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

January 2010
Preface

This 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, an implementation roadmap, and monitoring strategy that will guide the weather and climate enterprise (Enterprise) toward routinely providing the Nation with comprehensive, skillful, and reliable 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 engage the Enterprise in formulating a cross-enterprise plan to provide forecast uncertainty information to the Nation. The ACUF was commissioned in response to a growing number of studies\(^1\) recognizing the scientific, socio-economic, 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 within the Enterprise (as recommended by the National Research Council\(^2\)) 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. It leverages emerging results from THORPEX\(^3\), other scientific and socio-economic studies, and the best practices of hydrometeorological\(^4\) 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 plan suggests strategic goals, objectives, and implementation tasks that the four sectors comprising the Enterprise (i.e., government, industry, academia, and non-governmental organizations) should work to achieve in partnership over the next decade. 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.

Paul Hirschberg and Elliot Abrams, ACUF Co-Chairs

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\(^1\) See the 2006 NRC Report, *Completing the Forecast. Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts.*

\(^2\) See the 2003 NRC, *Fair Weather: Effective Partnerships in Weather and Climate Forecasts.*

\(^3\) 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](http://www.wmo.int/pages/prog/arep/wwrp/new/thorpex_new.html).

\(^4\) 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 ACUF and contributed to the development of this plan. This number of multi-sector 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, CWCE, and AMS Council. Special thanks go to the ACUF Subgroup Co-leads: John Gaynor, Betty Morrow, Douglas Hilderbrand, Thomas Hamill, Ross Hoffman, Bill Bua, John Sokich, Brenda Philips, 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, Thomas Hamill, Douglas Hilderbrand, Tom Dulong, and Jim Hansen. Finally, special thanks go to Andrea Bleistein, Thomas Hamill, Douglas Hilderbrand, and John Sokich who helped write, edit, and write again various portions of the many drafts leading to this final version of the plan.
Executive Summary

The ability to predict hurricanes, winter storms, severe weather, floods, 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 fundamental 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, an implementation roadmap, and monitoring strategy to guide the weather and climate enterprise (Enterprise) toward routinely providing the Nation with comprehensive, skillful, and reliable 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 The Observing System Research and Predictability Experiment3 (THORPEX), other scientific and socio-economic studies, and the best practices of hydrometeorological4 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 socio-economic areas which, if extrapolated nationally, sum up to potentially large benefits.

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

1. Understanding the nature of forecast uncertainty, how to quantify it, and how societal and human factors influence the communication and use of uncertainty information;
2. Generating uncertainty data, products, services, and information needed by user communities;
3. Communicating uncertainty information effectively, and Assisting users in interpreting and applying the information in their decision making; and
4. Enabling the development, acquisition, and operation of forecast uncertainty processing systems with necessary computational, telecommunications, and other types of infrastructure.

The plan lays out a comprehensive roadmap of objectives and tasks that the four sectors comprising the Enterprise (i.e., government, industry, academia, and non-governmental 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. The ACUF recommends that the AMS Commission Steering Committee, as part of the CWCE, monitor the progress of this plan on a biannual basis.
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1. Purpose and Introduction

A great success of 20th century science and technology was developing the ability to forecast future weather conditions. These forecasts have improved enough in skill⁵ and accuracy⁶ to affect 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, this ability has progressed to the point where seven- to ten-day weather forecasts are frequently skillful. Hurricanes, winter storms, severe weather, floods, and other hazardous conditions can be identified many days in advance with forecasting 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, so-called “weather regime” associated with seasonal to inter-annual climate variability, and even longer-term, scenario-based, climate change. However, despite these successes, the accuracies of hydrometeorological forecasts are far from perfect. Errors in forecasts can not only adversely affect decisions and decision 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, reliable⁷ and sharp⁸ information about the uncertainty of weather, water, and climate (collectively called hydrometeorological) forecasts. The plan is based on, and provides a foundation for, implementing the recommendations of the National Research Council (2006, hereafter NRC2006), the American Meteorology Society (2008, hereafter AMS2008), and the World Meteorological Organization (2008, hereafter WMO2008). These reference documents synthesize the emerging consensus of the scientific, socio-economic, and ethical value of quantifying and effectively communicating information about the uncertainty inherent in all hydrometeorological forecasts.

The degree or size of errors (i.e., forecast uncertainty) can vary depending on many factors. Generally, forecast uncertainty increases as the forecast lead time (forecast 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 the 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) is lost for nearly all types of weather⁹.

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⁵ Skill is a measure of how well a forecast performs relative to some standard of comparison, such as climatology or persistence.
⁶ Accuracy is the extent to which the forecasted value of some variable approaches the true (observed) value.
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 Simmons AJ. 2006. Observations, assimilation and the improvement of global weather prediction – some results
Uncertainties in forecasts can be reduced to some degree through more and better observations and improved data assimilation, and numerical modeling techniques. However, other factors causing uncertainty will never be completely eliminated no matter how much science and technology is applied to the problem\(^\text{10}\). The atmosphere, like other fluid systems, is inherently chaotic. This means, 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\(^\text{11}\), popularly known as the butterfly effect, routine nearly perfect forecasts can never be achieved because of this sensitivity, which manifests itself in the exponential growth of small errors in model initial conditions.

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 for most hydrometeorological applications. As the name implies, the goal of deterministic\(^\text{12}\) forecasting is to accurately determine a single, most accurate value (a single-value) for a future hydrometeorological 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. Deterministic forecasts have been the format of choice partly because of the public demand for easy-to-understand, non-ambiguous forecasts. In some cases, communication time and format restrictions have also played a significant role in the choice of presentation formats (i.e., broadcasters may only have so many seconds or minutes to deliver a weather forecast). This limitation is less important for online presentations. The consequence of conveying only single-value information is that decisions by users are being made without the benefit of their knowing and accounting for the uncertainties in the forecasts upon which their decisions are based (see Figure 2).

After reviewing the needs and potential benefits of forecast uncertainty information, NRC2006 and AMS2008 conclude that there are compelling reasons for the U.S. weather and climate enterprise (Enterprise) to consider uncertainty 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.


\(^\text{10}\) 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; with the spatial scale of motion of the phenomenon of interest (e.g., a thunderstorm, hurricane, winter storm, etc.).


\(^\text{12}\) 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.
practices of hydrometeorological services and industry from around the world (e.g., see Figure 3), serve as the foundation for this Enterprise implementation plan. In particular, NRC2006 provides guidance on how to identify and characterize needs for uncertainty information, discusses limitations in current methods for estimating and validating forecast uncