, want and need, and how they want the information formatted; and develop user/developer feedback mechanisms before and during product development.	•Develop cost-effectives ways to gather social science data via collaboration between social scientists and hydrometeorologists about how best to incorporate uncertainty into forecast products. (*GOV, ACA*) •Collaborate with sectors and users to understand what uncertainty data and products they need and how they should be formatted. (*GOV, COM*) •As NWS Web pages are modified to include probabilistic forecast information (see Obj. 3.4), develop training material and user feedback capabilities. *(GOV)* •Develop material to train broadcast meteorologists (e.g., adapt material from Obj. 2.6) to communicate forecast uncertainty *(NGO)* •Begin to incorporate uncertainty elements into broadcasts *(Com)*	•Using data from short-term results, provide test products and evaluate their effectiveness with more surveys, etc. Revise, based on feedback from first round. Repeat until process has converged on effective solutions for conveying uncertainty. (*GOV, ACA*) •Formally train broadcast meteorologists to communicate forecast uncertainty through Certified Broadcast Meteorologist and other programs. *(NGO)* •Develop short courses and presentations on using and conveying probabilistic information tailored to broadcast meteorologists. *(NGO)* •Expand short course for other end-users, such as emergency managers. *(NGO; GOV)* •Provide continuing education of certified consulting meteorologists in the context of energy usage, weather-related travel safety, infrastructure, and damage mitigation. *(NGO)*	•Build upon and sustain business practices that include user feedback, social science, and impact-based decision support. *(NGO)*
(2.2) **Prepare the next generation for using uncertainty forecasts through enhanced K–12 education**	Prepare supplementary material on probability and statistics related to weather that can be incorporated into K–12 curricula so future students are better prepared to use and interpret probabilistic forecast information.	•Charter committee to develop sample problems that illustrate the concepts of probability and statistics in hydrometeorological forecasting. *(NGO)* •Develop an on-line repository. *(NGO)*	• Work with other statistical organizations (e.g., American Statistical Assoc.) and school textbook manufacturers to incorporate uncertainty information. Encourage use of examples contained in repository. *(NGO)* • Contact state Ed Depts. and school boards on desired changes in forecast uncertainty products/services. *(NGO)*	• Develop mechanisms to maintain contact with institutions involved in K-12 education and update these institutions on new developments in hydro-meteorological uncertainty, appropriate to K–12 education. *(NGO; ACA)* • Obtain education-related (course-content) funding from NSF or related agencies. *(NGO)*

Objective	Solution Strategy	Tasks		
		Short-term (0–2 years)	*Medium-term (2–6 years)*	*Long-term (> 6 years)*
(2.3) Revise undergraduate and graduate education to include uncertainty training	Change hydrometeorological science courses to include material necessary to understand forecast uncertainty. Stress cross-disciplinary studies in the social sciences on use of forecast uncertainty.	•Build Web site for educators to share uncertainty training resources. This platform will serve as a bridge until textbooks can be updated to cover this material. *(ACA)* •Post materials and lectures [e.g., at The COMET Program (http://www.comet.ucar.edu)]. *(NGO, ACA)* •Develop student weather forecasting contests that apply probabilistic forecasting. *(ACA)* •Develop recommendations for curriculum changes, (e.g., students to take basic probability and statistics courses, statistical meteorology, and modify synoptic/dynamic courses to discuss chaos theory, and ensemble prediction methods). *(NGO)* •Encourage (create) opportunities for internships, field experiences, practicum research projects, etc., which emphasize generating and communicating forecast uncertainty. *(ACA)*	• Assimilate recommended uncertainty material into courses currently offered. *(ACA)*	• Develop mechanisms to maintain contact with institutions involved in post-secondary education, and update these institutions on new developments in hydrometeorological forecast uncertainty at a level appropriate to undergraduate and graduate education. *(ACA)*
(2.4) Improve the presentation of government-supplied forecast uncertainty products and services	Re-engineer government Web products to include uncertainty information with a standard look-and-feel based on best practices determined in collaboration with social scientists.	• Conduct social science studies (see also Obj. 1.1) focused on the NWS "point-and-click" public weather Web pages to determine how best to convey additional uncertainty information. *(GOV)* • In consultation with social scientists, develop some prototypes of possible presentation formats for uncertainty information on government Web pages *(GOV)*	• Test prototypes of uncertainty Web pages (see Obj. 4.4) and determine most readily accepted format. *(GOV)* • Modify the NWS Web pages to display uncertainty information in this most readily accepted format. Note: revised Web pages should also allow sophisticated users to obtain more quantitative information, such as numerical tables of probabilities that could readily be entered into decision-making software; Web pages should also include training material (see Obj. 3.9). *(GOV)*	• Continue to incorporate social science into standard research and development of uncertainty products and services. *(GOV)*

<table>
<tr><th rowspan="2">Objective</th><th rowspan="2">Solution Strategy</th><th colspan="3">Tasks</th></tr>
<tr><th>Short-term (0–2 years)</th><th>Medium-term (2–6 years)</th><th>Long-term (> 6 years)</th></tr>
<tr><td>(2.5)
Tailor data, products, services, and information for industry customers</td><td>Promote continuous and close collaboration between the Enterprise and its customers. In the broadcast arena development of best practices to communicate uncertainty will be combined with soft education materials to enable the broadcast meteorologist to successfully deliver uncertainty information to the public. In the business arena flexible yet stable products are needed for integration into business processes. Business meteorologists will be provided with materials to educate and train their customers on the interpretation and use of uncertainty information.</td><td>•Develop visualization techniques (i.e., time series) to communicate uncertainty that best fits the customer. (COM)
•Educate and train targeted customers who receive products about the meaning, use, and potential profitability of probability information. (COM)</td><td>• Publish best practices for the presentation of uncertainty. (NGO)
• Promote industry-wide acceptance of standard means of presentation of uncertainty information (analogous to how sports or financial statistics are now presented fairly uniformly across all major news outlets). (COM, NGO)
• Develop a framework for long-term collaboration between the NWS and the Enterprise on the introduction of new or improved NWS information such as modeling system changes or other products. (COM, GOV)</td><td>• Continue refinement of broadcast presentation approaches for uncertainty information. (COM, GOV)
• Develop personalized weather “apps” that fuse probabilistic forecast information with individual preferences and risk tolerances. (COM)
• Routinely integrate probabilistic weather information into business processes. (COM)</td></tr>
<tr><td>(2.6)
Develop and provide decision support tools and services</td><td>Develop forecaster tools that help forecasters provide critical users with optimally effective decision support.</td><td>•Identify how hydrometeorological information is used to make decisions. (GOV, ACA,NGO, COM)
•Determine which users/decisions can potentially benefit the most from probabilistic forecast information. (GOV, COM)
•Work with customers to develop decision-support tools for forecasters and their most critical customers, including impact-based, graphical information (see also Obj. 3.4). (GOV, COM, ACA)</td><td>•Work with critical customers to evaluate decision support tools (see Obj. 4.4). (GOV, COM)
•Implement decision support tools operationally for most critical customers. (GOV, COM)
•Work with secondary customers to develop decision-support tools and evaluate (see Obj. 4.4) (GOV, COM).
•Continue to survey for important new customers and determine whether new decision support tools should be created. (GOV, COM)</td><td>•Implement decision support tools operationally for secondary customers. (COM, GOV)
•Continue to survey for important new customers and determine whether new decision support tools should be created. (GOV, COM)
•Develop intelligent information services to anticipate user needs/thresholds and to provide them with just the right information independent of the customer realizing the need. (GOV, COM)</td></tr>
</table>

information because they don't allow users to apply probabilities to their own thresholds (i.e., risk assessment) when making decisions. In contrast, the multiple possible forecast outcomes produced by ensembles can support decisions of various levels of sophistication depending on a user's cost/loss considerations. Automated decision support systems can ingest probabilistic forecasts into pre-set user threshold/risk tolerance algorithms that generate a recommended decision based on optimizing the cost/benefit. To be successful, the Enterprise will need to collaborate with users to understand their decision framework. In the end, many decisions are deterministic—go or no go, do it or don't do it. But, in some cases, the timing, venue, methodology, etc. may be changeable, perhaps depending on various hydrometeorological outcomes. All of these decisions could be helped if the uncertainty/probability/whatever we call "not knowing for sure" information would be presented in a way the decision maker can understand and use to her or his best advantage.

Implementation Roadmap for Strategic Goal 3: Generate Forecast Uncertainty Data, Products, Services, and Information

The implementation roadmap for Strategic Goal 3 is summarized in Table 5 and detailed in Appendix F. Currently, the NWS (and other parallel organizations such as the Navy and Air Force) operationally generate mostly deterministic hydrometeorological forecast data and information by employing the following so-called "forecast process:" **collect** observations; **apply** data assimilation techniques to synthesize the observations together with prior forecasts to produce initial conditions for numerical prediction models; **run** the models to produce numerical prediction forecasts; **post-process** the raw model output statistically and otherwise to reduce errors; and **produce** objective and human forecaster–modified guidance, forecast, and warning data and information, which, for the most part, are all made available[36] to Enterprise partners. The Enterprise partners, including the NWS and similar government operational organizations, in turn use these data and information as a *foundation* for generating products, services, and other value-added information that they communicate to their customers and users.

A key to meeting Strategic Goal 3 is to enhance and establish a similar capability to generate and make available routinely to Enterprise partners a "foundational" set of *forecast uncertainty data and information* for a range of variables and forecast leads, which the Enterprise partners can use to meet their mission and customer needs. For the most part, the routine generation of this foundational set of forecast uncertainty data and information should remain primarily the responsibility of the government sector, owing to the resources and infrastructure required to support this activity. However, all Enterprise partners will be communicating this information to their users and customers either in its raw form or through value-added products, services, and information.

It will be necessary to continue to collaborate and work with users, social scientists, and partners using ongoing Strategic Goal 1 and 2 outcomes to define what this foundational forecast uncertainty data set should be and how it will evolve. This data set will include observation and analysis uncertainty information, raw and postprocessed ensemble model output, and human value-added information for forecast leads out to several weeks (see Table 4 for examples).

[36] NOAA makes all of its data, products, and information freely available. Other agencies may have certain restrictions on availability owing to their particular mission and the sensitivity of the information.

Table 4. A sample of the types of forecast uncertainty information that should be generated operationally and made freely available as part of a foundational set.

(1) Continuous variables
- Temperature and dew point
  - o Hourly, daytime maximum, nighttime minimum temperatures mean and range of uncertainty (e.g., 10/50/90th percentile of forecast distribution)
  - o Extreme temperature probability of exceedance
  - o User-specific probability of exceedance (e.g., sub-freezing thresholds for crop growers, materials applications thresholds for concrete pourers)
- Wind speed
  - o Exceedance values for pre-defined thresholds (e.g., gale, hurricane force, etc.)
  - o User-specific probability of exceedance (e.g., wind-energy industry)
- River level and flow
  - o Exceedance values for pre-defined thresholds (e.g., minor, moderate, major flood stage, etc.)
  - o Volume of water into reservoirs for optimal water management

(2) Quasi continuous variables
- Wind direction and wind gusts PDFs (critical for aviation, wind energy industry, temperature forecasts)
- Sky cover and cloud optical depth PDFs (critical for solar energy industry, aviation/transportation sector)
- Ceiling height PDFs (critical for aviation)
- Visibility PDFs (critical for aviation)
- Precipitation (PQPF, timing, precipitation type)
  - o PQPF probability of exceedance values such as 0.1", 0.25", 0.5", 1", 2", etc. including flooding exceedance values
  - o Probability of precipitation shortfalls (e.g., drought and water availability)
  - o Precipitation timing (onset/cessation) including timing of any changeover in precipitation type (e.g., 60% chance of snow will arrive in Boulder between 4-6 PM, 20% chance between 2-4 PM, 20% chance between 6-8 PM)

(3) Discrete weather elements
- Severe weather
  - o Probability of tornado occurrence within 25 miles of a point
  - o Probability of extreme tornado
  - o Probability of any severe weather (tornado, winds, hail)
- Tropical cyclones (current products at www.nhc.noaa.gov)
  - o Probabilistic intensity values (e.g., 50% chance of category 1 at landfall)
  - o Probabilistic storm surge values with inundation mapping of each probability
  - o Probabilistic storm track (e.g., probabilistic information within "cone of uncertainty")
- Flooding (current products at www.hpc.ncep.noaa.gov/nationalfloodoutlook/index.html)
  - o Probability of exceeding stream flow heights (focusing on location-specific levee heights, inundation mapping)
  - o Probability of time until exceeding river heights, duration above threshold

(4) Earth- and Near-terrestrial system elements
- Avalanche probability for a given area
- Mudslides/debris flows probability for a given area
- Tsunamis
- Space weather (e.g., solar storms)

(5) Multi variable probabilities
- Heat Index (e.g., combining temperature and dew point)
- Wind chill (e.g., combining temperature and wind speed)
- Fire weather (e.g., combining temperature, dew point, wind speeds, POP)

(6) Multiple weather and water, climate scenarios
- Aviation applications (individual gridded scenarios from an ensemble input into flight-routing software).
- Hydrologic forecast chains on weather and climate time scales (individual time series of possible rainfall/temperature and other hydrologic forcing scenarios fed into ensemble of hydrologic forecast models to produce ensemble of stream flow estimates)
- Probabilistic drought outlooks

Uncertainty information will be stored in manners that are both compact and informative; this may include the data to estimate the full probability density functions (PDF), central credible intervals (e.g., 10^{th}, 50^{th}, 90^{th} percentiles of the distribution), and event probability thresholds (e.g., probability of rain greater than 1 cm) as appropriate.

Generating and making available this foundational set of forecast uncertainty data and information will require changes and improvements in the forecast process. The needed changes and improvements are described in the objectives described in Table 5. These objectives will leverage the new understanding and knowledge about forecast uncertainty gained under Strategic Goal 1, and user and customer feedback that is part of Strategic Goal 2. Enhancements to IT and other infrastructure improvements will also be necessary to achieve these objectives; such supporting improvements are covered under Strategic Goal 4.

Objectives 3.1 – 3.9 focus on improving the steps by which forecasts are produced and uncertainty data and information are generated and made available to Enterprise partners. Note that while the observations that are used to initialize the forecast process are also uncertain, *no observation uncertainty objective is included here* since it is judged that observation uncertainty is already handled adequately by instrument designers and data assimilation scientists.

New and improved data assimilation techniques are needed (*Objective 3.1*) that can produce an ensemble of initial conditions that are accurate, sample the range of possible true analyses, and project upon growing forecast structures so that differences between member forecasts grow (appropriately) quickly. Existing techniques are typically designed to produce sets of initial conditions that primarily grow quickly, but in doing so do not accurately reflect flow-dependent analysis uncertainty. As forecast spatial and temporal resolution increases, these techniques must be able to estimate uncertainty at the mesoscale as well as the synoptic and planetary scales.

Improved ensemble prediction methods (*Objective 3.2*) are needed that can propagate the initial conditions forward in time and provide reasonably sharp and reliable probabilistic forecasts, correctly accounting for the uncertainty due to model error. Current-generation ensemble prediction systems produce uncertainty forecasts that are biased and underestimate the forecast uncertainty (i.e., underdispersion of the ensemble members collectively). This is partly because of the low resolution of the forecast models, partly because of improper initial conditions, and partly because the ensemble prediction systems do not include effective treatments for the error introduced by model deficiencies.

Often, the accuracy of the first few forecast hours of NWP model guidance, including ensemble guidance, is poor because the NWP models need several model hours to “spin up” (i.e., develop internally consistent vertical motions). Because of this, new probabilistic nowcasting techniques (*Objective 3.3*) are needed to generate reliable probabilistic forecast information for forecast lead times of zero to several hours. Most current nowcasting techniques are deterministically based and have their roots in extrapolation techniques used on existing features, which may not properly account for stochastic aspects, especially new feature development or dissipation of existing features.

The need for statistical postprocessing (*Objective 3.4*) of raw ensemble model output to ameliorate bias and other deficiencies will likely never be completely eliminated despite improvements in ensemble prediction methods (*Objectives 3.1 and 3.2*). Additionally, statistical postprocessing can also "downscale" relatively coarse-resolution model output to finer detail and also be used to derive quantities not directly predicted by the model that may be required by users. Most current statistical post processing techniques [e.g., NWS' Model Output Statistics (MOS)], are based on deterministic model output. A variety of new ensemble model–based calibration techniques appear to perform relatively competitively for normally occurring weather and relatively short forecast leads. However, for rare events and long-lead forecasts, longer training data sets of "reforecasts" and new statistical techniques may be needed; for example, in order to correct biases in the position of a hurricane in the Gulf of Mexico, observed and forecast tracks from many similar storms in the Gulf of Mexico will be needed. With limited computational resources, the requirement to generate these computationally expensive reforecast training data sets with a stable modeling system often conflicts with the desire to rapidly implement improvements in operational ensemble forecast systems.

Nonstatistical postprocessing techniques (*Objective 3.5*) are also needed to produce reliable and skillful forecast uncertainty information about forecast variables of interest that are not directly predicted by numerical models or derived from statistical relationships (using statistical postprocessing techniques discussed under Objective 3.4). Considering aviation as an example, a variety of groups (e.g., National Center for Atmospheric Research's Research Applications Laboratory, Massachusetts Institute of Technology's Lincoln Laboratory) have developed algorithms for estimating aviation-related parameters such as turbulence and icing from the weather model output. Many of these algorithms have been implemented for deterministic forecasts in the NWS at the Aviation Weather Center in Kansas City. However, little has been done to develop, test, and verify algorithms that produce skillful and reliable probabilistic forecasts of such nonobserved variables.

The specific role of human forecasters in the day-to-day generation of probabilistic forecasts will depend on their ability to add value to raw and/or postprocessed ensemble model output. In general, the role of human forecasters likely will expand from the current routine preparation of single-value (deterministic) forecasts to monitoring, quality controlling, and interpreting probabilistic forecast guidance; identifying and assigning confidence to alternate forecast scenarios; and when appropriate (e.g., during high-impact events) manually modifying automated model guidance. While most current forecast preparation systems and tools aiding human forecasters are focused on generating single-value forecasts, these new functions will require probabilistic forecast preparation systems (*Objective 3.6*) and tools that allow humans to interpret and manipulate entire ensemble distributions.

Regardless of the specific role that human forecasters eventually assume in the operational generation of forecast uncertainty information, they will need training (*Objective 3.7*). While some basic training on the theoretical basis for ensemble prediction systems has been developed[37], more is needed to provide knowledge of the general underlying theory behind and

[37] For example, at UCAR's Cooperative Program for Meteorological Education and Training (COMET) [http://www.comet/ucar/edu], the Meteorological Service of Canada (MSC) [http://tinyurl.com/56j5pz] and the European Center for Medium-Range Forecasting (ECMWF) [http://tinyurl.com/57q9o7].

of the performance of ensemble prediction and other probabilistic systems, the weaknesses in current operational systems, and what can and cannot be corrected with statistical postprocessing. Forecasters will also need to be trained in the new uncertainty forecast preparation tools they will use in addition to how to collaborate with users and assist them in interpreting and using uncertainty information in their decision processes (*Strategic Goal 2*).

The Enterprise also needs a comprehensive, agreed-upon set of standards and software algorithms for uncertainty verification (*Objective 3.8*). Currently, forecast verification methods focus on verifying the best single-value forecast estimate. Probabilistic forecast verification techniques must be developed and/or applied that will assess the characteristics of uncertainty forecasts and provide quantitative feedback to ensemble developers, forecasters, service providers, and end users to aid in interpretation and decision-making. Statistics generated from these techniques are needed to serve as a reference for user expectations, guide future improvements, and assess the value added during each step of the forecast process.

The final objective under Strategic Goal 3 (*Objective 3.9*) is to make all of this forecast uncertainty data and information available to Enterprise partners, who can then communicate it to their users and customers either in its raw form or through value-added products, services, and information. Currently, hydrometeorological observations and forecast products and information flow in various formats and via numerous push-pull technologies from their originating sources to partners, customers, and users inside and outside of the Enterprise. This direct, from source-to-user information flow, is not expected to diminish necessarily in the future. However, more powerful computational and telecommunications technologies now are enabling repositories of "one stop shopping" of archived and real-time data and information. The NWS for example, is already providing gridded mosaics of sensible surface weather elements in its National Digital Forecast Database (NDFD)[38] This concept is expected to expand to include more parameters and four dimensions (3 space and 1 time dimension). Moreover, the Federal Aviation Administration (FAA), NOAA, and other federal agency partners are envisioning using this weather information data storage approach to support NextGen. This so-called "4-Dimensional Weather Information Database" (WIDB)[39] will contain real-time observation and forecast data. Initial NextGen requirements state that all forecast products have probabilistic attributes. The ultimate vision is for a four-dimensional environmental information database that includes comprehensive hydrometeorological as well as other earth–system observations, predictions, and related information for users to access. Comprehensive forecast uncertainty data and information will need to be included in the planning, deployment, and access of these database systems as they evolve.

Implementation Roadmap Strategic Goal 4: Enable forecast uncertainty research, development, and operations with supporting infrastructure

The implementation roadmap for Strategic Goal 4 is summarized in Table 6 and detailed in Appendix F. The purpose of Strategic Goal 4 is to provide the infrastructure that will be necessary to carry out the objectives under the other three strategic goals. Specifically, many of the objectives under Strategic Goals 1 and 2, such as predictability studies (Objective 1.2), ensemble

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[38] See http://www.nws.noaa.gov/ndfd/
[39] See http://www.faa.gov/about/initiatives/nextgen/

Table 5. Summary of the implementation roadmap for Strategic Goal 3 consisting of objectives, solution strategies, and specific tasks to be performed over the short (0–2 years)-, medium (2–6 years)-, and long- (>6 years) term periods of the next decade. See Appendix F for details. Italicized and capitalized abbreviations in parenthesis refer to sector(s) recommended to take leadership in performing the task, not necessarily funding it (See Footnote 36). *GOV, ACA, COM*, and *NGO* stand for the government, academia, commercial and nongovernmental organization sectors, respectively.

Objective	Solution Strategy	Tasks		
		Short-term (0–2 years)	*Medium-term (2–6 years)*	*Long-term (> 6 years)*
(3.1) Improve the initialization of ensemble prediction systems	Develop ensemble data assimilation techniques, including improved methods for the treatment of model error in ensemble filters.	•Perform quasireal time tests during hurricane season and other high-impact events of an EnKF using a global forecast model. *(GOV)* •Continue R&D on the treatment of model error and sampling error in ensemble filters. *(GOV)* •Evaluate EnKF relative to 4D-Var for its ability to produce reduced-error initial conditions. *(GOV; ACA)* •Explore hybridization methods of variational and EnKF methods. *(GOV; ACA)*	•Transition EnKF into parallel testing/operations at NWP facilities. *(GOV)* • Further develop and implement hybrid 4D-Var / EnKF methods. *(GOV; ACA)* •Develop improved methods for initializing ensembles at the mesoscale, incorporating new, high-resolution data sets such as radar data *(GOV, utilizing ACA from Obj. 1.3)*	•Develop improved methods for initializing ensembles at the mesoscale, with perturbations that grow appropriately quickly and are consistent with analysis error *(GOV, utilizing ACA from Obj. 1.3)*
(3.2) Improve forecasts from operational ensemble prediction systems	Increase ensemble model grid resolution incorporating research results from Obj. 1.3; increase sharing of forecast data between operational facilities; and add a new, limited-area, high-resolution, high-impact event regional ensemble system.	•Exchange global ensemble forecast model output and develop products based on multi-model output *(GOV)* •Develop higher-resolution global ensemble prediction systems. *(GOV)* •Develop higher-resolution, short-range, limited-area ensembles *(GOV, ACA)* •Test promising experimental ensemble forecast system techniques developed in academia (see Obj. 1.2) *(GOV)* •Develop improved hydrologic ensemble forecast system models *(GOV; ACA)* •Develop hourly lagged ensemble forecast techniques for mesoscale models. *(GOV, ACA)*	•Implement three-fold higher-resolution ensemble model systems. (SREF to ~10 km) by 2012. *(GOV)* •Develop relocatable, 4-km high-resolution, explicit convection, limited-area ensemble forecast system for hurricanes, severe and fire weather *(GOV, ACA)* •Continue to test promising experimental ensemble forecast system techniques developed in academia and implement best methods into operations. (see Obj. 1.2) *(GOV)* •Compare performance of mesoscale lagged ensemble forecast systems to more conventional ensemble system designs. *(GOV, ACA)* •Upgrade hydrologic forecast models, to produce reliable streamflow forecasts. *(GOV, ACA)*	•Double ensemble forecast system horizontal resolution approximately every 8 years, consistent with Moore's Law. *(GOV)* •Continue to test promising experimental ensemble forecast system techniques developed in academia, and implement best methods into operations. (see Obj. 1.3) *(GOV)*

Objective	Solution Strategy	Tasks		
		Short-term (0–2 years)	*Medium-term (2–6 years)*	*Long-term (> 6 years)*
(3.3) Develop probabilistic nowcasting systems	Develop non-NWP based probabilistic forecast methods based on observations and extrapolations, as well as techniques that combine observations and NWP guidance.	• Incorporate probabilistic elements into current deterministic nowcast algorithms, including enlarging existing deterministic forecast by making use of known forecast error statistics. (*GOV, ACA*) •Begin to develop new techniques for generating probabilistic nowcasts. (GOV, ACA)	•Perform intercomparisons of nowcast algorithms to determine which are most suitable for applications. (*GOV, ACA*) •Based on the performance and evaluation of these, implement the most appropriate probabilistic nowcast algorithms. *(GOV, ACA, Com)* •Develop tools for blending together observationally based nowcast and NWP-based guidance as forecast lead increases. *(GOV, ACA)*	•Evaluate and implement techniques for blending together nowcast and NWP based guidance. (*GOV)* •Based on improvement of data assimilation and numerical weather prediction systems, decrease emphasis on separate nowcasting tools, and develop more NWP-based approaches. *(GOV, ACA)*
(3.4) Improve statistical postprocessing techniques	Develop supporting observational and reforecast data sets needed for postprocessing, and develop and implement improved statistical postprocessing techniques to improve the objective probabilistic forecast guidance.	•Develop a comprehensive implementation plan for statistical postprocessing, including defining requirements. *(GOV)* •Define which observational / reanalysis data set(s) will be used for testing techniques*. (GOV)* •Develop a robust global reforecast data set, and observations/analyses as needed, and make this readily available to researchers *(GOV)* •Determine the optimum reforecast training sample size, a compromise between postprocessing skill improvements (favors a large sample) and computational cost (favors a limited sample). *(GOV)* •Test, refine, and compare postprocessing algorithms. *(GOV, ACA)*	•Begin the regular generation of reforecast data sets corresponding to current operational models, based on previously determined optimal reforecast configuration*. (GOV)* • Implement most promising postprocessing techniques for common variables. (*GOV, ACA)* •Continue to test, refine, and compare postprocessing algorithms, but now using emerging standard verification techniques (see Obj. 3.8). *(GOV, ACA)* •Develop new postprocessing techniques for more specialized variables. •Compare objectively produced postprocessed forecast products to those modified by human forecasters (see Obj 3.6) using standard verification techniques (see Obj 3.8). *(GOV)* • Begin regularly monitoring the quality of postprocessed vs. raw numerical guidance. *(GOV)*	•Continue the regular generation of reforecast data sets corresponding to current operational models (*GOV*) •Implement most promising postprocessing techniques for more specialized variables. (*GOV*). •Develop specific postprocessing techniques for more specialized products with less standard variables and appropriateness of existing approaches. *(GOV)*

Objective	Solution Strategy	Tasks		
		Short-term (0–2 years)	*Medium-term (2–6 years)*	*Long-term (> 6 years)*
(3.5) Develop nonstatistical postprocessing techniques	Convert current deterministic forecast products that diagnose specialized forecast variables from model output into probablisitic products. Determine best methods for dealing with ensemble system bias with these algorithms, and implement best methods. .	•Test and evaluate the simple method of forming an ensemble of diagnosed values from ensemble model outputs. *(GOV)* •If bias-corrected members are available (see Objective 3.4 above), determine whether the input bias-corrected data produces a more reliable and skillful diagnosed ensemble. *(GOV)*	•Test the suitability of a preliminary suite of non-statistical techniques and implement if appropriate. *(GOV)* •Develop new techniques that produce appropriate sub-gridscale probabilistic forecast information based on the calibrated grid-scale information. *(GOV)*	•Evaluate and implement the most promising techniques. *(GOV, ACA)*
(3.6) Develop probabilistic forecast preparation and management systems	Develop and implement workstation tools that allow forecasters to examine and modify objectively produced ensemble forecast guidance.	•Conduct workshop(s) to determine development priorities and survey forecasters about how they use prob. forecast information. *(GOV; NGO; ACA)* •Complete plan to include ensemble information in AWIPS. *(GOV)* •Develop experimental tools that allow the graphical editing of probabilistic forecasts. *(GOV)*	•Gather forecaster feedback on workstation requirements. *(GOV)* •Implement new gridded ensemble products on the NDFD. *(GOV)* • Evaluate forecaster-modified guidance produced with experimental forecast tools relative to objective guidance (see Obj. 3.4). *(GOV)*	•If warranted, based on forecast evaluation, implement forecast editing tools in AWIPS. *(GOV)* •Refine ensemble display and graphical editing tools as necessary. *(GOV)*
(3.7) Train forecasters	Develop and run a program to train operational forecasters in how to use, interpret, and convey probabilistic forecast information, and how to work with users to help them make effective decisions.	• Identify Enterprise collaborators. *(GOV)* •Identify existing Web-based training on uncertainty NWP. *(GOV)* • Identify best practices in other disciplines using uncertainty. *(GOV; ACA)* •Develop in-person and online training materials. *(GOV)* •Obtain operational reviewer feedback on training. *(GOV; ACA)* •Develop training courses and position description requirements for training and hiring proper support personnel. *(GOV)*	•Run uncertainty training courses for forecasters including Weather Event Simulator (WES) cases. *(GOV)* •Identify good cases for future training material. *(GOV; ACA; NGO)*	•Sustain training developed over the mid-term to remain current and relevant to forecast operations. *(GOV)*

Objective	Solution Strategy	Tasks		
		Short-term (0–2 years)	*Medium-term (2–6 years)*	*Long-term (> 6 years)*
(3.8) **Develop probabilistic verification systems**	Develop forecast uncertainty verification standards and best practices.	•Continue research into new verification methods. *(GOV; ACA)* •Work with social scientists, partners, users to identify meaningful verification products, such as visual comparisons between observations and forecasts. *(GOV; COM; ACA)* •Form a panel of verification experts, and have them begin to formulate a standard reference for the verification of probabilistic forecasts. (*NGO*)	•Develop an "uncertainty verification manual" that specifically indicates how each metric is to be computed. *(NGO, GOV, ACA)* •Build a standardized library of routines based on the uncertainty verification manual, as well as software for the display of verification data. *(NGO, GOV, ACA)* •Make the verification data and software publicly available. *(NGO, GOV, ACA)* •Institute a verification "clearing house" where verification results are made available. *(GOV)* •Develop prototype probabilistic verification packages for particular applications, such as for aviation forecasts. *(GOV)*	•Develop and test new uncertainty verification techniques as specialized new products are developed. *(GOV, ACA)*
(3.9) **Include digital forecast uncertainty information in database and access systems**	Add probabilistic grids to NWS' NDFD, leverage planning and development of NextGen's WIDB, and eventual extension to an environmental information database.	•Develop common data standards and protocols (e.g., term lexicon). (*GOV*). •Add forecast probability grids to NDFD. *(GOV)* •Develop specification and implementation plan for probabilistic information in WIDB, indicating variables, spatial/temporal resolution, etc. (*GOV*) •Develop techniques to synthesize probabilistic forecast information from various sources (different forecast systems, obs., human-modified guidance, etc.). *(GOV)*	•Implement preliminary techniques for synthesizing probabilistic forecast information from various sources. *(GOV)* •Integrate WIDB probabilistic information into Air Traffic Management Systems. *(GOV)*	•Meet all probabilistic NextGen requirements. *(GOV)* • Provide full network connectivity ensuring consistent information use across service areas and user groups. *(GOV)* •Upgrade techniques for synthesizing information from various sources. Upgrade spatial / temporal resolution of WIDB as warranted by user requirements. *(GOV)* •Migrate to Environmental Information Database. (*GOV*)

design (Objective 1.3), operational ensemble initialization and prediction (Objectives 3.1 and 3.2), and statistical postprocessing (Objective 3.4) will require increases in high-performance computing (*Objective 4.1*). Despite advances that may be possible by sharing multimodel ensemble forecast data among U.S. and international centers, the production of skillful and reliable probability products cannot be achieved fully without a large increase in computational resources dedicated to the production of improved uncertainty forecasts[28]. Currently, the Enterprise does not focus as much high-performance computing to ensemble prediction systems as some other international hydrometeorological organizations. For example, in comparison to the NWS' National Centers for Environmental Predication (NCEP), the European Center for Medium Range Weather Forecasts (ECMWF) runs a larger global ensemble (51 members, vs. 21 for NCEP), at approximately three times higher resolution (T399 in week 1 vs. T126), and includes the regular production of real-time reforecasts that can be used for calibration. Although NCEP runs its ensemble system 4 times daily to ECMWF's twice daily, it may take as much as 50 times more computational resources for NCEP to fully match the ECMWF system.

A readily accessible public archive of past operational ensemble forecasts and verification statistics is also needed (*Objective 4.2*) to facilitate research (Objectives 1.2 and 1.3), the calibration (statistical adjustment) of ensemble forecasts (Objective 3.4), the ensemble technique development process, and product development and forecaster training. Currently, the NOAA Operational Model Archive and Distribution System (NOMADS) is an emerging Enterprise-wide resource for storing numerical forecast guidance. NOAA has a cooperative agreement with the Meteorological Service of Canada (MSC) to share ensemble forecast information on NOMADS and is developing similar agreements to share forecasts with the U.S. Navy and Air Force. The THORPEX Interactive Grand Global Ensemble (TIGGE) currently archives a base set of global medium-range ensemble forecast and analysis information from nine different forecast centers worldwide. However, more data storage is required.

Data access systems are needed (*Objective 4.3*) that are capable of transferring very large amounts of data from forecast uncertainty providers to clients, and/or that allow these data to be parsed into subsets, transformed, and reformatted prior to the transfer to the client. A number of current projects are exploring facets of ensemble data access, including NOMADS, Unidata, and the Global Interactive Forecasting System.

A testbed is needed (*Objective 4.4*) where developers, forecasters, and users can interact and test forecast uncertainty products, services, and information prior to implementation. There is currently no facility that permits users (e.g., operational NWS and industry forecasters, emergency managers, other officials responsible for public safety, utility companies and other sectors, general public) to conveniently evaluate and critique experimental products. A testbed avoids the challenges of testing in a live production environment, and provides a forum for feedback among all providers and users before operational implementation

Finally, users will need assistance (*Objective 4.5*) defining the infrastructure they will need to make use of new forecast uncertainty data and information. Universities, industry, and consumers all have made significant and continuing investments in infrastructure. Technological advances keep increasing capabilities without increasing the price. However, current user software systems are mostly oriented toward single deterministic forecasts. Software systems and decision aids that

Table 6. Summary of the implementation roadmap for Strategic Goal 4 consisting of objectives, solution strategies, and specific tasks to be performed over the short (0-2 years)-, medium (2-6 years)-, and long- (>6 years) term periods of the next decade. See Appendix F for details. *Lead* refers to sector(s) recommended to take leadership in performing the task, not necessarily funding it (See Footnote 32). *GOV, ACA, COM*, and *NGO* stand for the government, academia, commercial and nongovernmental organization sectors, respectively.

Objective	Solution Strategy	Tasks		
		Short-term (0–2 years)	*Medium-term (2–6 years)*	*Long-term (> 6 years)*
(4.1) Acquire necessary high performance computing (HPC) capability	Acquire more computer resources.	•Determine CPU cycles necessary to run global, regional, and extreme-event systems envisioned in Objectives 3.1, 3.2, as well as the reforecasts necessary for calibration in Objective 3.4. *(GOV)*	•Procure and install HPC sufficient to carry out Objectives 3.2 and 3.3. *(GOV)*	•Regularly upgrade HPC roughly in accordance with Moore's Law (a doubling of CPU power approximately every 2 years). *(GOV)*
(4.2) Establish a comprehensive archive	Expand NOAA's NOMADS system so it provides ready access to ensemble predictions, postprocessed guidance, analyses, observations, and other forecast uncertainty information.	•Determine hardware and software resources necessary for a comprehensive archive, allowing for anticipated growth; obtain resources and install the system. *(GOV)* •(Ideal) Archive full model output at high temporal resolution. (Practical) Query relevant members of the community (to determine what subset of data must be kept on fast storage. Archive this subset on fast storage, and the rest on slow storage. *(GOV)*	• Upgrade NOMADS system to accommodate higher temporal and spatial resolution output. *(GOV)*	•Expand user interface to archive to allow more analytic services, .e.g., the ability to derive results using archived data. *(GOV)*
(4.3) Ensure easy data access	Continue to evolve data access services to conserve bandwidth based on varying combinations of speed and agility.	•Collect information on data requests to guide future developments of currently existing distribution systems. *(GOV)*	•Implement requirements defined in short-term and continue requirements definition. *(GOV)*	•Keep archive and user interface capability at pace with model and usage growth. *(GOV)* •Build robust, flexible, and extensible system, and include analytic services (i.e., results derived from the archive). *(GOV)*
(4.4) Establish forecast uncertainty testbed(s)	Establish capabilities for model developers, forecasters, and users to interact prior to product implementation.	•Explore possibilities for testbed(s) including expanding existing testbeds, establishing new onsite facilities or virtual capabilities. *(GOV, COM, ACA)*	•Establish testbed(s) and processes for testing/evaluating experimental techniques and products well before implementation; and for easy transition to operations. *(GOV, COM, ACA)*	•Continue to refine/improve testbed approaches. *(GOV, COM, ACA).*

Objective	Solution Strategy	Tasks		
		Short-term (0–2 years)	*Medium-term (2–6 years)*	*Long-term (> 6 years)*
(4.5) **Work with users to define their infrastructure needs**	Inform, educate, and work with users on the amount of information that will be available early so they can design and plan for infrastructure commensurate with their needs.	•Add sessions on this topic at appropriate meeting and conferences. *(NGO)*	•Make plans for ensemble system upgrades readily available through publication and other means. *(GOV)* •Work with users and determine how much uncertainty-related information they need to access daily and to store, and help them determine specifications for their information technology purchases *(NGO, COM, GOV, ACA)*	• Sustain medium-term tasks. *(NGO, COM, GOV, ACA)*

deal with a single value forecast and no probabilistic information will need to be upgraded and optimized in a manner that most easily allows later improvements.

6. Summary and Next Steps

This document defines a weather and climate enterprise strategic implementation plan for generating and communicating forecast uncertainty information. In particular, the Plan defines a vision, strategic goals, roles and responsibilities, and a roadmap to guide the Enterprise toward routinely providing the nation with comprehensive, skillful, and reliable information that describes and quantifies the uncertainty of weather, water, and climate forecasts for better decision making. The Plan is based on, and intended to provide a foundation for, implementing recent recommendations regarding forecast uncertainty by the NRC, AMS, and WMO. It leverages emerging results from THORPEX, other scientific and socioeconomic studies, and the best practices of hydrometeorlogical services and industry from around the world.

As an overview of the use and benefits of forecast uncertainty information, the Plan provides a synopsis of several scenarios illustrating how hydrometeorological forecast uncertainty information can improve decisions and outcomes in various socioeconomic areas, which if extrapolated nationally, sum up to potentially large benefits. Strategic goals are defined to guide the Enterprise toward a future where societal benefits of forecast uncertainty information are fully realized—a vision in which the use of forecast uncertainty information in decision making helps to:

- Protect lives and property;
- Improve national airspace, and marine and surface transportation efficiency;
- Strengthen national defense and homeland security;
- Improve water resources management;
- Sustain ecosystem health;
- Improve energy production, safety, and management;
- Increase business and agricultural productivity and competitiveness; and
- Enhance public well being.

In order to meet the cultural, scientific, and technical challenges associated with a greater focus on probabilistic forecasting, the Enterprise must build capabilities under four key, interrelated strategic goals: (1) Understanding; (2) Communicating and Collaborating; (3) Generating; and (4) Enabling. The Plan lays out a comprehensive roadmap of objectives and tasks that the four sectors comprising the Enterprise (i.e., Government, Industry, Academia, and Nongovernmental Organizations) should work on to achieve in partnership over the next decade to meet these strategic goals and transition the nation to the probabilistic forecasting paradigm. The implementation roadmap objectives are described to support the four strategic goals and the Plan highlights the interplay among the goals.

Likely, the most important next step for this Plan is to identify a lead to implement it. The ACUF believes strong leadership in organizing and motivating Enterprise resources and expertise will be necessary to reach the Plan's vision and goals, and to shift the Enterprise and the nation successfully to a greater emphasis on forecast uncertainty. To this end, the committee endorses the recommendation in NRC (2006) for NOAA and in particular, the NWS as the nation's public weather service, to take on this leadership role. Furthermore, the ACUF recommends that the AMS Commission Steering Committee (CSC) as part of the CWCE monitor progress and provide executive oversight for this Weather and Climate Enterprise Strategic Implementation Plan for Generating and Communicating Forecast Uncertainty Information since the CSC is a body of senior representatives from the entire Enterprise.

Another important next step is to develop an overarching strategy of how the Enterprise will resource and implement the proposed tasks. Examples of such a strategy would be: 1) to attempt to establish a single large program, 2) to use the Plan to guide various independent, but nevertheless, connected projects, or 3) some combination of 1 and 2.

Activities under the second option are occurring already and have informed and are leveraging this Plan. For example, the National Unified Operational Prediction Capability (NUOPC) Program[40] is using the Plan to help build a national R&D agenda that will be used to improve the Tri-Agency (NOAA, Navy, Air Force) unified ensemble system. Another example is the national workshop on mesoscale probabilistic prediction, which was held in September 2009 and sponsored by NCAR and the NWS. Nearly one hundred attendees from government, industry, and academia examined the current state of mesoscale probabilistic prediction in the US and discussed how to expedite progress. The recommendations from this workshop[41] support and extend modeling and enabling infrastructure (such as a developmental testbed) objectives and tasks under Strategic Goals 3 and 4 in this Plan. Moreover, the workshop recommended the formation of working groups, led by a national advisory committee, to perform the needed R&D effort and to use the Plan to help guide their activities.

Finally, while the implementation roadmap suggests sector roles and responsibilities, and sector leadership for the various tasks in the Plan, the Plan itself is not programmatic in the sense of defining specific program/project plans with accompanying cost, schedule, and performance information. These important details are beyond the scope of this Plan and should be also considered among the next steps in implementing the Plan and the purview and responsibility of Enterprise decision makers throughout the partnership.

[40] See http://www.weather.gov/nuopc/
[41] See http://www.weather.gov/ost/S&TRoadmap/

List of Acronyms

ACUF	Ad-Hoc Committee on Uncertainty in Forecasts
AMS	American Meteorological Society
CSC	AMS Commission Steering Committee
CWCE	Commission on the Weather and Climate Enterprise
COMET	Cooperative Program for Operational Meteorology and Training
ECMWF	European Centre for Medium Range Weather Forecasts
EnKF	Ensemble Kalman Filter
HABs	Harmful Algal Blooms
HPC	High Performance Computing
MSC	Meteorological Service of Canada
MOS	Model Output Statistics
NAS	National Air Space System
NCEP	National Centers for Environmental Predication
NCAR	National Center for Atmospheric Research
NDFD	National Digital Forecast Database
NextGen	Next Generation Aviation Traffic Management System
NGO	Non-Government Organization
NOAA	National Oceanic and Atmospheric Administration
NOMADS	NOAA Operational Model Archive and Distribution System
NHWC	National Hydrologic Warning Council
NRC	National Research Council
NUOPC	National Unified Operational Prediction Capability
NWA	National Weather Association
NWS	National Weather Service
NWP	Numerical Weather Prediction
ORM	Operational Risk Management
PDF	Probability Density Function
PoP	Probability of Precipitation
PQPF	Probabilistic Quantitative Precipitation Forecast
THORPEX	The Observing System Research and Predictability Experiment
TIGGE	THORPEX Interactive Grand Global Ensemble
UCAR	University Corporation for Atmospheric Research
WIDB	4-Dimensional Weather Information Database
WMO	World Meteorological Organization

Appendix A
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  Florida International University
- Rebecca Morss
  National Center for Atmospheric Research
- David Myrick
  NOAA/National Weather Service
- Daniel Nietfeld
  NOAA/National Weather Service

- David Novak
  NOAA/National Weather Service
- Paul Nutter
  University of Northern Colorado
- Dan O'Hair
  University of Oklahoma
- Steven Payne
  CNMOC 0TM
- Brenda Philips
  University of Massachusetts
- Carla Roncoli
  The University of Georgia
- Scott Sandgathe
  APL-University of Washington
- Dan Satterfield
  WHNT-TV
- John Schaake
  Retired NOAA/National Weather Service
- Paul Schultz
  NOAA/Office of Oceanic and Atmospheric Research
- Leonard A. Smith
  London School of Economics
- John Sokich
  NOAA/National Weather Service
- Alan E. Stewart
  The University of Georgia
- Dan Stillman
  Institute for Global Environmental Strategies
- Neil Stuart
  NOAA/National Weather Service
- Zolton Toth
  NOAA/National Weather Service
- Steve Tracton
  Retired NOAA/National Weather Service
- Robyn L. Weeks
  The Weather Channel
- Dick Westergard, CCM
  Shade Tree Meteorology, LLC
- Bernadette Woods
  WJZ-TV

Appendix B
Recommendations from the 2006 National Research Council Report:
Completing the Forecast, Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts

Overarching Recommendations

Recommendation 1.0: The entire Enterprise should take responsibility for providing products that effectively communicate forecast uncertainty information. NWS should take a leadership role in this effort.

Recommendation 2.0: The NWS should improve its product development process by collaborating with users and partners in the Enterprise from the outset and engaging and using social and behavioral science expertise.

Recommendation 3.0: All sectors and professional organizations of the Enterprise should cooperate in educational initiatives that will improve communication and use of uncertainty information. In particular, 1) hydrometeorological curricula should include understanding and communication of risk and uncertainty, 2) ongoing training of forecasters should expose them to the latest tools in these areas, and 3) forecast providers should help users, especially members of the public, understand the value of uncertainty information and work with users to help them effectively incorporate this information into their decisions.

Recommendation 4.0: The NWS should develop and maintain the ability to produce objective uncertainty information from the global to the regional scale.

Recommendation 5.0: To ensure widespread use of uncertainty information, NWS should make all raw and postprocessed probabilistic products easily accessible to the Enterprise at full spatial and temporal resolution. Sufficient computer and communications resources should be acquired to ensure effective access by external users and NWS personnel.

Recommendation 6.0: The NWS should expand verification of its uncertainty products and make this information easily available to all users in near real time. A variety of verification measures and approaches (measuring multiple aspects of forecast quality that are relevant for users) should be used to appropriately represent the complexity and dimensionality of the verification problem. Verification statistics should be computed for meaningful subsets of the forecasts (e.g., by season, region) and should be presented in formats that are understandable by forecast users. Archival verification information on probabilistic forecasts, including model-generated and objectively generated forecasts and verifying observations, should be accessible so users can produce their own evaluation of the forecasts.

Recommendation 7.0: To enhance development of new methods in estimation, communication, and use of forecast uncertainty information throughout the Enterprise, and to foster and maintain collaboration, confidence, and goodwill with Enterprise partners, NWS should more effectively use testbeds by involving all sectors of the Enterprise.

Recommendation 8.0: The committee endorses the recommendation by the NRC "Fair Weather" report to establish an independent advisory committee and encourages NOAA to bring its evaluation of the recommendation to a speedy and positive conclusion.

Recommendation 9.0: The NWS should dedicate executive attention to coordinating the estimation and communication of uncertainty information within NWS and with Enterprise partners.

Section 2. Uncertainty in Decision Making Recommendations

Recommendation 2.1: For users who have difficulty with numeric probabilities and prefer a less analytic approach, forecast uncertainty should be expressed using relative frequencies rather than probabilities.

Recommendation 2.2: The Enterprise should signal to users the different sources of uncertainty in their probabilistic forecasts and risk communication products.

Recommendation 2.3: The utility of any forecast uncertainty product should be evaluated within the individual, social, and institutional contexts of the recipient. What to include and not include should in part be a function of the intended user and their ability to handle different sorts of information.

Recommendation 2.4*:* The NWS should acquire social and behavioral science expertise including psychologists trained in human cognition and human factors, with training in behavioral decision theory, statistical decision theory, survey design and sampling, and communication theory, with special focus on graphics and product development.

Section 3. Estimating and Validating Uncertainty Recommendations

Recommendation 3.1: As the Global Climate and Weather Modeling Branch and the Mesoscale Modeling Branch of the Environmental Modeling Center continue to develop their ensemble forecasting systems, they should evaluate the full range of approaches to the generation of initial ensembles and apply the most beneficial approach. The Environmental Modeling Center should focus on exploring the utility of ensemble-based data assimilation approaches (and extensions) to couple ensemble generation and data assimilation at both the global and the mesoscale levels.

Recommendation 3.2: The National Centers for Environmental Prediction (NCEP) should complete a comprehensive evaluation to determine the value of multiple dynamical cores and models, in comparison to other methods, as sources of useful diversity in the ensemble simulations.

Recommendation 3.3: The NCEP should (a) reprioritize or acquire additional computing resources so that the Short-Range Ensemble Forecasting system can be run at greater resolution, or (b) rethink current resource use by applying smaller domains for the ensemble system or by releasing time on the deterministic runs by using smaller nested domains.

Recommendation 3.4: The NOAA National Operational Model Archive and Distribution System (NOMADS) should be maintained and extended to include (a) long-term archives of the global and regional ensemble forecasting systems at their native resolution, and (b) reforecast datasets to facilitate postprocessing.

Recommendation 3.5: The NCEP, in collaboration with appropriate NOAA offices, should identify the length of reforecast product necessary for time-scales and forecasts of interest, and produce a reforecast product each time significant changes are made to a modeling/forecasting system.

Recommendation 3.6: Efforts on the proposed National Digital Guidance Database should be accelerated and coordinated with those on the NOAA National Operational Model Archive and Distribution System (Recommendation 3.4).

Recommendation 3.7: NWS should work toward a culture and systems that encourage interactions among all components of the Enterprise and should use testbeds as a means of bringing together diverse groups from different disciplines and operational sectors. With the help of external users and researchers, NWS centers and research groups should construct and disseminate a prioritized list of operational goals and associated research questions. These lists should be dynamic, providing mechanisms by which NWS can elicit feedback from the research and user communities and the research and user communities can support and drive the direction of NWS. Potential solutions to these research questions could then be explored in testbeds.

Recommendation 3.8: The Climate Prediction Center (CPC) should investigate methods to use the full distribution of the Climate Forecast System ensemble members (e.g., through a postprocessing step) rather than relying solely on the ensemble mean or median. In addition, the center should make use of reforecast datasets and historical forecast performance information for developing the monthly and seasonal probabilities.

Recommendation 3.9: The CPC should develop more effective objective methods for combining forecast components to improve forecast performance.

Recommendation 3.10: The CPC should examine whether it is appropriate to distribute forecasts with little skill and whether projections should be limited to shorter time lengths. Information about prediction skill should be more readily available to users.

Recommendation 3.11: The NWS and the NCEP should fully support the Climate Testbed to engage the Enterprise, particularly the research community, in operational problems and develop meaningful approaches that enhance and improve operational predictions.

Recommendation 3.12: The Office of Hydrologic Development (OHD) should implement operational hydrology databases that span a large range of scales in space and time. The contribution of remotely sensed and onsite data and the associated error measures to the production of such databases should be delineated.

Recommendation 3.13: The OHD should organize workshops with participation from all sectors of the Enterprise to design alternatives to the Advanced Hydrologic Prediction System ensemble prediction system components and develop plans for intercomparisons through retrospective studies, demonstration with operational data, and validation, and for participation in testbed demonstration experiments.

Recommendation 3.14: The OHD should develop methods for seamlessly blending short-term (weather) with longer-term (climate) ensemble predictions of meteorological forcing within the operational ensemble streamflow prediction system. This will require NCEP model output downscaling and bias adjustment, and real-time data availability.

Recommendation 3.15: The NWS should expand its verification systems for ensemble and other forecasts and make more explicit its choice of verification measures and rationale for those choices. Diagnostic and new verification approaches should be employed, and the verification should incorporate statistical standards such as stratification into homogeneous subgroups and estimation of uncertainty in verification measures. Verification information should be kept up to date and be easily accessible through the Web.

Section 4. Communicating Forecast Uncertainty Recommendations

Recommendation 4.1: The NWS should expedite development of the Interactive Forecast Preparation System toward a system that can access, produce, and communicate uncertainty guidance for most forecast parameters. Such a revised system should be able to access deterministic and ensemble prediction systems, historical error statistics, and statistically postprocessed forecast information (e.g., Model Output Statistics) to allow production of uncertainty information with varying levels of subjective and objective contributions. The system should be capable of preparing probabilistic products to communicate probability density functions and other types of uncertainty information (e.g., probability of temperature less than freezing or wind speed greater than 26 knots).

Recommendation 4.2: The NWS should release the Area Forecast Discussion only in layperson English to facilitate its broad use and understanding. For more sophisticated users, NWS could provide more detailed technical information linked to the Area Forecast Discussion.

Recommendation 4.3: The CPC should provide full exceedence probability distributions of the projected monthly and seasonal temperature and precipitation values in both graphical and tabular forms. A straightforward graphical presentation of this information should be developed that is understandable to relevant user groups.

Recommendation 4.4: To ensure consistency in the communication of uncertainty information and user comprehension, NWS should more fully study and standardize uncertainty terms, icons, and other communications methods through all pathways of forecast dissemination.

Recommendation 4.5: The NWS should amend NWS Directive 10-102 to require collaboration with users on product development throughout the development process. Moreover, users' comprehension and interpretation of products should be formally evaluated at several stages during the product development process.

Appendix C
Overview of Probability Theory Applied to Hydrometeorological Forecasting
(Bob Glahn)

Formally, there are two primary interpretations of probability[42] – the so-called Bayesian (or subjective) and the relative frequency concepts.

The **Relative Frequency Interpretation** states that if an *x* percent forecast of an event is made many times, the relative frequency of the actual occurrence of the event should approach *x*. This is easily comprehended in the random toss of a coin or roll of a die. If we were to roll a die, we would expect a 1 to appear 1/6 of the time; that would be our forecast of a 1 occurring—1/6. That would be a better forecast than saying "a 1 will appear," or "a 1 will not appear." After many tosses, a calculation of the number of 1s that occurred divided by the total number of tosses would approach 1/6. This concept is based on the repeatability of the event. If no other information were available, the probability of a weather event is just its long-term (climatological) relative frequency.

The **Bayesian Interpretation** of probability represents the degree of belief, or quantified judgment, of a particular individual or group about the occurrence of an uncertain event. Some events, like the outcome of football game or a horse race, are nonrepeatable, and the relative frequency concept is of limited use in making a probability forecast of a winner.

Discussion of the Interpretations

Usually, a specifically defined weather event, like the occurrence of measurable precipitation over a specific period at a specific point, is a repeatable event, even though the weather situation surrounding the event is different each time. A person, with or without aids such as climatological relative frequencies, can make a subjective judgment of the probability of the event. Also, a forecast can be based on the relative frequency concept. For instance, if a numerical model were run many times, each run being based on slightly different, but reasonable, initial conditions (analyses of the state of the atmosphere), the ratio of the number of times the model produced measurable rain at the forecast spot over the designated period to the total number of runs would be an estimate of the probability of the event. This is the concept of the numerical weather prediction (NWP) ensembles now being run at many centers over the world.

Also, a simple statistical regression equation can yield an estimate of the probability of the event, with its independent variables being taken from relevant data, especially from the output of one or more numerical models

Whatever the interpretation of probability or the way a forecast is produced, one indisputable fact remains—if a forecast is made for a repeatable event many times, the relative frequency of occurrence of the event for every probability value used should approach that probability value as the number of events increases. For instance, if a 20 percent forecast of the precipitation event is made many times, the event should occur about 20 percent of the time. If that is true for all the probability levels used, then the forecasts are said to be unbiased or reliable.

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[42] While others exist, they are generally less recognized and useful. The recommendations in this document encompass other interpretations as well as these two.

While some persons believe that only the subjective interpretation is correct, and some believe that only the relative frequency interpretation is correct, there is room for both, and it doesn't really matter which viewpoint you favor; the forecasts you make, or that the user needs, should be unbiased in the relative frequency sense.

Probability Forecasts of Discrete Events

The discussion thus far has been confined to probability in terms of a discrete event. Such an event could be naturally defined, such as precipitation falling at a particular time and place. That is easy to conceptualize—precipitation is either falling or not. Or an event could be the type of precipitation, such as snow occurring at a particular time and place. Or an event could be defined as a meteorological variable having a value below (or above) a particular value. For instance, temperature at a particular time and place being 32 degrees F or below is an event for this purpose. A probability forecast can be made for any such event, and is expressed as one number.

Probability forecasts of Continuous Variables

Many meteorological variables, such as temperature, are not discrete, but can take on almost any value within climatological limits. Some particular threshold can be used to define an event, as discussed above, but different users will have different thresholds, so the situation is a bit more difficult to deal with. For this purpose, a Cumulative Distribution Function (CDF) is defined. Basically, it is a distribution such that there is a probability value for every conceivable value of temperature, as shown in Figure 4. While such a distribution may not be definable analytically, in practice it is a rather smooth, nondecreasing function, and can be digitally represented by about a dozen or so points on it. While that does not completely describe the function, it is as specific a definition as is warranted by our accuracy in probability forecasting. This then, becomes, in effect, a series of events with the thresholds defined by the dozen or so points on the curve. Probabilities associated with intermediate thresholds can be found by interpolation. This CDF can also be used to find the probability of temperature being between any two thresholds. There can be no doubt there is more information content in a forecast that contains uncertainty information than in one that doesn't. Two important questions are: How should uncertainty be expressed and how can it be used? The answers to these questions divide themselves into two broad areas, one involving human perceptions, interests, and actions for daily activities, and one involving hard business or institutional decisions generally involving data processing by some means, predominately by computer.

Appendix D
Overview of Decision Theory (Bob Glahn)

Business or Institutional Decisions

A large economic benefit could be achieved nationwide if the uncertainty in weather forecasts were quantified and then used in decision models designed specifically for particular businesses. Sometimes this possibility is viewed too simplistically, and the impression might be that a decision should be based (solely) on the weather forecast. In reality, weather is usually only one of several factors that go into a decision. That being the case, it becomes difficult, if not impossible, for the human brain to most effectively process the myriad facts to arrive at the best decision. Yet that is primarily what is done today, partly because probabilistic forecasts have not been generally available, and because the algorithms needed are complicated to build, and depend on hard facts about the business and institutions not always known. Once reliable probabilistic forecasts are available, such decision models can be seriously considered by those not already using them. Because weather affects so many endeavors, the nation with the best probabilistic forecast system—reliable, accurate, stable, and affordable—could have an economic advantage over other nations without such an infrastructure. But even given such a weather forecast system, its effective use will have to grow with time because of the complexity of the decision theory required to use it to its fullest potential. America's weather and climate industry could provide significant value to customers using probabilistic forecasts and specific knowledge of users' needs to tailor the information provided, both in terms of the expected range of the parameter(s) of interest, and in the method of communicating the likely and possible outcomes.

Decision Theory Concepts

Decision theory in the weather industry is not new. Decision theory concepts entered the mainstream of meteorology with the pioneering work of Thompson (1952, 1962) and Brier (1944; Thompson and Brier 1955), although tentacles reach even farther back [e.g., Bilham (1922), Bijvoet and Bleeker (1951)]. A comprehensive treatment of the subject, not limited to weather, was given early on by Chernoff and Moses (1959) and Miller and Starr (1960); those references are still applicable today. An early application to aviation weather is given by Glahn (1964). Epstein (1962) discusses the Bayesian approach to decision making. The simplest, and oft quoted, decision model is the Cost/Loss model originally defined by Thompson (1952). For instance, Murphy (1976, 1977) has extensively analyzed the Cost/Loss model and shown that probabilistic forecasts are more useful than categorical ones. More recent work, and more extensive models, exist, such as those put forth by Krzysztofowicz (1986).

There is only nascent literature on the actual use of decision theory in weather forecasting. Although models are proposed, use of them is not well documented. This is attributed to three reasons. First, and sufficient, is that there has been a dearth of a consistent source of probability forecasts readily available to the public and businesses that might use them. Large businesses can afford to pay for such service, but it may not be cost effective for smaller ones to do so. Secondly, as stated earlier, decisions depend on more than the weather, and realistic models are complicated to build. Information relating to the company's or institution's operation must have been recorded, analyzed, and put into a form usable by the model. There has not been enough emphasis put, nationwide, on how to build models that are of real use, and not just a simple application that is too naive to be actually useful. And finally, what use has been made of decision models is not widely publicized nor details made known, because the information is often proprietary; the companies actually using probability forecasts in business models do it for a competitive advantage, and are not eager to share the information.

In general, the application of decision theory is not elementary. For a particular business, the factors that affect the decision needed must be known. If there is a degree of uncertainty about these factors, then the likelihood of them taking on certain values must be known or estimated. The CEO of the business must decide on a business strategy, and this may vary from time to time. For instance, what decision to make may depend on the amount of capital on hand compared to the amount at risk for a bad decision. It will take considerable investment for a business to build up its capability in using decision models.

Because of the complexity of real-life business decisions, it is difficult to analyze the effect of various characteristics of weather forecasts on outcomes. However, in the case of the simple, but very useful, cost/loss situation, Murphy (1977) has shown that, "...if the probabilistic forecasts of concern are (completely) reliable, then the value of these forecasts is greater than the value of climatological and categorical forecasts for all activities or operations (i.e., for all values of the cost/loss ratio C/L). On the other hand, if the forecasts are unreliable, then the value of climatological and/or categorical forecasts may be greater than the value of probabilistic forecasts for some values of C/L." He concludes, "These implications relate to the desirability of formulating and disseminating a wide variety of weather forecasts in probabilistic terms and of achieving and maintaining a high degree of reliability in probabilistic forecasts." This latter statement is very important; the need is for <u>unbiased</u> probabilities.

Appendix E
Forecast Uncertainty Application Examples

Application Example 1: Protecting Life and Property (Andrea Bleistein)

A typical year brings 6 hurricanes, 1200 tornadoes, 5000 floods, 10,000 violent thunderstorms, and various other hydrometeorological threats to the United States causing on average 500 deaths, 5000 injuries, and approximately $14 billion in losses each year.[43]

Lengthening warning lead times to allow people more time to take appropriate action before hazardous storms occur is one key to saving more lives and property. Currently, for many severe weather threats (particularly those such as tornadoes that are small in areal extent and short in duration), warnings can only be confidently issued when the threat is able to be detected from observations because models are not able to predict them accurately. Tornado warnings, for example, are only issued when there has been a visual confirmation of a tornado by an experienced "storm spotter" or there has been detection of a tornadic signature in Doppler radar observations. This practice of so-called "warn on detection" (WOD) limits the length of warning lead times for these events. For individual tornadoes, approximately 13 minutes lead time is the best that can be achieved with WOD (Stensrud et al. 2009). Further, those locations where a tornado first develops may receive very little or no lead time. So, an

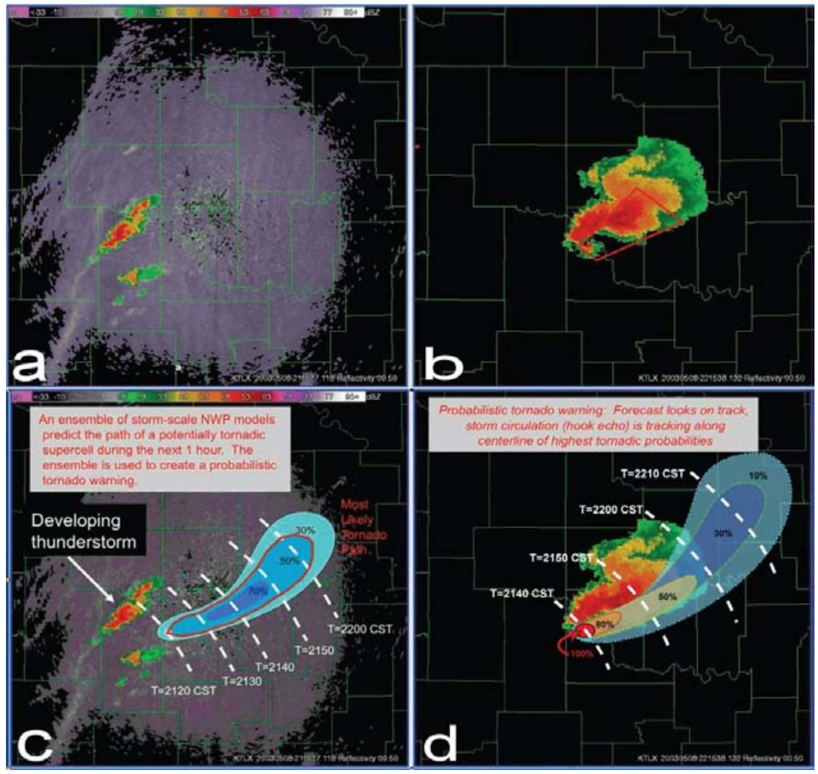

Figure E1.1. Comparison of a tornadic thunderstorm evolution and the issuance of tornado warnings under the currently opeational "warn on detection" (WOD) paradigm and a hypothetical warning application under a "warn on forecast" (WOF) or "warn on probability" (WOP) paradigm. Figure E1.1a is radar reflectivity of a developing thunderstorm. The radar reflectivity does not yet indicate the presence or formation of a tornado. Figure E1.1b is radar reflectivity of the same thunderstorm after it has developed a mature mesocyclone radar signature (hook echo) and a warning polygon (red box) indicating the geographic area under a tornado warning. Under the WOD paradigm, the warning polygon can only be issued when a mesoscylone signature (such as indicated in E1b) is detected by the radar or there is an actual observation (e.g., by a trained spotter) indicating the formation of a tornado. Figure E1.1c is same radar reflectivity of a developing thunderstorm in Figure E1.1a, except with a conceptual 1-hour lead time probabilistic tornado path superimposed. Figure E1.1d is the same radar reflectivity of the mature mesocyclone in b), except with an updated conceptual 1-hour probabilistic tornado path instead of a warning polygon. Under a WOF/WOP paradigm, a tornado warning using appropriate probabilistic thresholds may be able to be issued when thunderstorms are in their incipient stages (as in Figue E1.1a), providing more lead time. Adapted from Stensrud et al. (2009).

[43] See http://www.economics.noaa.gov/?goal=climate&file=users/government/nws

alternative strategy is required to get accurate warning lead times beyond 30–45 minutes.

Advanced ensemble prediction systems, which produce reliable probabilistic forecasts, provide an opportunity to substantially lengthen warning lead times as appropriate, and ultimately, help save more lives and better protect property by transforming WOD to "warn on forecast" (Stendsrud et al. 2009) (WOF) (more precisely, "warn on probability" - WOP). In a WOF/WOP paradigm, high-resolution ensemble models with sophisticated physics will predict with known reliabilities the genesis and evolution of tornadic thunderstorms and other hazardous storms (see Figure E1.1). Shifting to a WOF/WOP capability, which incorporates probabilistic thresholds into the warning criteria, could increase warning lead times two- or three-fold over current lead times[44], which would help lower yearly average losses nationwide owing to hazardous storms. Imagine having appropriately worded statements warning the public one hour ahead of tornadoes and two hours ahead of severe thunderstorms. This extra time would allow more families to gather together safely in their basement before a tornado strikes or for a little-league team to clear a baseball field and get under safe cover before a lightning storm struck.

Application Example 2: Optimizing Tropical Cyclone Evacuations (Tom Hamill)

Imagine yourself as a state emergency manager, responsible for ordering the evacuation of coastlines when a hurricane threatens. You must decide 72-h prior to the hurricane landfall to either evacuate a particular city, not evacuate, or to postpone the decision risking loss of life and confusion if you need to order an evacuation closer to the time of hurricane landfall. Envision three forecast scenarios, portrayed in Figure E2.1.

Scenario 1: You are presented with a deterministic, single-value forecast. Your meteorological support team also provides you with uncertainty information on past storms of a similar forecast magnitude, and how much they erred in intensity and location. The data show that the city of interest is on the edge of a cone of uncertainty.

Scenario 2: Your meteorological support team shows you a new forecast with a storm-unique cone of uncertainty, based on calibrated ensemble forecast information. The cone shows that the city is **outside** the region that is likely to be affected by the hurricane.

Scenario 3: Your meteorological support team shows you a new forecast with a storm-unique cone of uncertainty, based on calibrated ensemble forecast information. The cone shows that the city is **inside** the region that is likely to be affected by the hurricane.

Your decision in scenario 1 is ambiguous, whereas the decision is much more clear in scenario 2 (do not evacuate city) and scenario 3 (order the evacuation).

[44] Future official warning criteria will depend likely on various other factors, including but not limited to the results of social science research and the specific requirements of emergency managers and other public safety officials. Warning lead time and accuracy improvements will also be reliant on advances in observations and deterministic numerical models, which will contribute to ensemble model predictions.

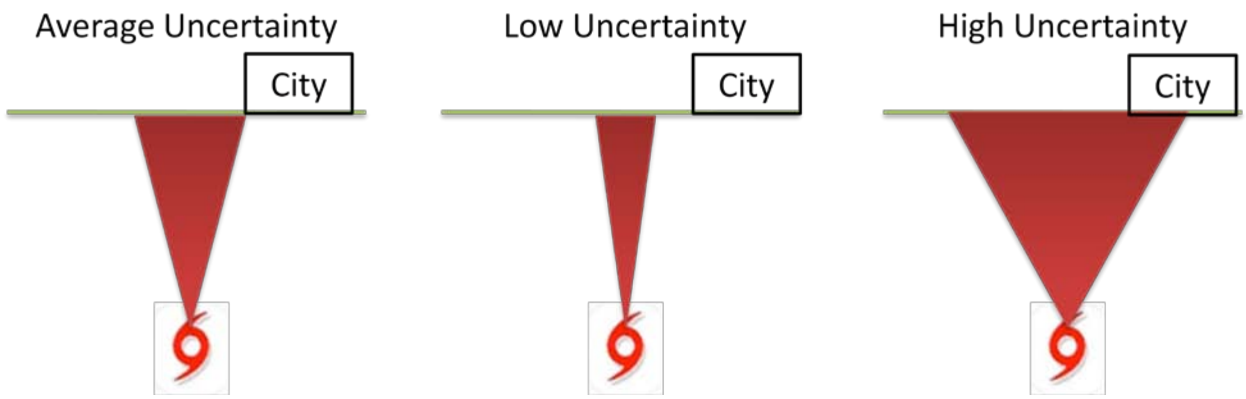

Figure E2.1. A graphical representation of the three scenarios. On the left, the time averaged range of track uncertainty, portrayed with a cone, barely overlaps the edge of a coastal city. Presuming ensemble information is available that permits a case-by-case determination of uncertainty in a reliable manner, we now consider two other scenarios. In the middle scenario, there is less than average uncertainty, and the city is far outside the cone. With the right-hand scenario, the city is clearly within the cone of uncertainty.

Application Example 3: Using Probabilistic Information to Fight Wildfires (Douglas Hilderbrand)

Uncontained wildfires, which can be the result of a runaway prescribed fire, an unintended ignition, or arson, result in property losses averaging $1.2 B per year[45]. Catastrophic wildfire is a growing national issue, as demonstrated by the Florida wildfires in 1998 and wildfires across many Western states over the past decade. Since 2000, most western states have experienced severe fire seasons which set new benchmarks in terms of lives lost, properties destroyed, and costs in fire suppression. Of particular concern is the spread of wildfires into wild land-urban interface (WUI) areas where communities are adjacent to, and intermixed with, significant vegetation. In 2003 WUI fires in the vicinity of San Diego displaced nearly 100,000 people, destroyed over 3500 homes and took the lives of 22 people. The weather plays a major, and often dominant role in determining the magnitude of this kind of loss. The trend in wildfire occurrence is expected to continue along its increasing path. The recent 2007 San Diego fires (see Figure E3.1), while burning fewer acres and structures, still had the same devastating impact on residents and businesses. The continued movement of residents into wild land areas is cause for an increasing need to provide improved services to emergency managers, land managers and fire fighting agencies.

Figure E3.1. Residential areas are increasingly vulnerable to wildland fires such as this San Diego neighborhood in 2007. Wind speed and direction are essential factors in the spread of fires.

45 See http://www.sab.noaa.gov/Reports/2008/FWRWGreportFINALfromSABtoNOAA_11_03_08.pdf

Probabilistic Information Use in Fire Suppression

NOAA/NWS Incident Meteorologists (IMETs) and Incident Managers provide critical weather information in support of fire suppression operations. Incident Commanders (IC's) continue to request more effective tools to improve the prediction of fire behavior in order to "get ahead" of events. Probabilistic information (e.g., wind speed and direction) ingested into decision support tools (i.e., decisions based on risk tolerance thresholds) provides ICs with contingency scenarios and alternative actions to minimize risk to firefighters and unsuspecting communities. Preparing for alternative scenarios instead of just the "most likely scenario" can save lives by removing firefighters and residents from being trapped "in the wrong place at the wrong time". Additionally, resources can be more effectively positioned based on possible changes in wind speed and direction. Cost/loss models, ingesting probabilistic information, can increase resource effectiveness. Tactical efficiency improvements reduce cost for most severe fires (Type-1 fires) by approximately $10M for every 1% reduction in deployment time.

Hypothetical Example of Fire Weather Probabilistic Information—California in 2015

The drought in the western third of the United States has worsened over the first 15 years of the new millennium. The historical fire season (June–September) has expanded to all months of the calendar for the state of California. Resources have been stretched thin as uncontrolled fires continue east of the San Diego metro area as well as in the Sierra-Nevada Mountains where a forest fire was threatening communities along the western shore of Lake Tahoe. NOAA IMETs were stationed at the command center 4 miles from the southern front of the fire. The Short Range Ensemble Forecast (SREF) model generated a wind direction probability curve with a 70 % chance of continued northerly winds over the next 24 hours. However, the IMET at the scene noticed a secondary maximum of 20 percent chance of winds shifting to the west. After discussing with the fire behavior specialists at the command center, the IC was concerned embers could "hop" the lake and continue eastward into the more densely populated eastern shore of Lake Tahoe in Nevada. The IC contacted Nevada state officials who immediately predeployed firefighters to respond to any shift in the winds to the west. Diurnal thunderstorms developing to the northeast indeed caused this westerly shift in winds. However, because of the predeployment of fire personnel, the embers that were carried across the lake were quickly extinguished and the eastern side of the lake was spared any damage.

Application Example 4: Reducing Aviation Delays and Costs (Tom Dulong)

In 2007, flight delays associated with increasing air traffic within the National Airspace System (NAS) accounted for almost 20% of total flight time equating to a cost of $41 billion[46]. By 2025, demand is projected to double or triple with associated delays costing ~$143 billion between 2015 and 2025. The Next Generation Air Transportation System (NextGen) is being designed by the FAA and federal partners to address this national challenge by infusing 21st century technologies to improve air traffic management (ATM).

Currently, weather impacts are associated with 70% of all air traffic delays within the NAS (~$28 billion per year) and about 2/3 of these delays could be avoided with better weather information (Abelman et al. 2009). Consequently, one key NextGen goal is to improve weather information and the use of weather information in ATM decision making. The NextGen Network

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[46] Joint Economic Committee of the House and Senate, May 22, 2008, *Your Flight Has Been Delayed Again*, Available at: http://www.jec.senate.gov/

Enabled Weather (NNEW) system is envisioned to provide a common weather picture with new and improved weather information for all air traffic users. The foundation for NNEW will be a 4-dimensional (3 in space and 1 in time) database, the Weather Information Database (WIDB), which will include global, regional, and local observations and forecasts.

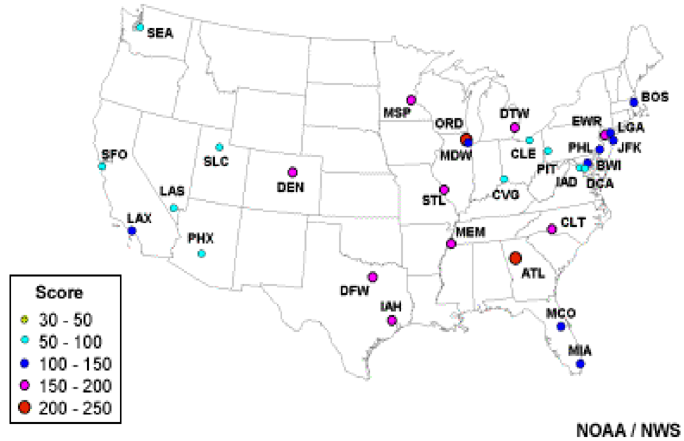

Figure E4.1. Thirty busiest airports as weighted by weather frequency.

Traditionally, operational aviation weather forecasts, such as Terminal Aerodrome Forecasts (TAFs), have been deterministic. However, this will change in the future with documented requirements for the WIDB already including probabilistic forecast information (JPDO 2007). In particular, studies are showing how probability information can be used to reap considerable fuel carriage savings and be translated into anticipated air space capacity reductions. For example, one study (Keith and Layton 2007) projected that American Airlines could potentially save $50 million annually on domestic flights by relying on statistically driven, probabilistic terminal forecasts versus traditional TAFs. Considering that other major U.S. carriers share many of the same weather prone airports (Figure E4.1), the airline industry could collectively save hundreds of millions of dollars annually by incorporating such information into decision making.

Another study (Steiner et al. 2008) examined the value of applying probabilistic thunderstorm forecasts to en-route operations. According to this study, air traffic managers currently utilize radar and deterministic forecast products to issue so-called "playbook routes" as a method of directing traffic flow. Playbook routes are predetermined alternate routes used when weather is severe and serve as conduits into which traffic from the more heavily populated areas is channeled and sent across the country. The major benefit of using playbooks is the time savings gained by the reduced coordination to use these routes, since they have already been developed and coordinated nationally (FAA 2007). As shown in Figure E4.2, playbook routes may be swapped to reroute traffic around lines of thunderstorms. Although it has been the traditional way of rerouting traffic flow around hazardous weather, use of playbook routes can be expensive. A large number of aircraft may be impacted, especially when the area of avoidance is large. This typically results in higher fuel costs and delays. Probabilistic predictions

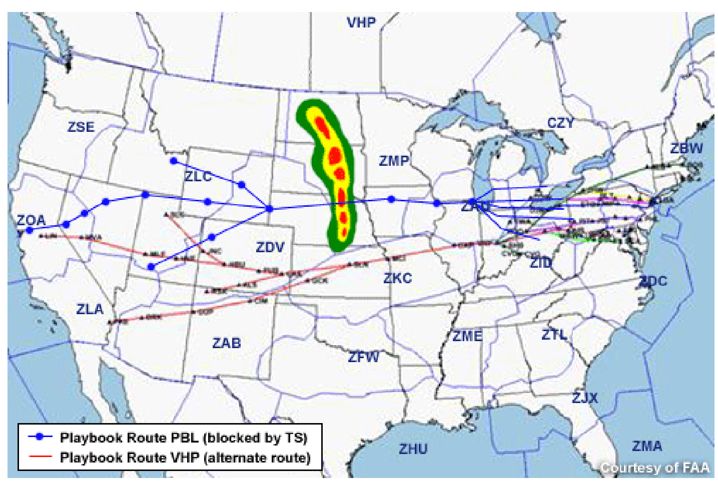

Figure E4.2. Example of playbook swap, whereby the PBL route (blue) is blocked by a line of thunderstorms, so the VHP route (red) is used to take traffic flow past the south end of the weather.

may offer a new and more efficient way of managing air traffic around hazardous weather. Ensemble-based predictions could be used to provide impact-relevant forecast information at a relatively high resolution (e.g., 50 km x 50 km grid boxes) across the NAS. Specifically, each box could be routinely updated with its predicted probabilistic available flow capacity radio. Per the example in Figure E4.3, individual aircraft could be progressively routed from east to west through the boxes that have the lowest forecast likelihood of capacity reduction below a pre-determined flow capacity ratio threshold (e.g., 0.7 in this case). A similar prediction field may be calculated for west to east traffic. Fuel costs and delay time overall should be lower, since many aircraft could fly shorter routes around weather hazards using this method versus following a standard playbook route. Projected savings from this method have yet to be quantified in dollars, but they should be substantial.

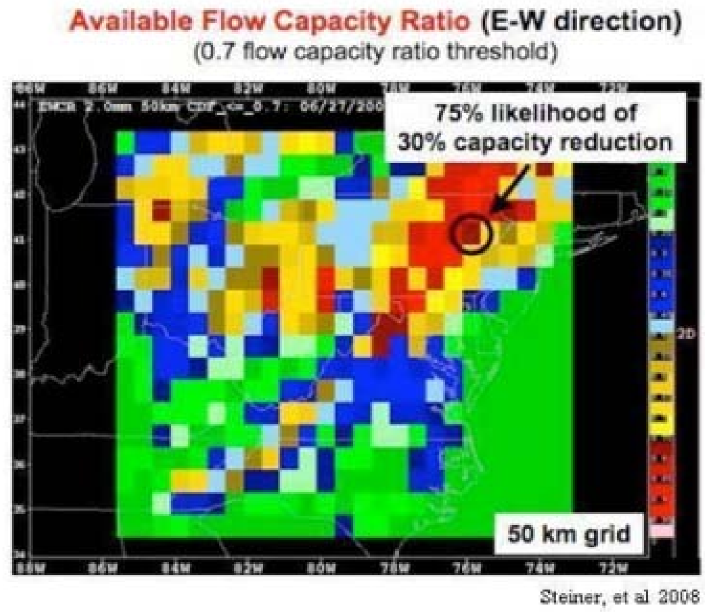

Figure E4.3. Example of predicted probabilistic available flow capacity ratio based on expected weather hazards. Warmer colors have higher likelihood of capacity reduction then cooler colors.

Application Example 5: Strengthening Security (Jim Hansen)

The U.S. Navy has developed a risk matrix technique called the "Operational Risk Management" (ORM) process, a decision tool to increase operational effectiveness by identifying, assessing, and managing risks[47]. The Naval Safety Center believes that ORM best practices are capable of saving the Navy up to 50 lives and $200 million per year.[48]

The ORM Risk Management Matrix (RMM) scales risk numerically with a so-called Risk Assessment Code (RAC) from 1 (critical) to 5 (negligible), according to the intersection of two matrix elements: severity of a hazard and the probability of its occurrence (Figure E5.1). The use of forecast uncertainty information in ORM to identify, assess, and mitigate risk owing to hydrometeorological hazards is a natural. Atmospheric and oceanic hazards (such as strong winds and high seas) pose risks for ships at sea and many other types of naval operations. Forecast probabilities (obtained by using ensemble prediction systems and/or other techniques) of these and other hazards exceeding certain thresholds (with escalating impact on the mission) can be used to populate the RMM.

To demonstrate the use of weather forecast uncertainty information in operational decision making, the Navy is developing a capability to employ ORM to translate objective weather

[47] See OPNAV Instruction 3500.39B available at: www.usa-federal-forms.com/navy/3-pdf-forms_pubs/.../**3500.39B**.pdf
[48] See http://safetycenter.navy.mil/presentations/orm/5yearvision.htm

uncertainty guidance directly to piracy risk. The region around the Horn of Africa (HOA) has seen a ten-fold increase in piracy activity in 2009 relative to the same period in 2008 despite an increased effort by United Nations Naval forces. The U.S. Department of Transportation Maritime Administration outlines several economic impacts associated with enhanced piracy activity around the HOA[49] and it is estimated that piracy costs the U.S. maritime industry between $1 billion and $16 billion per year[50]. Knowledge of the risk that pirates will assume by operating in a particular region at a particular time can be exploited to protect shipping through various forms of interdiction and avoidance efforts. Pirates operate in small vessels and therefore are particularly vulnerable to adverse wind and seas.

Risk Management Matrix **OPNAVINST 3500.39B**		PROBABILITY			
		A Likely	**B** Probable	**C** May	**D** Unlikely
SEVERITY	I Death, Loss of Asset	1	1	2	3
	II Severe Injury, Damage	1	2	3	4
	III Minor Injury, Damage	2	3	4	5
	IV Minimal Threat	3	4	5	5

1-Critical 2-Serious 3-Moderate 4-Minor 5-Negligible

Figure E5.1. Risk Assessment Code (RAC) from 1 (critical) to 5 (negligible), according to the intersection of two matrix elements: severity of a hazard and the probability of its occurrence.

Fleet Numerical Meteorological and Oceanic Center ensemble forecasts are used to identify the probability of various thresholds of surface winds and seas enabling each parameter to populate a RMM at every forecast lead and every location in the domain around the HOA. The overall risk is defined by the parameter that provides the smallest RAC, and resulting minimum RAC values are plotted on a map to create a so-called risk surface.

Figure E5.2 is an example risk surface for an 84-hour forecast. At a glance an operator can see that the meteorological risk to pirates in the Mogadishu area is much smaller than near the Gulf of Aden area at hour 84 (the pattern of risk changes with forecast lead). Decision makers can then take action based on these risk estimates by, for example moving naval assets to areas that are favorable for piracy activity, providing divert recommendations to shipping, or other means.

This piracy interdiction application will enable the production of a set of best practices for hydrometeorological applications of ORM in the Navy. The risk surface idea can be applied to any operation that has specified hydrometeorological impacts.

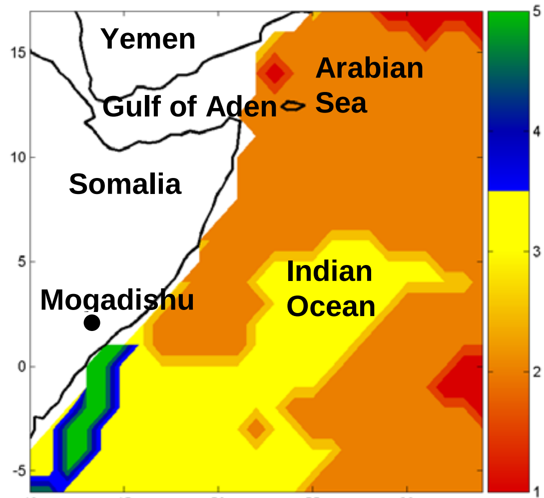

Figure E5.2. Example risk surface for an 84-hour forecast initialized at 0000 UTC 14 November 2008. At each point in the domain the probability of exceeding the four severity thresholds for surface winds and seas were estimated from an ensemble and used to populate the RMM. The maximum risk (lowest value) is then extracted and plotted in the figure [low values (warmer colors) are high risk, high values (cooler colors) are low risk].

[49] Economic Impact of Piracy in the Gulf of Aden on Global Trade. See http://www.marad.dot.gov/documents/HOA_Econonmic Impact of Piracy.pdf
[50] Peter Chalk, senior policy analyst, Rand Corporation. Feb 4 2009 testimony to the House Committee on Transportation and Infrastructure, Subcommittee on Coast Guard and Maritime Transportation.

Application Example 6: Generating and Communicating Uncertainties for Air Quality Forecasts (Luca Delle Monache)

High concentration levels of surface ozone and $PM_{2.5}$ cause respiratory and cardiovascular problems leading to premature deaths and high costs associated with health care, school absences, missed work, and potential lost income from premature deaths and damages to crops and forests. Consuming seafood contaminated with high levels of mercury can harm the brain and other organs, especially during in-utero and early childhood development. Moreover, acidic and nitrogen compounds deposited onto watersheds and water surfaces can degrade water quality, impair ecosystem health and reduce commercial and recreational use of these areas. It has been estimated that in the U.S. poor air quality causes as many as 60,000 premature deaths each year with costs between $100 [51] and $150 billion per year[52].

Accurate air quality predictions can provide individuals and communities with timely information to help them limit exposure and reduce health problems caused by poor air quality, and even save lives. It is difficult to estimate how may lives and costs could be saved with accurate and reliable air quality predictions. Nevertheless, assuming that such predictions reduce by 1% the premature deaths and the costs listed above, about 600 lives and over $1 billion could be saved each year. It is worth noticing that these would be more lives saved than the 500 deaths caused on average each year by all the hydrometeorological threats (including hurricanes, tornadoes, floods, violent thunderstorms, etc.)[53].

The U.S. Weather Research Program and its Prospectus Development Team on Air Quality Forecasting (e.g., Dabbert et al. 2004) has recommended a probabilistic approach to air quality forecasting because of the chaotic nature of the atmosphere and chemistry nonlinearity. Recently several efforts have focused on the exploration and development of probabilistic predictions for short-term air quality forecasts (e.g., Delle Monache et al. 2006) and to estimate the impact of emission control policies (e.g., Vautard et al. 2009). Moreover, recent developments have shown that air quality predictions can be improved through the assimilation of chemical data (e.g., Carmichael et al. 2008).

While searching for efficient ways to communicate uncertainties, air quality forecasting faces very similar challenges as discussed in this document for NWP, and in fact a good portion of the advances and lessons learned in the NWP arena can be useful and applied also to provide comprehensive, skillful, and reliable information about the uncertainty of air quality predictions. For instance, plots of the ensemble mean and the ensemble spread provides very useful information about the most accurate prediction and its uncertainties as shown in Figure E6.1.

An operational multimodel air quality ensemble is currently employed in Europe by the European Centre for Medium-Range Weather Forecasts (ECMWF) under the European Union funded projects Global and regional Earth-system (Atmosphere) Monitoring using Satellite and in-situ data (GEMS**)** and Monitoring Atmospheric Composition and Climate[54]. Figure E6.2 shows the predictions of different pollutants at a specific location (Amsterdam, The Netherlands) and is an example of the products available to the public generated with this state-of-the-science prediction capability for regional air quality. The boxes show the minimum, median and maximum

[51] http://www.nrc.noaa.gov/plans_docs/2009/AQSOSFactSheetFinal.pdf
[52] http://www.weather.gov/ost/air_quality/Fact%20Sheet%200208.pdf
[53] http://www.economics.noaa.gov/?goal=climate&file=users/government/nws
[54] See http://gems.ecmwf.int/d/products/raq/ensemble/epsfields/plot_ensemble_o3/.

value of the ensemble predictions, along with the 10th, 25th, 75th, and 90th percentile of the distribution of predictions, a convenient way to conveny clearly the large amount of information provided by an ensemble. In this case the median can be seen as the most likely value, while the spread of predictions around it can be interpreted as a surrogate for the confidence in that prediction.

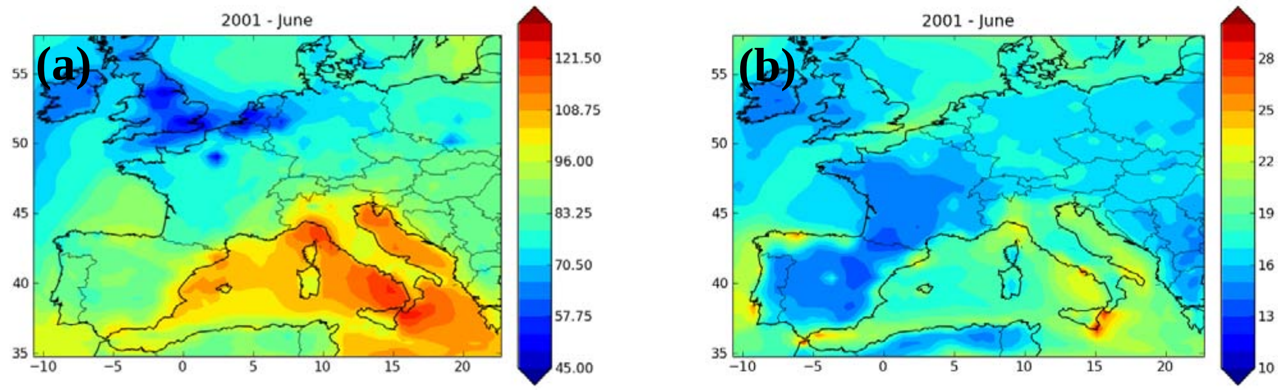

Figure E6.1. June 2001 monthly averages of ensemble mean (a) and ensemble spread (b) of a 30-member ensemble for ground-level ozone (µg m^{-3}) generated with the Polyphemus system. Courtesy of Damien Garaud and Vivien Mallet.

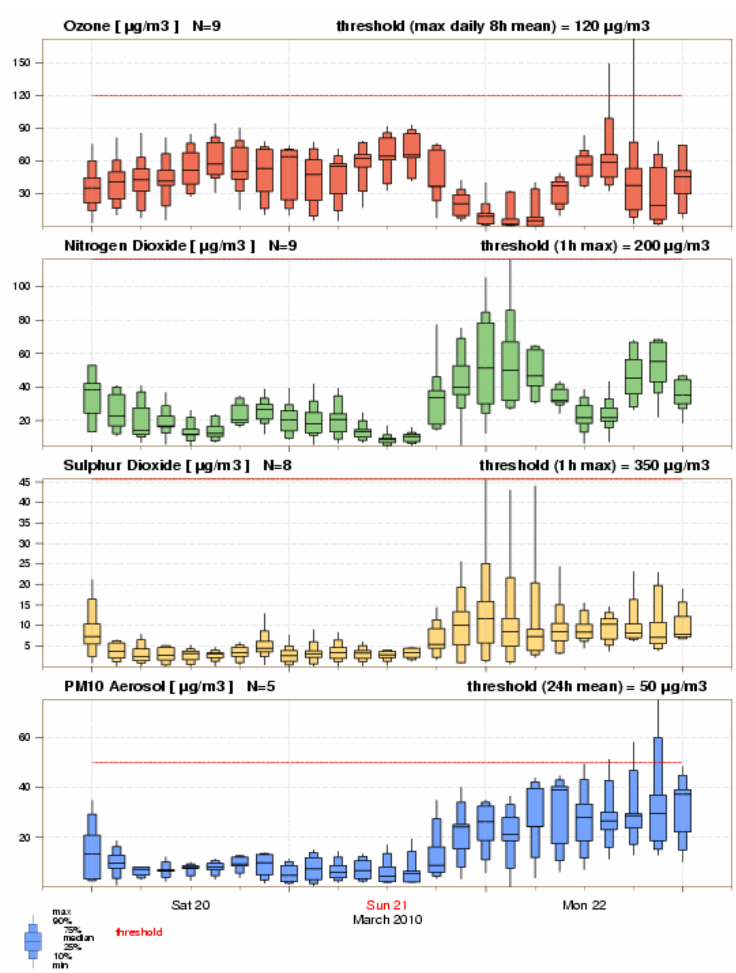

Figure E6.2. Air quality predictions issued at 0000 UTC 20 March 2010, at Amsterdam, The Netherlands. The boxes show at a given time, the minimum, median, and maximum, as well as the 10th, 25th, 75th, and 90th percentile of the values predicted by the ensemble members (see legend at the bottom left). Dashed red lines represent the thresholds above which a pollutant is considered harmful.

Appendix F
Detailed Description of Objectives

The objectives are organized under the strategic goals as follows:

Strategic Goal 1. Understand forecast uncertainty.
- Obj. 1.1 Identify societal needs and best methods for communicating forecast uncertainty.
- Obj. 1.2 Understand and quantify predictability.
- Obj. 1.3 Develop the theoretical basis for and optimal design of uncertainty prediction systems.

Strategic Goal 2. Communicate forecast uncertainty information effectively, and collaborate with users to assist them in interpreting and applying the information in their decision making.
- Obj. 2.1 Reach Out, Inform, Educate, and Learn from Users.
- Obj. 2.2 Prepare the next generation for using uncertainty forecasts through enhanced K–12 education.
- Obj. 2.3 Revise undergraduate and graduate education to include uncertainty training.
- Obj. 2.4: Improve the presentation of government-supplied forecast uncertainty products and services.
- Obj. 2.5: Tailor data, products, services, and information for industry customers.
- Obj. 2.6 Develop and provide decision support tools and services.

Strategic Goal 3. Generate Forecast Uncertainty Data, Products, Services, and Information
- Obj. 3.1 Improve the initialization of ensemble prediction systems.
- Obj. 3.2 Improve forecasts from operational ensemble prediction systems
- Obj. 3.3 Develop probabilistic nowcasting systems.
- Obj. 3.4 Improve statistical postprocessing techniques.
- Obj. 3.5 Develop non-statistical postprocessing techniques.
- Obj. 3.6 Develop probabilistic forecast preparation and management systems.
- Obj. 3.7 Train forecasters
- Obj. 3.8 Develop probabilistic verification systems.
- Obj. 3.9 Include digital forecast uncertainty information in database and access systems.

Strategic Goal 4. Enable forecast uncertainty research, development, operations, and communications with supporting infrastructure.
- Obj 4.1 Acquire necessary high performance computing.
- Obj 4.2 Establish a comprehensive archive.
- Obj 4.3 Ensure easy data access.
- Obj 4.4 Establish forecast uncertainty test bed(s).
- Obj 4.5 Work with users to define their infrastructure needs.

Objective 1.1: Identify societal needs and best methods for communicating forecast uncertainty

Background: The ability of users to understand and make appropriate decisions based on forecast uncertainty information may depend upon the manner in which the uncertainty information is communicated. Social science programs in government, academia, industry, and NGOs can assist the Enterprise effectively communicate forecast uncertainty.

Need: The Enterprise needs to know how to communicate forecast uncertainty effectively to provide products, services, and information that enable customers and end users to optimally interpret and use the information. At best, if this need is not met, the forecast uncertainty information the Enterprise makes available will continue to go largely unused. At worst, uncertainty information will be misinterpreted or misused, leading to poor decisions and negative outcomes. Also needed is a better understanding of the benefits of uncertainty information in weather forecasts. The potential benefits are the main drivers to including uncertainty. *Current capabilities*: A few preliminary studies exist on the effective ways for communicating probabilistic information, including a WMO publication (http://tinyurl.com/676dyd). *Capability Gaps*: There is limited knowledge on effective communication of hydrometeorological forecast uncertainty and risk to various customer and user groups. While communicating uncertainty and risk has been studied in other fields and contexts, it is not apparent how this knowledge applies to communicating hydrometeorological forecast uncertainty. Limited knowledge of the value of uncertainty information in weather forecasts also limits its use. *Performance Measures and Targets:* Peer-reviewed research publications that provide useful guidance on best practices for communicating forecast uncertainty. Testing (see testbed) and implementation of ideas developed in the research community on communication of forecast uncertainty. Development and implementation measurements of improvements in saving of life and property based on provision of forecast uncertainty and probability of threshold exceedance information	*Solution Strategy:* Conduct social science research to determine the best methods of conveying hydrometeorological forecast uncertainty guidance to the public. Short-term *(0-2 years)* •Host forums for social scientists to interact with hydrometeorological forecasters and service providers. *(NGO)* •Hold workshop(s) to entrain new social science and interdisciplinary researchers into study of hydrometeorological forecast uncertainty. *(NGO)* •Hold workshop(s) to prioritize social science needs and include in calls for research. (*Gov*) Begin grants-driven projects to perform social science research on communicating uncertainty. *(ACA)* *Medium-term (2-6 years)* •Fund social science proposals to examine most effective ways to communicate forecast uncertainty to different audiences in different contexts. *(GOV)* •Deliver research findings to Enterprise on how users prefer to receive uncertainty information for a spectrum of products (rainfall, severe weather, daily temperatures, etc.). *(ACA)* •Facilitate building public/private consortiums for funding research on communication of forecast uncertainty. *(NGO, ACA)* *Long-term (6+ years)* •Sustain research based on 2-6 year results. *(GOV, NGO, ACA)*

Objective 1.2 Understand and quantify predictability

Background: "Predictability" refers to the time limit at which a phenomenon can be predicted with skill, i.e., with more specificity than climatology. Predictability is an innate characteristic of the atmosphere, not of forecast models. However, predictability is typically estimated using numerical models. Predictability is known to vary with the spatial scale of motion of the phenomenon of interest (e.g., a thunderstorm, hurricane, winter storm, etc.).	
Need: A more complete understanding of the characteristics of predictability is needed in order to set reasonable forecast accuracy and reliability goals and to prioritize the development of forecast uncertainty products and services; with limited resources, uncertainty products should first emphasize product development for the relatively predictable. A more complete understanding of predictability will also provide insights about forecast model errors and will also help assess and improve data assimilation and other techniques to quantify forecast uncertainty. *Current Capability*: It is accepted that the time scale of predictability generally increases with increasing scales of motion. Predictability time scales are longer for data that represents averages over large areas and/or long periods of time. Some rough quantifications exist (see tinyurl.com/dfegwl). *Capability Gaps*: Knowledge about the predictability of specific phenomena is lacking. For example, is a 3-day tornado outlook at the county scale more or less predictable than a 10-day hurricane track and intensity forecast? It is not easy with the current level of understanding to quantify the relative gap between the ability to forecast a phenomena and the phenomena's intrinsic predictability. Quantifying how this gap changes for various phenomena may help determine which aspects of the forecast model are in greatest need of improvement. *Performance Measures and Targets:* • Peer-reviewed publications that quantify predictability estimates over a range of phenomena. • Convergence of predictability estimates: consistent (and hence more trustworthy) estimate even when evaluated with diverse techniques.	*Solution strategy:* Perform research to determine quantitatively the limits of predictability. *Short-term(0-2 years):* •Synthesize and publish results of previous studies to document current understanding of the limits of predictability. *(ACA)* •Sustain current funding of ensemble and predictability research through programs such as THORPEX. *(ACA, GOV)* •Develop funding programs/requests for proposals focusing on quantifying estimates of the limits of predictability. *(GOV)* *Medium-term (2-6 years):* •Perform research with higher-resolution models that better quantify estimates of the limits of predictability. Studies should be prioritized based on the largest combined scientific and societal impact, e.g., predictability of the position and intensity of landfalling hurricanes. *(ACA)* *Long-term steps (6+ years):* •Sustain predictability studies using improved, higher-resolution models that increasingly incorporate stochastic elements. *(ACA)*

Objective 1.3: Develop the theoretical basis for and optimal design of uncertainty prediction systems

Background: There are two sources of error that must be accounted for properly when generating probabilistic forecasts, initial-condition error and model error. Methods for generating initial conditions for ensemble modeling systems are mature relative to methods for dealing with errors in the forecast model. For example, there is now a general theory on what are the appropriate properties of initial conditions for ensemble forecasts. Building and testing ensemble Kalman filter techniques for improving data assimilation and initializing ensemble forecasts reflects an attempt to move from more ad-hoc approaches of initializing ensembles to ones that are consistent with such theoretical principles. However, there is not a similar underpinning for the treatment of numerical model error in ensembles.

Need: A fuller understanding of the sources of forecast uncertainty is needed as well as efficient numerical methods for estimating uncertainty in prediction systems.

Current Capability: Current approaches to estimate the effects of uncertainty in ensemble prediction systems include: (1) designing improved methods for initializing ensembles, e.g., ensemble Kalman filters. (2) reducing model error via improving the numerical models used in ensembles and/or by increasing ensemble model resolution, (3) estimating the uncertainty introduced by model error by using multiple models, and (4) introducing random elements into the integration of the ensemble.

Capability Gaps: Current ensemble prediction systems do not yet incorporate effective, theoretically justifiable methods for quantifying the effects of model errors in ensemble systems. Further, the relative tradeoffs between applying extra computational resources to add more ensemble members vs. increase model resolution vs. improve model numerics is not well understood. For example, more ensemble members decrease the sampling error associated with spread estimates, but if those more members are from a lower-resolution model, there may be a systematic underestimate of the spread.

Performance Measures and Targets:
- Peer-reviewed research publications that provide useful guidance on advanced methods for addressing initial-condition and model error in probabilistic predictions.
- Experimental systems at academic institutions and government labs that demonstrate the effects of new prediction methods.

Solution Strategy: Perform research on the underlying theory and optimal design of probabilistic prediction systems.

Short-term (0-2 years):
- Continue research supported by existing research grants programs. (*ACA)*

Medium-term (2-6 years):
- Expand research program on improved numerical techniques for estimating analysis and forecast uncertainty, especially at the mesoscale and for techniques that estimate the uncertainty contributions from model errors. *(ACA)*
- Work with operational model developers (see Obj3.2) to implement proven superior research techniques. (ACA*)*

Long-term (6+ years):
- Sustain uncertainty prediction system research. *(ACA)*

Objective 2.1: Reach out, inform, educate, and learn from users

Description and Purpose: Many users are conditioned to the current deterministic forecasts, and products that include uncertainty may be perceived as wishy-washy. Public education will be needed to educate users in how to comprehend the added uncertainty information and how to effectively use it to improve their decision making. Users can provide valuable advice on how probabilistic information can be expressed in intuitive ways that improve their decision making.

Need: As probabilistic forecasts become more common, diverse "publics" will need to be taught how to best use probabilistic products, and meteorologists will need to listen to and understand users concerns about how their decision making could be improved through changes in the weather forecast format. Additionally, forecast product formats will be undergoing significant change as forecast providers work to include more probabilistic information in their forecasts. Forecasters and users must be able to: (a) communicate the information (forecasters), (b) state how this information is understood (users), and (c) determine whether the information is understood as intended (forecasters and users). Ideally, there will be a continuing formal and informal dialog with customers and the public allowing for better understanding of customer needs for uncertainty information, educating customers on new products, promulgating best practices for using the products, and communicating how well the products perform. This dialog will facilitate intelligent development of new uncertainty products and improve the use of existing ones.

Current Capability: "Outreach" is the communication of ideas or principles to diverse groups or communities. Meteorological outreach can be within the profession (one discipline to another) or between the profession and the broader community, including the general public, educators, scientists, and government administrators. Policy makers and planners need to understand uncertainty to make informed decisions, which may affect people's lives or community planning. Outreach provides the opportunity for meteorologists to educate and learn from their users.

Examples of outreach from the meteorological and social science community to users are the WAS*IS (Weather and Society, Integrating Studies) workshop, hosted by NCAR. Many universities also have meteorological outreach programs. For example, the University of Wisconsin provides a four-day workshop for prospective students to learn about the disciplines of meteorology, astronomy, land remote sensing, and geology.

Capability Gaps: The biggest challenge is likely with the general public. This is mainly the result of their limited knowledge of basic probability and statistics, and that NWS and other providers' probabilistic weather and climate forecast products definitions are not consistent. Further discussion of this problem and potential solutions can be found under sections on K-12 and post-secondary education. Additionally, while basic research (Objective 1.3) will help meteorologists understand some of the principles about communicating uncertainty, there is no substitute for regular feedback. Opportunities for such feedback are presently quite limited. The costs of misunderstanding and misusing probabilistic forecast include, for the general public, bad decisions regarding travel or event planning. For industry and governmental users,

Solution Strategy: Educate users about forecast uncertainty and probabilistic forecast products through information campaigns, broadcast meteorologists, and other educational information and feedback mechanisms (e.g., Web sites); find out what users understand, want and need, and how they want the information formatted; and develop user/developer feedback mechanisms before and during product development.

Short-term(0-2 years):

- Develop cost-effectives ways to gather social science data via collaboration between social scientists and hydrometeorologists about how best to incorporate uncertainty into forecast products. (*GOV, ACA*)
- Collaborate with sectors and users to understand what uncertainty data and products they need and how they should be formatted. (*GOV, COM*)
- As NWS Web pages are modified to include probabilistic forecast information (see Obj. 3.4), develop training material and user feedback capabilities. *(GOV)*
- Develop material to train broadcast meteorologists (e.g., adapt material from Obj. 2.6) to communicate forecast uncertainty *(NGO)*

Begin to incorporate uncertainty elements into broadcasts *(Com)*

Medium-term (2-6 years):

- Using data from short-term results, provide test products and evaluate their effectiveness with more surveys, etc. Revise, based on feedback from first round. Repeat until process has converged on effective solutions to conveying uncertainty. (*GOV, ACA*)
- Formally train broadcast meteorologists to communicate forecast uncertainty through Certified Broadcast Meteorologist and other programs. *(NGO)*
- Develop short courses and presentations on using and conveying probabilistic information tailored to broadcast meteorologists. *(NGO)*
- Expand short course for other end users, such as emergency managers. *(NGO; GOV)*

Provide continuing education of certified consulting meteorologists in the context of energy usage, weather-related travel safety, infrastructure damage mitigation. *(NGO)*

Long-term steps (6+ years):

- Build upon and sustain business practices that include user feedback,

the consequences of misunderstanding and misuse may be significantly greater, involving large economic losses and, in the case of security agencies such as DHS and other emergency management agencies, involving potential injury and/or loss of life. *<u>Performance Measures and Targets</u>:* • *Web hits in a given time period* • *Viewership of digital cable channel that displays more detailed probabilistic weather information than conventional broadcasts.* • *Response/feedback rate within a given time period per new product/service released*	social science, and impact-based decision support. *(NGO)*

Objective 2.2: Prepare the next generation for using uncertainty forecasts through enhanced K-12 education

<table>
<tr><td colspan="2"><u>Description and Purpose:</u> To utilize new uncertainty information, it will be helpful to ensure that K-12 students understand some of the background concepts such as probability. The AMS will contact state school boards to suggest emphasizing more probability and statistics in high-school math curricula, and will develop and disseminate some relevant meteorology- and uncertainty-related problems to textbook manufacturers.</td></tr>
<tr><td>
<u>Need</u>: In order for our society to understand and use probabilistic information, primary and secondary education standards must include basic concepts in statistics and probability.

<u>Current Capability</u>: National math education standards dictate that students in grades K-12 “should be able to develop and evaluate inferences and predictions that are based on data” and “understand and apply basic concepts of probability.” The National Mathematics Advisory Panel recently recommended that high school algebra include material on combinatorics and finite probability. It is likely that the topic of uncertainty and use of probabilities in weather information only arises if students in math class happen to be given a probability example that has to do with weather; this is unlikely to happen unless the meteorological community can affect the content of textbooks that are used.
Many meteorological organizations are already involved in K-12 education, and it may be useful to leverage these already existing relationships. Resources and organizations include:
• UCAR/NCAR: Education and Outreach (http://eo.ucar.edu/); COMET/MetEd (http://www.meted.ucar.edu/comm_k12.htm) and links therein. Digital Library for Earth System Education (DLESE) (http://www.dlese.org); UCAR Digital Image Library (http://www.fin.ucar.edu/ucardil/).
• NSF National Science Digital Library (http://nsdl.org)
• AMS Education Program
• NOAA Office of Education (http://www.oesd.noaa.gov)
• Universities: University of Illinois Urbana-Champaign Urban Extension (http://www.urbanext.uiuc.edu/kalani/); Florida State University EXPLORES! (http://www.met.fsu.edu/explores/)
• Private: How the Weatherworks (http://www.weatherworks.com); The Weather Channel (http://www.weather.com/wxclass/education/); USA Today Web Science for Teachers (http://www.usatoday.com/weather/wteach.htm)

<u>Capability Gaps</u>: The NRC (2006) “Completing the Forecast” report recommended that uncertainty information be incorporated into all products disseminated to the weather forecast user. Without uncertainty education and training, many will be unable to fully use this information. Exposure to the basic concepts of probability and statistics as a child or adolescent, with some salient weather examples, may help students grow into educated forecast users, more capable of utilizing the extra uncertainty information.
</td><td>
<u>Performance Measures and Targets:</u> AMS Committee produces examples and test question, incorporated into DLESE (2012)

<u>Solution Strategy:</u> Prepare supplementary material on probability and statistics related to weather that can be incorporated into K-12 curricula so future students are better prepared to use and interpret probabilistic forecast information.

<u>Short-term(0-2 years):</u>
•Charter committee to develop sample problems that illustrate the concepts of probability and statistics in hydrometeorological forecasting. (NGO)
Develop an on-line repository. (NGO)

<u>Medium-term (2-6 years):</u>
• Work with other statistical organizations (e.g. American Statistical Assoc.) and school textbook manufacturers to incorporate uncertainty information. Encourage use of examples contained in repository. (NGO)
Contact state Ed Depts. and school boards on desired changes in forecast uncertainty products/services. (NGO)

<u>Long-term steps (6+ years):</u>
• Develop mechanisms to maintain contact with institutions involved in K-12 education and update these institutions on new developments in hydrometeorological uncertainty, appropriate to K-12 education. (NGO; ACA)
Obtain education-related (course-content) funding from NSF or related agencies. (NGO)
</td></tr>
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Objective 2.3: Revise undergraduate and graduate education to include uncertainty training

Background: The standards for meteorological education currently do not require much training on chaos theory and the fundamentals of ensemble prediction, probabilistic forecasting, and the use of uncertainty guidance in decision making. On the other side of the spectrum, cross-discipline education in the social sciences (e.g., psychology, economics, anthropology, communications) will provide meteorologists the skills to communicate uncertainty information effectively.

Need: Undergraduate and graduate students should have a basic understanding of chaos theory, fundamentals of ensemble predication, probabilistic forecasting and the use of uncertainty guidance for decision making, as well as a broad understanding in the social sciences. This will help them should they choose a career in forecasting. Students who are not versed in these topics will be less marketable, and those that are hired but who are uninformed will require extra training. Further, with graduate programs increasingly including research on uncertainty, an improved curriculum will prepare them to participate in this research. Cross-discipline studies are needed as the Enterprise stresses the effective communication of uncertainty information.

Current Capability: The course requirements for undergraduate and graduate degrees in meteorology / atmospheric science vary by college/university. The American Meteorological Society (AMS) recommends that bachelor degree programs include a suite of courses that cover a broad range of topics in atmospheric science, as well as prerequisites in calculus, physics, statistics, chemistry, computer science, professional writing and oral communication (http://tinyurl.com/5ueo9s). Similar coursework is necessary to obtain employment by the United States federal government as a meteorologist. These recommendations/requirements leave a lot of room for each college/university to develop unique course content. Thus, there are no specific requirements related to interpreting ensemble, probabilistic and uncertainty forecast information. At the graduate level, the local meteorology/atmospheric sciences department determines course requirements.
In the social sciences, there are few atmospheric science professionals with formal education in related disciplines. A workforce is optimized with cross-discipline expertise.

Capability Gaps: The atmospheric science curriculum at many universities does not include the relevant training in the theoretical and practical aspects of uncertainty. Statistical courses in probability are not required. There are few if any social science courses in typical meteorology undergraduate curricula.

Performance Measures and Targets:
- Addition of courses at top 15% of meteorological/atmospheric science college/universities
- Revise AMS standards for Bachelor's degree

Solution Strategy: Change hydrometeorological science courses to include material necessary to understand forecast uncertainty. Stress cross-disciplinary studies in the social sciences on use of forecast uncertainty.

Short-term(0-2 years)
- Build Web site for educators to share uncertainty training resources. This platform will serve as a bridge until textbooks can be updated to cover this material. *(ACA)*
- Post materials and lectures (e.g., at The COMET Program (http://www.comet.ucar.edu). *(NGO, ACA)*
- Develop student weather forecasting contests that apply probabilistic forecasting. *(ACA)*
- Develop recommendations for curriculum changes, e.g., students to take basic probability and statistics courses, statistical meteorology, and modify synoptic/dynamic courses to discuss chaos theory, and ensemble prediction methods. *(NGO)*

Encourage (create) opportunities for internships, field experiences, practicum research projects, etc., which emphasize generating and communicating forecast uncertainty. *(ACA)*

Medium-term (2-6 years):
- Assimilate recommended uncertainty material into courses currently offered. *(ACA))*

Long-term (>6 years):
- Develop mechanisms to maintain contact with institutions involved in post-secondary education, and update these institutions on new developments in hydrometeorological forecast uncertainty at a level appropriate to undergraduate and graduate education. *(ACA)*

Objective 2.4: Improve the presentation of government-supplied uncertainty forecast products and services

Background: For most users, the uncertainty forecast information they encounter will not be from digital sources such as the Weather Information Database (Objective 2.8) but rather through regularly available products. These products must convey that uncertainty information effectively.

Need: Determine specific formats for uncertainty products that do the best job possible of conveying the breadth of uncertainty information iconically, graphically, textually, and/or numerically. Also, for NWS applications, design a general "look-and-feel" for presentation of the products so that there is consistency, to the extent possible, common across diverse locations, product types, etc... This objective leverages the research performed in Objective 1.3, "identify the best methods for communicating forecast uncertainty," and uses test beds, Objective 4.6, for product testing.

Current Capabilities: For general weather forecast information, the NWS has designed a standard weather forecast page format; see http://tinyurl.com/29wvor for an example. This page contains a mix of iconic, numeric, text, imagery, and even a small amount of probabilistic information, conveyed through the PoP. There is also generally a consistent format across many of the NCEP Climate Prediction Center products, e.g., the color scheme for 6-10 day forecast uncertainty products at http://tinyurl.com/34ocd is the same general format as for a 3-month forecast. While the NWS home pages currently provide only a small amount of uncertainty information, its consistency from one location to the next makes it easy for users. This consistency should be emulated as these pages are upgraded to provide additional uncertainty information. There are also other selected uncertainty products such as the "cone of uncertainty" for hurricane forecasts.

Capability Gaps: There is virtually no established capability in standard graphical products for uncertainty in the NWS. Most of the products will be developed from scratch. There are some ideas for preferable ways of displaying data. The NRC report "Completing the Forecast" provided some ideas about how probabilistic information could be conveyed effectively. The World Meteorological Organization issued a publication entitled "Guidelines for Communicating Forecast Uncertainty" (http://tinyurl.com/676dyd). These documents are a starting point for a complex process of designing appealing new Web pages and Web services for uncertainty products.

Performance Measures and Targets:

- Products are tested by potential users during the development process in a "proving ground" environment with the assistance from social scientists.

Solution Strategy: Re-engineer government Web products to include uncertainty information with a standard look-and-feel based on best practices determined in collaboration with social scientists.

Short-term(0-2 years):

- Conduct social science studies (see also Obj. 1.1) focused on the NWS "Point-and-Click" public weather Web pages to determine how best to convey additional uncertainty information. *(GOV)*
- In consultation with social scientists, develop some prototypes of possible presentation formats for uncertainty information on government Web pages *(GOV)*

Medium-term (2-6 years):

- Test prototypes of uncertainty Web pages (see Obj. 4.4) and determine most readily accepted format. *(GOV)*
- Modify the NWS Web pages to display uncertainty information in this most readily accepted format. Note: revised Web pages should also allow sophisticated users to obtain more quantitative information, such as numerical tables of probabilities that could readily be entered into decision-making software; Web pages should also include training material (see Obj. 3.9). *(GOV)*

Long-term (>6 years):

- Continue to incorporate social science into standard research and development of uncertainty products and services *(GOV)*

Objective 2.5: Tailor data, products, services and information for private-sector customers

<table>
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<u>*Need*</u>: There is a need to communicate (oral, visual, written) forecast uncertainty and risk. Develop specialized uncertainty products to meet the needs of specific forecast user communities, such as the energy industry or television broadcasters. Also, provide novel visualization approaches for public or specialized Web pages. For the most part, commercial products will be tailored by industry specific to their commercial clients.

<u>*Current Capability*</u>: Most tailored forecasts are still deterministic, but some probabilistic offerings are now available. For example, at AER, Inc. ensemble forecasts are postprocessed for energy traders. Most commercial weather companies communicate information via their Web pages or through specific communication channels to their clients (radio broadcast, forecast for a client's event, etc.). Radio broadcast and oral communication do not involve visual tools; therefore, the forecast uncertainty needs to be expressed in words. For Website presentation or television broadcast, visual elements can be brought into play to demonstrate forecast uncertainty or to better communicate changes in weather. Probabilistic forecast information is widely conveyed by industry, yet the general public struggles with understanding the meaning of probability. This gap in understanding needs to be bridged (see Objective 3.4).

<u>*Capability Gaps*</u>: Customers may require more specific information about forecast uncertainty than may be available by the baseline set of products that will be produced by the NWS. For these customers to make optimal decisions, reliable and skillful probability forecasts are required that are tailored to match the required inputs of their decision processes. Visualizations tailored for specific applications can aid in quick, accurate decisions.

Most people can follow and understand a time series representation; however, this representation is under utilized in forecast communication, particularly to the general public. A forecast of 70% probability of precipitation that is mainly during a two-hour period during frontal passage may be better portrayed in time series than a 12-hour pictograph that carries the same probability value. In many instances, a time series graphic can better refine the actual risk or trend of risk.

Furthermore, in a string of pictographs showing daily or period forecasts, customers and the general public are often not cognizant of the fact that forecast accuracy decreases over time. Many people perceive Day 6 to have the same accuracy as Day 1, yet this is not true in reality.

<u>*Performance Measures and Targets*</u>: In the commercial sector, performance is generally measured by customer satisfaction, particularly those who pay for a tailored product. If greater forecast uncertainty can be conveyed through tailored product and the customer derives (or perceives to derive) improved performance, then the objective is met.

</td>
<td>

<u>*Solution Strategy*</u>: Promote continuous and close collaboration between the Enterprise and its customers. In the broadcast arena development of best practices to communicate uncertainty will be combined with soft education materials to enable the broadcast meteorologist to successfully deliver uncertainty information to the public. In the business arena flexible yet stable products are needed for integration into business processes. Business meteorologists will be provided with materials to educate and train their customers on the interpretation and use of uncertainty information.

<u>*Short-term(0-2 years)*</u>:

- Develop visualization techniques (i.e., time series) to communicate uncertainty that best fits the customer . *(COM)*
- Educate and train targeted customers who receive products about the meaning, use, and potential profitability of probability information. *(COM)*

<u>*Medium-term (2-6 years)*</u>:

- Publish best practices for the presentation of uncertainty. *(NGO)*
- Promote industry-wide acceptance of standard means of presentation of uncertainty information (in analogy to how sports or financial statistics are now presented fairly uniformly across all major news outlets. *(COM, NGO)*
- Develop a framework for long-term collaboration between the NWS and the Enterprise on the introduction of new or improved NWS information such as modeling system changes or other products. *(COM, GOV)*

<u>*Long-term steps (6+ years)*</u>:

- Continue refinement of broadcast presentation approaches for uncertainty information. *(COM, GOV)*
- Develop personalized weather "apps" that fuse probabilistic forecast information with individual preferences and risk tolerances. *(COM)*
- Routinely integrate probabilistic weather information into business processes. *(COM)*

</td>
</tr>
</table>

Objective 2.6: Develop and provide decision support tools and services

<u>Description and Purpose:</u> Decision support systems (DSS) provide a link between forecast information and user applications. The sophistication of DSS can vary greatly. Single value forecasts severely limit the utility of weather, water, or climate forecast information as they allow decisions made at a single level only (yes or no, based on whether an event is forecast or not). In contrast, the multiple scenarios in an ensemble support decisions to be made at multiple levels of certainty or probability, depending on the users' cost/loss considerations. More formal DSS systems can use either derived ensemble products (e.g., probability of an event), or the basic ensemble solutions as input. Through case studies, users can find the optimum decision criterion (i.e., threshold probability of a forecast event) at which they must take action that best exploits weather forecast information for their application.

<u>Need</u>: The availability of forecast uncertainty information for decision support and decision assistance will require extensive understanding and interpretation for different levels of decision makers.

<u>Current Capability</u>:
Only ad hoc services exist as needed from government agencies during high impact events (i.e. Red River flooding in 2009). Ad hoc use of technologies and on-site support to various state, local EOCs and FEMA through the NWS Incident Meteorologist program.

<u>Capability Gaps</u>:
- Communicating probabilistic information
- Frequency and accuracy of probabilistic estimates
- No standard skill set of support personnel
- Integrated water resource management
- Ecosystem Support
- Homeland Security/Air Quality
- Aviation/Space Weather/Tsunami
- Climate Services

NOAA's Disaster Response Center initiative

<u>Performance Measures and Targets</u>:
- User-driven automated decision support tools (# of sector-specific tools such as marine interests, fire management, etc.)

<u>Solution Strategy</u>: Develop forecaster tools that help forecasters provide critical users with optimally effective decision support.

<u>Short-term(0-2 years)</u>:
- Identify how hydrometeorological information is used to make decisions *(GOV, ACA,NGO, COM)*
- Determine which users/decisions can potentially benefit the most from probabilistic forecast information. *(GOV, COM)*
- Work with customers to develop decision-support tools for forecasters and their most critical customers, including impact-based, graphical information (see also Obj. 3.4). *(GOV, COM, ACA)*

<u>Medium-term (2-6 years)</u>:
- Work with critical customers to evaluate decision support tools (see Obj. 4.4) *(GOV, COM)*
- Implement decision support tools operationally for most critical customers *(GOV, COM)*
- Work with secondary customers to develop decision-support tools and evaluate (see Obj. 4.4) *(GOV, COM).*

Continue to survey for important new customers and determine whether new decision support tools should be created *(GOV, COM)*

<u>Long-term steps (6+ years)</u>:
- Implement decision-support tools operationally for secondary customers *(COM, GOV)*
- Continue to survey for important new customers and determine whether new decision support tools should be created *(GOV, COM)*

Develop intelligent information services to anticipate user needs/thresholds and to provide them with just the right information independent of the customer realizing the need *(GOV, COM)*

Objective 3.1: Improve the initialization of ensemble prediction systems

<table>
<tr><td colspan="2"><u>Background:</u> Ensemble prediction systems require an ensemble of initial conditions. Ideally, these comprise a sample from the distribution of possible analysis states, and reflect the flow-dependent uncertainties due to the synoptic conditions and the distribution of observations, past and present. Within the last few years, ensemble Kalman filter (EnKF) methods have been developed that, for the first time, provide an ensemble of initial conditions that are theoretically justifiable, unlike past methods such as “breeding” and “singular vectors.” However, EnKF methods are just beginning to be tested in a quasi-operational setting.</td></tr>
<tr><td><u>Need</u>: An ensemble of initial conditions that are accurate, that sample the range of possible true analysis states (there is inevitably uncertainty in the analyses, especially at the mesoscale), and that project upon growing forecast structures so that differences between member forecasts grow (appropriately) quickly.

<u>Current Capability</u>: NCEP currently runs an “Ensemble Transform” (ET) technique, an update to their “breeding” technique. Other centers still use breeding or singular vector techniques. The Canadians are the only ones running an operational ensemble Kalman filter.

<u>Capability Gaps</u>: The existing sets of initial conditions are typically designed primarily to grow quickly, but in doing so do not accurately reflect the flow-dependent analysis uncertainty. Sets of initial conditions that both grow quickly and which correctly sample analysis uncertainty are needed in order for ensemble prediction systems to produce more realistic uncertainty forecasts at all leads. While NCEP continues to pursue 4D-Var, the 4D-Var strategy will only produce a single best-guess analysis, not provide an ensemble.

<u>Performance Measures and Targets</u>:
(1) Reduced error of deterministic forecast from the ensemble-mean initial condition relative to deterministic forecast from current alternatives such as 3D-Var. Target is gain of at least 12-h lead time in precipitation and hurricane track forecasts by 2014.
(2) Improved uncertainty forecast scores (flatter rank histograms, sharper, more reliable forecasts, increased skill, especially for high-impact weather). Together with improvements provided by objective 2.2, the target is gain of at least 24-h lead time in skill of high-impact weather (heavy precipitation, hurricane track, etc.) by 2014.</td>
<td><u>Solution Strategy</u>: Develop ensemble data assimilation techniques, including improved methods for the treatment of model error in ensemble filters.

<u>Short-term(0-2 years)</u>:
•Perform quasi-real time tests during hurricane season and other high-impact events of an EnKF using a global forecast model. (GOV)
•Continue R&D on the treatment of model error and sampling error in ensemble filters. (GOV)
•Evaluate EnKF relative to 4D-Var for its ability to produce reduced-error initial conditions. (GOV; ACA)
Explore hybridization methods of variational and EnKF methods. (GOV; ACA)

<u>Medium-term (2-6 years)</u>:
•Transition EnKF into parallel testing/operations at NWP facilities. (GOV)
• Further develop and implement hybrid 4D-Var / EnKF methods. (GOV; ACA)
•Develop improved methods for initializing ensembles at the mesoscale, incorporating new, high-resolution data sets such as radar data (GOV, utilizing ACA from Obj. 1.3)

<u>Long-term steps (6+ years)</u>:
•Develop improved methods for initializing ensembles at the mesoscale, with perturbations that grow appropriately quickly and are consistent with analysis error (GOV, utilizing ACA from Obj. 1.3)</td></tr>
</table>

Objective 3.2: Improve forecasts from operational ensemble prediction systems

Background: Ensemble prediction systems are a fundamental way for producing uncertainty forecasts. Multiple versions of a model (or different models) are run from slightly different initial conditions, and/or parameterizations. They produce a range of possible future weather scenarios.

Need: Ensemble of future weather scenarios that provides reasonably sharp and reliable probabilistic forecasts, correctly accounting for uncertainties due to model error.

Current capabilities: Current-generation ensemble prediction systems in the US produce uncertainty forecasts that are biased and underestimate the forecast uncertainty. Partly this is because of the low-resolution of the forecast models, partly because of improper initial conditions (see objective 2.1) and partly because the ensemble prediction systems do not include effective treatments for the error introduced by model deficiencies. Currently, NCEP runs global and regional ensemble prediction systems. The global ensemble currently runs at T190 (approximately 80-km grid spacing) with 20 members; 4x daily. For comparison, ECWMF runs a 50-member global ensemble at T649, greater than 3 times the resolution of the NCEP global ensemble. NCEP also runs a regional, short-range ensemble with 21-members, 87-h forecasts with a model with ~32-km grid spacing. NOAA has experimentally evaluated a 10-member small-domain ~4 km grid spacing ensemble for severe weather applications on the Great Plains. NOAA also has a short-range, higher-resolution lagged ensemble available over the CONUS from the Rapid Update Cycle, which generates a new forecast every 1h. By 2010 this system will use the WRF model with a 13-km grid spacing. The US Navy and Air Force also have their own suites of operational forecast models, and some university run quasi-operational ensemble systems (e.g., the U. of Washington). Results from using the THORPEX Interactive, Grand Global Ensemble also indicate that more skillful, reliable forecasts may be possible through exchange of global ensemble forecast data.

Capability Gaps: The raw output from existing ensemble forecast systems do not provide reliable probabilistic forecasts in all circumstances. There are several root causes, including: (1) systematic model errors, grid resolution, and parameterizations of sub-gridscale physical processes (deep convection, boundary layer, surface layer, land surface, microphysics) often provide unrealistic estimates of the effects of the unresolved scales of motion, and their uncertainty. (2) poor initialization of the ensemble with model states that do not properly represent the uncertainty in the analysis (this latter topic is covered in objective 2.1).

Performance Measures and Targets:

- Comparisons with the much higher resolution ECMWF ensemble forecasts suggest that such improvements should result in a general 1-day improvement in forecast lead (i.e., a 5-day forecast as skillful as a current 4-day forecast), with greater improvements for many severe-weather phenomena. Accordingly (see also objective 2.1) the target is gain of at least 24-h lead time in skill of high-impact weather (heavy precipitation, hurricane track, etc.) by 2014.

Solution Strategy: Increase ensemble model grid resolution incorporating research results from Obj. 1.3; increase sharing of forecast data between operational facilities; and add a new, limited-area, high-resolution, high-impact event regional ensemble system.

Short-term(0-2 years):

- Exchange global ensemble forecast model output and develop products based on multi-model output *(GOV)*
- Develop higher-resolution global ensemble prediction systems. *(GOV)*
- Develop higher-resolution, short-range, limited-area ensembles *(GOV, ACA)*
- Test promising experimental ensemble forecast system techniques developed in academia (see Obj. 1.2) *(GOV)*
- Develop improved hydrologic ensemble forecast system models *(GOV; ACA)*

Develop hourly lagged ensemble forecast techniques for mesoscale models. *(GOV, ACA)*

Medium-term (2-6 years):

- Implement three-fold higher-resolution ensemble model systems. (SREF to ~10 km) by 2012. *(GOV)*
- Develop relocatable, 4-km high-resolution, explicit convection, limited-area ensemble forecast system for hurricanes, severe and fire weather *(GOV, ACA)*
- Continue to test promising experimental ensemble forecast system techniques developed in academia and implement best methods into operations. (see Obj. 1.2) *(GOV)*
- Compare performance of mesoscale lagged ensemble forecast systems to more conventional ensemble system designs. *(GOV, ACA)*
- Upgrade hydrologic forecast models, to produce reliable streamflow forecasts. *(GOV, ACA)*

Long-term steps (6+ years):

- Double ensemble forecast system horizontal resolution approximately every 8 years, consistent with Moore's Law. *(GOV)*
- Continue to test promising experimental ensemble forecast system techniques developed in academia, and implement best methods into operations. (see Obj. 1.3) *(GOV)*

Objective 3.3: Develop probabilistic nowcasting systems

Background: The accuracy of the first few forecast hours of NWP model guidance, including ensemble guidance, is often poor relative to observationally based methods as the NWP models develop internally consistent vertical motions. Beyond forecast lead times of several hours, the need for alternate forecast techniques is obviated as this so-called model "spin-up" process completes and ensemble systems are able to provide useful forecast uncertainty information.

Need: New techniques are needed to generate reliable probabilistic forecast information for forecast lead times of zero to several hours. This includes developing approaches for adding uncertainty estimates to current nowcast systems and variably weighting nowcast output with classical ensemble-based forecast products as a function of forecast lead time.

Current Capability: Several research groups have developed observationally based tools for making nowcasts. NOAA/MDL has developed "SCAN" software that makes short-range forecasts of severe weather and hail using regression relationships between radar reflectivity and observations of storms and hail. For severe weather, several tools involve the detection of significant features using radar or other remotely sensed data and then the extrapolation of this data using wind or derived motion vectors; and perhaps some development/decay mechanism (e.g., the NCAR/RAL's AutoNowcaster). Another nowcast system in the western US makes short-range extreme precipitation forecasts using expected wind and moisture-flux information and thermodynamic stability, estimating how much precipitation may occur as a column interacts with the complex terrain along the US west coast. As demonstrated with these two examples, typically the nowcast tools may be application- and location-specific.

A smaller body of work has been performed to date to develop *probabilistic* nowcast tools; some exceptions include the "S-PROG" technique (Seed, 2003, JAM, 42, p. 381) that uses a spectral decomposition model to produce scale-dependent temporal evolution of existing feature. Xu et al. (J. Amer. Stat. Assoc, v 100, pp 1133) discuss a Bayesian hierarchical probabilistic nowcast technique. John Williams and colleagues at NCAR have developed a prototype probabilistic nowcast technique based on a neural net. A NOAA-FAA-NCAR collaboration has produced a probabilistic nowcast tool for aviation, NCWF-2, "National Convective Weather Forecast, V2." Bowler et al. (2006 QJRMS) discussed a technique for blending probabilistic nowcasts together with short-range ensemble guidance.

Capability Gaps: The NRC report recommends the inclusion of uncertainty information throughout the spectrum of forecast products, including those at the shortest lead times. For these short lead times, most of the techniques have their roots in extrapolative techniques of existing features and may not properly account for stochastic aspects, especially new feature development or dissipation of existing features.

Performance Measures and Targets:
Consistent improvement of forecast skill using persistence as a baseline measure.

Solution Strategy: Develop non-NWP based probabilistic forecast methods based on observations and extrapolations, as well as techniques that combine observations and NWP guidance.

Short-term (0-2 years):
- Incorporate probabilistic elements into current deterministic nowcast algorithms, including enlarging existing deterministic forecast by making use of known forecast error statistics. (*GOV, ACA*)
- Begin to develop new techniques for generating probabilistic nowcasts. (GOV, ACA)

Medium-term (2-6 years):
- Perform intercomparisons of nowcast algorithms to determine which are most suitable for applications. (*GOV, ACA*)
- Based on the performance and evaluation of these, implement the most appropriate probabilistic nowcast algorithms. *(GOV, ACA, Com)*
- Develop tools for blending together observationally-based nowcast and NWP-based guidance as forecast lead increases. *(GOV, ACA)*

Long-term (>6 years):
- Evaluate and implement techniques for blending together nowcast and NWP based guidance. (*GOV)*
- Based on improvement of data assimilation and numerical weather prediction systems, decrease emphasis on separate nowcasting tools, and develop more NWP- based approaches. *(GOV, ACA)*

Objective 3.4: Improve statistical postprocessing techniques

Background: Statistical postprocessing here refers to the adjustment of the current operational forecast using relationships derived from past forecast and observed/analyzed data. These techniques are applied in order to ameliorate the deficiencies in the raw model output, which, in the case of ensemble prediction systems, are typically manifested in biased, overly sharp uncertainty forecasts. Statistical postprocessing can also "downscale" the coarse-resolution output to the fine detail available at an observation location or to a high-resolution analysis.

Need: Uncertainty guidance must be reliable and skillful in order to be widely used and accepted. Uncertainty estimates from unadjusted ensemble models are liable to be sub-optimal due to the small ensemble size, the biases inherent in forecast model(s) and methods used to initialize the ensemble, and the comparatively coarse grid spacing used in current ensemble prediction systems. While improved ensemble prediction methods (see Objective 2.2) may reduce the need for postprocessing, they will never completely eliminate it. A comprehensive program is thus needed to determine the optimal calibration techniques across the spectrum of high-impact applications, develop routine methods for computing the supporting data sets, and implementing the calibration techniques. Additionally, information of interest to users (e.g., some esoteric variables at a particular point in space and time) may be different from the information generated by numerical models (i.e., a grid-box average of standard NWP variables). Therefore numerical model output, even if bias free, typically requires some sort of "downscaling" to increase utility.

Current capabilities: Dissemination of statistically based guidance in the NWS has a long history as "Model Output Statistics" (MOS). MOS uses regression relationships based on prior forecasts and observations to statistically adjust current numerical guidance. These regression relationships correct for model bias and can implicitly perform a statistical downscaling, adjusting the sub-gridscale weather to be colder and wetter on the mountain peaks inside a model grid box, for example. Most existing MOS products are deterministic, though implicitly the MOS regression analyses produce uncertainty forecast information, and this guidance could be disseminated with little additional effort as a baseline uncertainty product. More recently, with the advent of ensemble-prediction techniques, a variety of new extensions to the basic MOS techniques have been developed that leverage the extra information in the ensemble. So-called "Ensemble-MOS" techniques may improve estimates of the most likely outcome in situations where the ensemble mean provides a more accurate estimate than a deterministic forecast (this characteristic is common at leads longer than a day or two). If the ensemble spread provides information on the situation-dependent uncertainty (high spread is related to lower forecast skill, low spread to higher skill), then ensemble-MOS techniques may provide improved, weather-dependent uncertainty estimates as well. A variety of ensemble-based calibration techniques are currently being developed and tested at many NOAA facilities (for example, MDL, NCEP, ESRL, and OHD), and at many universities. NCEP has its own bias-correction technique running operationally on NAEFS forecasts.

For every-day weather such as surface temperature at short forecast leads, a

Solution Strategy: Develop supporting observational and reforecast data sets needed for postprocessing, and develop and implement improved statistical postprocessing techniques to improve the objective probabilistic forecast guidance.

Short-term(0-2 years):

- Develop a comprehensive implementation plan for statistical postprocessing, including defining requirements. *(GOV)*
- Define which observational / reanalysis data set(s) will be used for testing techniques. *(GOV)*
- Develop a robust global reforecast data set, and observations/analyses as needed, and make this readily available to researchers *(GOV)*
- Determine the optimum reforecast training sample size, a compromise between postprocessing skill improvements (favors a large sample) and computational cost (favors a limited sample). *(GOV)*
- Test, refine, and compare postprocessing algorithms. *(GOV, ACA)*

Medium-term (2-6 years):

- Begin the regular generation of reforecast data sets corresponding to current operational models, based on previously determined optimal reforecast configuration. *(GOV)*
- Implement most promising postprocessing techniques for common variables. (*GOV*, *ACA)*
- Continue to test, refine, and compare postprocessing algorithms, but now using emerging standard verification techniques (see Obj. 3.8). *(GOV, ACA)*
- Develop new postprocessing techniques for more specialized variables.
- Compare objectively produced postprocessed forecast products to those modified by human forecasters (see Obj 3.6) using standard verification techniques (see Obj 3.8). *(GOV)*
- Begin regularly monitoring the quality of postprocessed vs. raw numerical guidance. *(GOV)*

Long-term steps (6+ years):

- Continue the regular generation of reforecast data sets corresponding to current operational models (*GOV*)
- Implement most promising postprocessing techniques for more specialized variables. (*GOV*).

Develop specific postprocessing techniques for more specialized products with

variety of calibration techniques appear to perform relatively competitively and small training samples appear to be adequate. For rare events and long-lead forecasts, more training samples (perhaps many years or even decades of "reforecasts" from a stable model/data assimilation system) are needed, and the calibration technique of choice may depend upon the particular application and data at hand. The need for large training data sets from a stable model conflicts with the desire to rapidly implement improvements in ensemble forecast systems. There are two possible compromises: (1) maintain one model that is rapidly upgraded but unaccompanied by reforecasts and another model that is only occasionally updated (say, every third year) but which has an accompanying reforecast data set. Forecasters could choose which products to utilize; and (2) conduct a more limited set of reforecasts in real time for whatever model is being run operationally, thereby devoting a percentage of the CPU time for the ensemble forecast system to the accompanying reforecasts as is the current ECMWF practice. *Capability Gaps*: There are some important limitations in using current MOS-based uncertainty guidance and in the guidance produced directly from unadjusted ensemble output. Existing MOS guidance is based mostly on deterministic forecast model output rather than an ensemble and could be improved through inclusion of ensemble information. While methods used in the traditional forecast process often suppress realistic variability on fine temporal and spatial scales for the sake of reduced errors in a single forecast, the inclusion of such variability in downscaled ensemble forecasts (while ensuring the grid-scale characteristics are unchanged) is desirable and can improve the realism, skill and utility of forecasts. *Performance Measures and Targets*: Consistent improvement of forecast skill using persistence as a baseline measure.	less standard variables and appropriateness of existing approaches. *(GOV)*

Objective 3.5: Develop non-statistical postprocessing techniques

<table>
<tr><td colspan="2"><u>Background:</u> Many forecast variables that are of interest to users may not be produced directly by the ensemble prediction systems, variables such as the amount of aircraft icing that can be expected in flight, or cloud ceiling.</td></tr>
<tr><td><u>Need</u>: Many of the forecast variables that will be of interest to Enterprise user and customers, such as turbulence and icing forecasts for aviation interests, are not directly predicted or output by numerical models. Their presence must be diagnosed from physical relationships with other available model prognostic variables (this objective) or related statistically to the forecast variables (see objective 2.4), or combinations thereof. Postprocessing methods will be needed that can produce reliable, skillful forecasts of these uncertainty elements.

<u>Current capabilities</u>: Considering aviation as an example, a variety of groups (e.g., NCAR/RAL and MIT's Lincoln Lab) have developed algorithms for estimating aviation-related parameters from the weather model output. Many of these algorithms have been implemented for deterministic forecasts in the NWS at the Aviation Weather Center.

<u>Capability Gaps</u>: Little has been done to test and verify probabilistic algorithms. Implicitly, an ensemble of aviation-related parameters could be diagnosed from short-range ensemble forecasts. However, suppose an ensemble of turbulence or icing forecasts are generated by applying the diagnostic algorithms to each member of a weather forecast ensemble. This diagnostic ensemble will be biased and unreliable as long as the input weather ensemble itself produces biased and unreliable ensemble forecasts for the explicitly forecast variables; and even if the ensemble's forecast of model variables are reliable, this provides no guarantee that the diagnosed output will be reliable. The community does not yet know which methodologies will lead to skillful, reliable probabilistic forecasts of such non-observed variables. The evaluation process is further hindered by a paucity of observations. For example, if severe turbulence is forecast, a plane will usually be routed around the volume with the turbulence, and no verifying observations of this high-impact event will be available.

<u>Performance Measures and Targets</u>:
• Consistent improvement of forecast skill using persistence as a baseline measure.</td>
<td><u>Solution Strategy</u>: Convert current deterministic forecast products that diagnose specialized forecast variables from model output into probablisitic products. Determine best methods for dealing with ensemble system bias with these algorithms, and implement best methods.

<u>Short-term(0-2 years):</u>
•Test and evaluate the simple method of forming an ensemble of diagnosed values from ensemble model outputs. (GOV)
•If bias-corrected members are available (see Objective 3.4 above), determine whether the input bias-corrected data produces a more reliable and skillful diagnosed ensemble. (GOV)

<u>Medium-term (2-6 years):</u>
•Test the suitability of a preliminary suite of non-statistical techniques and implement if appropriate (GOV).
•Develop new techniques that produce appropriate sub-gridscale probabilistic forecast information based on the calibrated grid-scale information. (GOV)

<u>Long-term steps (6+ years)</u>:
•Evaluate and implement the most promising techniques. (GOV, ACA)</td></tr>
</table>

Objective 3.6 Develop and probabilistic forecast preparation and management systems

<table>
<tr><td colspan="2"><u>Background:</u> Automated probabilistic forecast guidance, e.g. from ensembles and statistical postprocessing, may be improved through incorporating forecaster judgment. Computer tools are needed that will allow forecasters to modify objective guidance.</td></tr>
<tr><td>
<u>Need</u>: The specific role of human forecasters in the day-to-day generation of probabilistic forecasts will depend on their ability to add value to raw and/or postprocessed ensemble model output. In general, the role of human forecasters likely will expand from the current routine preparation of single-value (deterministic) forecasts to monitoring, quality controlling, and interpreting probabilistic forecast guidance; identifying and assigning confidence to alternate forecast scenarios; and when appropriate (e.g., during high-impact events) manually modifying automated model guidance. These new functions will require probabilistic forecast preparation systems and tools that allow humans to interpret and manipulate entire ensemble distributions.

<u>Current Capability</u>: Current forecast preparation systems and tools aiding human forecasters are focused on generating single-value forecasts. Tools aiding human forecasters to monitor, interpret, and modify forecast uncertainty information are limited to NWS forecast preparation systems, which are in the process of a systematic upgrades of the Advanced Weather Interactive Processing System (AWIPS). This workstation, which will serve all NWS field offices, will incorporate capabilities for ensemble data processing that currently exist only on the platform used by the National Centers (Hydrometeorological Prediction Center, Storm Prediction Center, Aviation Weather Center, etc.). These capabilities include a blender tool that allows forecasters to interactively and subjectively weight certain ensemble members, and the ability to compute anomalies of certain fields computed against multi-decadal climatologies.

<u>Capability Gaps</u>: Probability forecast preparation systems must have the following attributes, beyond those currently available only to the National Centers: ability to acquire guidance products and ensemble model members and a verification record of past performance; a variety of display methods to visualize and manipulate guidance products and other forecast inputs, such as “spaghetti” plots displaying a single (or few) contours from multiple models and “plume” diagrams representing time series plots from multiple models, valid for a single point; “postage stamp” displays presenting miniature image or contour plots from many models arranged in a rectangular matrix; methods for the local calculation of estimated probability distribution functions (PDFs); and an interactive tool allowing the forecaster to manually edit PDFs and then propagate these adjustments to adjacent points in space and/or time; statistical tools for computing PDF attributes; and the ability to post final gridded forecast products for public consumption.

<u>Performance Measures and Targets:</u>
Determine, based on verification results, skill added by forecasters for particular weather elements or forecast periods (e.g., short-term or longer-term). Attention should be focused on longer developing high impact events (e.g., winter storms, heavy rainfall)
</td><td>
<u>Solution Strategy:</u> Develop and implement workstation tools that allow forecasters to examine and modify objectively produced ensemble forecast guidance.

<u>Short-term(0-2 years):</u>
•Conduct workshop(s) to determine development priorities and survey forecasters about how they use prob. forecast information. (GOV; NGO; ACA)
•Complete plan to include ensemble information in AWIPS (GOV)
Develop experimental tools that allow the graphical editing of probabilistic forecasts (GOV)

<u>Medium-term (2-6 years):</u>
•Gather forecaster feedback on workstation requirements. (GOV)
•Implement new gridded ensemble products on the NDFD (GOV)
•Evaluate forecaster-modified guidance produced with experimental forecast tools relative to objective guidance (see Obj. 3.4) (GOV)

<u>Long-term steps (6+ years):</u>
•If warranted, based on forecast evaluation, implement forecast editing tools in AWIPS. (GOV)
•Refine ensemble display and graphical editing tools as necessary. (GOV
</td></tr>
</table>

Objective 3.7 Train forecasters

Background: Operational government and private-sector forecasters produce mostly deterministic products and may mostly thinki deterministically, too. Forecaster should be trained for their responsibilities in a new era where uncertainty forecasting is an important part of their job.

Need: To make best use of probabilistic forecast information, forecasters must have detailed knowledge of the general underlying theory behind and of the performance of ensemble prediction and other probabilistic systems, the weaknesses in the current operational systems, and what can and cannot be corrected with statistical postprocessing. Further, this knowledge must be kept fresh—everything potentially changes as the model and postprocessing systems change. This training must be done at all time and spatial scales from continental and seasonal scales to county and short-fuse warning scales for severe local storms and tornadoes. Forecasters will also need to be trained in the new uncertainty forecast preparation tools they will use.

Current capabilities: Some basic training on the theoretical basis for ensemble prediction systems has been developed, for example, at UCAR's Cooperative Program for Meteorological Education and Training (COMET) [http://www.comet/ucar/edu], the Meteorological Service of Canada (MSC) [http://tinyurl.com/56j5pz] and the European Center for Medium-Range Forecasting (ECMWF) [http://tinyurl.com/57q9o7]. The COMET training is included in the NOAA Learning Management System as well, thus allowing for feedback to the learner on how well they understand this theoretical material.

Capability Gaps: While some NWS forecast offices have taken initiative to develop training cases using EPS, insufficient formal training has been developed for use of EPS in the forecast process and other operational applications. Moreover, such efforts have not typically been shared, perhaps because they are locally based and it is assumed that these cases will not have applicability in other locations. Additionally, the operational forecasting culture in the NWS and elsewhere continues to generally be deterministic, though there has been some experimental probabilistic forecasting done in the government and commercial sectors. No generally accepted format for delivering probabilistic forecasts to the public is currently in place. This includes the widely used National Digital Forecast Database (NDFD) produced by NWS. Without universally accepted formats for probabilistic forecasting in place, it is difficult to develop training in this.

Performance Measures and Targets:
- *Uncertainty training curriculum implemented online and/or at location such as COMET (2011). 25 percent of NWS, military forecasters trained by 2012, additional 25 percent each year thereafter.*

Solution Strategy: Develop and run a program to train operational forecasters in how to use, interpret, and convey probabilistic forecast information, and how to work with users to help them make effective decisions.

Short-term steps (0-2 years; lead: government):
- Identify Enterprise collaborators. *(GOV)*
- Identify existing Web-based training on uncertainty NWP. *(GOV)*
- Identify best practices in other disciplines using uncertainty. *(GOV; ACA)*
- Develop in-person and online training materials. *(GOV)*
- Obtain operational reviewer feedback on training. *(GOV; ACA)*
- Develop training courses and position description requirements for training and hiring proper support personnel. *(GOV)*

Medium-term (2-6 years; lead: government):
- Run uncertainty training courses for forecasters including Weather Event Simulator (WES) cases. *(GOV)*
- Identify good cases for future training material *(GOV; ACA; NGO)*

Long-term steps (6+ years; lead: government):
- Sustain training developed over the mid-term to remain current and relevant to forecast operations. *(GOV)*

Objective 3.8: Develop probabilistic verification systems

Background: The weather enterprise currently evaluates models and generates weather forecasts with deterministic metrics. Once forecasts are expressed with uncertainty information, they will need to be evaluated using metrics that quantify the skill of uncertainty forecasts.	
Need: The enterprise needs a comprehensive, agreed-upon set of standards and software algorithms for uncertainty verification. Currently, forecast verification methods focus on verifying the best single-value estimate. Probabilistic forecast verification techniques must be developed and/or applied that will assess the characteristics of uncertainty forecasts and provide quantitative feedback to ensemble developers, forecasters, service providers, and end users to aid in interpretation and decision-making. Statistics generated from these techniques are needed to serve as a reference for user expectations, guide future improvements, and assess the value added during each step of the forecast process. *Current capabilities*: A variety of verification methodologies are currently used to assess forecast uncertainty products. These include measures of reliability such as the rank histogram and reliability diagrams, and measures that incorporate probabilistic forecast accuracy/greater specificity than climatology, such as the Brier Score, Ranked Probability Skill Score, and the Relative Operating Characteristic, and end-user relevant metrics such as Potential Economic Value diagrams. *Capability Gaps*: While there is general agreement that it will be important to monitor the characteristics of both reliability and sharpness (specificity) in probabilistic forecasts, there is no universally agreed-upon set of metrics that provide a comprehensive diagnosis of forecast uncertainty. Inter-comparisons are currently complicated by the use of different data sets by different model developers, verification on different grids, and comparisons of ensembles of different sizes. Further, while metrics have been developed that are appropriate for assessing some aspects of uncertainty forecasts, such as their reliability, other aspects such as event timing and forecast covariance in time and space are not standardized, or even developed. Another problem is that even for the basic uncertainty statistics, their availability varies widely. For operational forecasts, a common but not universal practice is to post verification scores to a Web page. Verification information from non-governmental forecast producers typically is difficult to obtain. *Performance Measures and Targets:* • Publication of an uncertainty verification manual (2012). • Version1.0 of uncertainty forecast verification software library (2013) • First results from verification clearing house (2014).	*Solution Strategy:* Develop forecast uncertainty verification standards and best practices. *Short-term(0-2 years):* •Continue research into new verification methods. *(GOV; ACA)* •Work with social scientists, partners, users to identify meaningful verification products, such as visual comparisons between observations and forecasts. *(GOV; COM; ACA)* •Form a panel of verification experts, and have them begin to formulate a standard reference for the verification of probabilistic forecasts. (*NGO*) *Medium-term (2-6 years):* •Develop an "uncertainty verification manual" that specifically indicates how each metric is to be computed. *(NGO, GOV, ACA)* •Build a standardized library of routines based on the uncertainty verification manual, as well as software for the display of verification data. *(NGO, GOV, ACA)* •Make the verification data and software publicly available. *(NGO, GOV, ACA)* •Institute a verification "clearing house" where verification results are made available. *(GOV)* Develop prototype probabilistic verification packages for particular applications, such as for aviation forecasts. *(GOV)* *Long-term steps (6+ years):* •Develop and test new uncertainty verification techniques as specialized new products are developed *(GOV, ACA)*

Objective 3.9: Include digital forecast uncertainty information in database and access systems

Background: Sophisticated users will need an interface to the uncertainty forecast information. This will be handled by including digital probabilistic forecasts and other forecast uncertainty information in the "Weather Information Database" that NOAA plans to build

Need: Currently, hydrometeorological observations and forecast products and information flow in various formats and via numerous push-pull technologies from their originating sources to partners, customers, and users inside and outside of the Enterprise. This direct, from source-to-user information flow is not expected to diminish necessarily in the future. However, more powerful computational and telecommunications technologies now are enabling repositories of "one-stop-shopping" of archived and real-time data and information. The NWS already is providing gridded mosaics of sensible weather elements in its' so-called National Digital Forecast Database (NDFD). This concept is expected to expand to include more parameters and into four dimensions (3 space and 1 time dimension). Moreover, the Federal Aviation Administration, NOAA, and other federal agency partners are envisioning using this weather information data storage approach to support the Next Generation Aviation Traffic Management System (NextGen). This so-called "4-Dimensional Weather Information Database" (WIDB) will contain real-time observation and forecast data. The WIDB will be a net-centric (or net-enabled) virtual repository with no single physical database or computer allowing information to be pushed to known users and be made available to be pulled by others. Including probabilistic forecast information in the WIDB is already a requirement for NextGen decision making. The Weather Information Database (WIDB) will contain continuously updated weather observations, high resolution (in space and time) analysis and 4-dimensional (x,y,z,t) forecast information, and will initially be aviation-focused for the Next Generation Air Transportation System (NextGen). Initial NextGen requirements state that all forecast products have probabilistic attributes. However, the probabilistic forecast output will be available for other users to integrate into their own decision support tools (e.g., emergency managers looking to define evacuation thresholds). The need is to provide probabilistic information into the WIDB, where partners, customers, and NWS forecasters can access probabilistic weather forecast information to integrate into decision support systems or other forecast applications.

Current capabilities: The current NWS NDFD system is a precursor to this expanded functionality, acting as the NWS flagship repository of gridded forecasts. In addition, NOAA Operational Model Archived Distributed System (NOMADS) distributes NCEP's operational data sets to researchers and the public.

Capability Gaps: Probabilistic forecast information is currently not integrated into decision support systems, and is limited in other forecast production systems (e.g., AWIPS). Steps in the forecast process do not exist that ensures consistency among probabilistic forecast information, as well as with other "deterministic" forecasts. The NextGen concept for the SAS is a response to this forecast gap.

Performance Measures and Targets: All decision support systems have capability to ingest probabilistic forecast information. 100% consistency in probabilistic forecast information in relation with the full array of products and services (elimination of contradicting weather forecast information)
General probability forecasts for the following elements: ambient temperature, dew point temperature, wind direction, sustained wind speed, wind gust speed, surface pressure, precipitation amount, sky condition.
Aviation-based probability forecasts for the following elements: ground temperature, runway surface temperature, wind squall speed, obstruction to vision, convection, in-flight icing.

Solution Strategy: Add probabilistic grids to NWS' NDFD, leverage planning and development of NextGen's WIDB, and eventual extension to an environmental information database.

Short-term(0-2 years):
- Develop common data standards and protocols (e.g., term lexicon). (*GOV*).
- Add forecast probability grids to NDFD. *(GOV)*
- Develop specification and implementation plan for probabilistic information in WIDB, indicating variables, spatial/temporal resolution, etc. (*GOV*)
- Develop techniques to synthesize probabilistic forecast information from various sources (different forecast systems, obs., human-modified guidance, etc.). *(GOV)*

Medium-term (2-6 years):
- Implement preliminary techniques for synthesizing probabilistic forecast information from various sources. *(GOV)*
- Integrate WIDB probabilistic information into Air Traffic Management Systems. *(GOV)*

Long-term steps (6+ years):
- Meet all probabilistic NextGen requirements. *(GOV)*
- Provide full network connectivity ensuring consistent information use across service areas and user groups. *(GOV)*
- Upgrade techniques for synthesizing information from various sources.

Upgrade spatial / temporal resolution of WIDB as warranted by user requirements. *(GOV)*
Migrate to Environmental Information Database. (*GOV*)

Objective 4.1: Acquire necessary high performance computing

<table>
<tr><td colspan="2"><u>Background:</u> Many of the other strategic goals' objectives, such as the predictability studies (Objective 1.1), ensemble design (Objective 1.2), operational ensemble initialization and prediction (Objectives 2.1 and 2.2), and statistical postprocessing (Objective 2.4) require high-performance computing.</td></tr>
<tr><td><u>Need</u>: Uncertainty forecasts will be based largely upon ensemble predictions and the postprocessing of them. These operational ensemble predictions in turn require ensembles of initial conditions and a set of knowledge about predictability and the optimal techniques for uncertainty forecasting. All of these steps require high-performance computing. The NWS is behind other competing centers in how much high-performance computing is devoted to ensembles. In order to provide uncertainty forecasts that are state-of-the-art, a large increase in computing resources will be needed.

<u>Current Capability</u>: NCEP currently runs a suite of ensemble forecast systems; see Objective 2.2 for a description of the current suite. However, in comparison to other operational centers, NCEP devotes a much smaller number of CPU cycles to their ensembles. For example, ECMWF currently runs a larger global ensemble (51 members, vs. 21 for NCEP), at approximately three times higher resolution (T399 in week 1 vs. T126), and includes the regular production of real-time reforecasts that can be used for calibration (however, NCEP runs its system 4 times daily to ECMWF's twice daily). Overall, ECMWF dedicates approximately 50 times more computational resources to the production of its global medium-range ensemble than does NCEP. Without a computer upgrade, some improvement in uncertainty products in the US may be possible by sharing ensemble forecast data with other countries and with the US military (see description of NUOPC and GIFS in Obj 2.2). Accordingly, NCEP has worked out cooperative agreements to exchange ensemble forecast data with Canada and hopes to share forecast data with the US Navy and Air Force in the coming years.

<u>Capability Gaps</u>: Despite the advances that may be possible by sharing multi-model ensemble forecast data, the production of skillful, reliable probability products cannot be achieved in full without a massive increase in computational resources dedicated to the production of improved uncertainty forecasts.

<u>Performance Measures and Targets</u>:
• Track model resolution and ensemble size relative to state-of-the-art. Acquire high-performance computing to support increases in resolution from, e.g., current threefold coarser resolution to comparable resolution by 2016.</td>
<td><u>Solution Strategy</u>: : Acquire more computer resources.

<u>Short-term(0-2 years)</u>:
•Determine CPU cycles necessary to run global, regional, and extreme-event systems envisioned in Objectives 3.1, 3.2, as well as the reforecasts necessary for calibration in Objective 3.4. (GOV

<u>Medium-term (2-6 years)</u>:
•Procure and install HPC sufficient to carry out Objectives 3.2 and 3.3. (GOV)

<u>Long-term steps (6+ years)</u>:
•Regularly upgrade HPC roughly in accordance with Moore's Law (a doubling of CPU power approximately every 2 years). (GOV)</td></tr>
</table>

Objective 4.2: Establish a comprehensive archive

Description and Purpose: Build a readily accessible public archive of past ensemble forecasts and verification statistics for operational forecast models to facilitate the calibration (statistical adjustment) of ensemble forecasts, the ensemble technique development process, and for use in training.

Need: Information from past forecasts allows for identifying and correcting forecast errors. Thus the primary requirement for a comprehensive archive is to make readily available the training data needed for statistical postprocessing (Obj 2.3) and tailored product development (Obj 3.5). For these purposes past forecasts, observations, and analyses, are required. In some cases a few weeks of data are sufficient but to make useful adjustments for high-impact, but rare events, years or decades of data from stable models are required (see Obj 2.3). The archive will also be useful for providing data for sufficient case studies to improve ensemble prediction systems (Obj 2.2) and to support predictability research (Obj 2.1). Finally, an archive provides past cases that can be used to educate university students (Obj 1.3), customers (Obj 1.6), and forecasters (Obj 1.5). For example, forecasters commonly learn how to improve their forecasts of high-impact events by studying the model performance and systematic error characteristics of similar past cases.

Current Capability: NOMADS, the NOAA Operational Model Archive and Distribution System, is NOAA's current system for storing numerical forecast guidance. NOMADS has been storing all NCEP operational ensemble outputs (in GRID format) since 2007. The files are stored in fast-access storage in near-real time. As the files age, they migrate to off-line storage, but are still easily, although not so quickly accessible (see Obj 3.3). NOAA has a cooperative agreement with the Meteorological Service of Canada (MSC) to share ensemble forecast information and derived products through a program called GIFS (the Global Interactive Forecast System). Through this program, MSC ensemble data is available on NOMADS as well. NOAA is also attempting to develop cooperative agreements to share forecasts with the US Navy and Air Force through NUOPC (National Unified Operational Prediction Capability). The THORPEX Interactive Grand Global Ensemble (TIGGE) currently archives a base set of global medium-range ensemble forecast and analysis information from nine different forecast centers worldwide. TIGGE archive facilities are currently located at ECMWF, NCAR, and CMA (China Meteorological Agency

Capability Gaps: Very large data storage is required. To limit the amount of data transported to clients, a user interface that allows for some aggregation would be desirable (see Obj. 4.3). Statistical postprocessing works best if the same systems (observing, modeling, and data assimilation systems) are used to prepare the historical data as in the system providing the current data. Creation of a reforecast data set that matches the current model requires a significant amount of computer resources.
For this purpose then it should not be necessary to maintain archive data that corresponds to a model or model version that is no longer operational. However, for forensic purposes, all the data that was used to prepare actual forecasts should be archived, but the timeliness requirements to access such data are considerably relaxed.

Performance Measures and Targets:
- Number of days of all forecast data produced that can be maintained online. A target is 45 days.

Solution Strategy: Expand NOAA's NOMADS system so it provides ready access to ensemble predictions, postprocessed guidance, analyses, observations, and other forecast uncertainty information.

Short-term(0-2 years):
- Determine hardware and software resources necessary for a comprehensive archive, allowing for anticipated growth; obtain resources and install the system. *(GOV)*
- (Ideal) Archive full model output at high temporal resolution. (Practical) Query relevant members of the community (to determine what subset of data must be kept on fast storage. Archive this subset on fast storage, and the rest on slow storage. *(GOV)*

Medium-term (2-6 years):
- Upgrade NOMADS system to accommodate higher temporal and spatial resolution output. *(GOV)*

Long-term steps (6+ years):
- Expand user interface to archive to allow more analytic services, .e.g., the ability to derive results using archived data. *(GOV)*

Objective 4.3: Ensure easy data access

Description and Purpose: Data access systems must be developed that are capable of transferring very large amounts of data from provider to client, and that allow these data to be parsed into subsets, transformed, and reformatted prior to the transfer to the client. For some applications the important transformation will be interpolating the data cube to an observational set.	
Need: Client application, R&D, and R2O all require access to the data archive. For client applications individual postprocessing algorithms will be executed. R&D and R2O will require data from past cases. *Current Capability*: A number of current projects are exploring facets of ensemble data access. These include • The NOAA National Operational Model Archive and Distribution System (NOMADS) is a Web-services based project providing both real-time and retrospective format-independent access to climate and weather model data [http://nomads.ncdc.noaa.gov]. NOMADS provides applications/Web services for variable and area sub-setting. • The Unidata Local Data Manager (LDM) is a collection of cooperating programs that select, capture, manage, and distribute arbitrary data products. [http://www.unidata.ucar.edu/software/ldm] • The Global Interactive Forecasting System (GIFS) plans to build on real time data access capabilities and provide real time probability products based on ensembles stored in TIGGE and possibly other systems. Some of these products may be generated in real time in response to online requests, requiring capabilities like NOMADS. • The Unidata Internet Data Distribution (IDD) is a peer-to-peer (P2P) system designed for disseminating near real-time earth observations via the Internet. IDD is based on LDM, is designed for real-time distribution, not archival, but could be considered a prototype P2P system for observational archives. [http://www.unidata.ucar.edu/software/idd] Current trends include the distribution of services on scalable servers, and the provision of transforming and sub-setting service applications (e.g., OPENDAP) for user convenience and to conserve bandwidth. In terms of applications, NOMADS already allows the user to calculate the probability of a particular weather event (e.g., probability of frost) and setting alarms—all on the server side. [http://nomads.ncdc.noaa.gov/data.php?name=ensembles]. *Capability Gaps*: Without adequate access, data in archives will not be used. Larger data transport capabilities will be required. More flexibility on the server side will be needed. For example, producers might allow operational postprocessing codes to run on the producer systems to reduce bandwidth requirements.	*Performance Measures and Targets:* Time to transmit forecasts to clients will always be a key performance metric. This should be measured in time since the forecast begins, not in time since the forecast ends since data for day one of the forecast can be transmitted while the forecast proceeds to day two.. *Solution Strategy:* Continue to evolve data access services to conserve bandwidth based on varying combinations of speed and agility. *Short-term(0-2 years):* • Collect information on data requests to guide future developments of currently existing distribution systems. *(GOV)* *Medium-term (2-6 years):* •Implement requirements defined in short-term and continue requirements definition. *(GOV)* *Long-term steps (6+ years):* •Keep archive and user interface capability at pace with model and usage growth. *(GOV)* •Build robust, flexible, and extensible system, and include analytic services (i.e., results derived from the archive) *(GOV)*

Objective 4.4: Establish a forecast uncertainty test bed(s)

<table>
<tr><td colspan="2"><u>Description and Purpose:</u> Implement an ensemble product test bed, a place where model developers, forecasters, and users can interact prior to product implementation to discuss the efficacy of experimental uncertainty products and visualization techniques. Feedback from the test bed would be collated by an independent third party and may result in an "implement" recommendation for a new product, or a "needs more refinement." Such objective feedback is especially crucial for the new suite of uncertainty products, where standards and expectations are not yet developed.</td></tr>
<tr><td><u>Need:</u> : A "sandbox" is needed for the testing of new techniques and applications before the investments are made to operationally implement a new product.

<u>Current Capability</u>: Only a very informal test bed now exists at NCEP for examination and feedback on experimental ensemble prediction systems (EPS) and related products pre-implementation. This test bed consists of NCEP making data available for review, with data provided either via the Web (graphical products) or pulled in through ftp by participants. Data is not yet available via NWS forecaster workstations (AWIPS). Operational forecasters at NWS national centers and some WFOs participate. Testing and evaluation are not monitored by an objective third party independent of operations.

<u>Capability Gaps</u>: The NRC report "Completing the Forecast" recommended that uncertainty information should be provided across the whole suite of weather and climate forecast products. The rewards that may be gained from effective use of this additional uncertainty information are likely to be fully realized only when users understand the product, how to use it, and have a chance to evaluate experimental products and determine whether it suits their needs.

There is currently no facility that permits users (e.g., operational NWS and industry forecasters, emergency managers, other officials responsible for public safety, utility companies, general public) to conveniently evaluate and critique experimental products. A test bed avoids the hazards of testing in a live production environment, and provides a forum for feedback among all providers and users before operational implementation

Performance Measures and Targets:
• Target is to make a copy of the operational system available to test-bed users.
• Must be sufficiently capable that experiments can be run in quasi-real time to allow operational units to compare the test bed version to the current operational capability</td><td><u>Solution Strategy:</u> Establish capabilities for model developers, forecasters, and users to interact prior to product implementation.

<u>Short-term(0-2 years)</u>:
•Explore possibilities for test bed(s) including expanding existing test beds, establishing new on-site facilities or virtual capabilities. (GOV, COM, ACA)

<u>Medium-term (2-6 years)</u>:
•Establish test bed(s) and processes for testing/evaluating experimental techniques and products well before implementation; and for easy transition to operations. (GOV, COM, ACA)

<u>Long-term steps (6+ years)</u>:
• Continue to refine/improve testbed approaches. (GOV, COM, ACA)</td></tr>
</table>

Objective 4.5: Work with users to define their infrastructure needs

<table>
<tr><td colspan="2"><u>Description and Purpose:</u> Define and implement adequate compute power, storage, network resources, software systems outside of NOAA and other data providers. User infrastructure enables users to make use of what is received through data access (3.3).</td></tr>
<tr><td>
<u>Need:</u> Clients need to be brought up to speed, to envision what capabilities future ensemble prediction systems will bring to their organization, and to recognize the required investments to be prepared to fully utilize the new resources.

<u>Current Capability</u>: Universities, industry meteorologists, and consumers all have made significant and continuing investments in infrastructure. Technological advances keep increasing capabilities for the same price. Current software systems are mostly oriented towards a single deterministic forecast.

<u>Capability Gaps</u>: Will the existing and planned infrastructure be adequate to make use of the ensemble forecast data deluge. Software systems and decision aids that deal with a single forecast and no probabilistic information will ignore the new data streams. Postprocessing requirements add another dimension to the problem.

<u>Performance Measures and Targets</u>:
• A goal is for each organization to have the ability to collect, archive, and process an ensemble where now they deal with a single deterministic forecast.
• A metric is to measure the fraction of the ensemble data stream that is actually used compared to the fraction of the deterministic data stream that is actually used.
</td><td>
<u>Solution Strategy</u>: Inform, educate, and work with users on the amount of information that will be available early so they can design and plan for infrastructure commensurate with their needs.

<u>Short-term(0-2 years)</u>:
•Add sessions on this topic at appropriate meeting and conferences. (NGO)

<u>Medium-term (2-6 years)</u>:
•Make plans for ensemble system upgrades readily available through publication and other means. (GOV)
Work with users and determine how much uncertainty-related information they need to access daily and to store, and help them determine specifications for their information technology purchases (NGO, COM, GOV, ACA)

<u>Long-term steps (6+ years)</u>:
•Sustain Medium-term tasks
</td></tr>
</table>

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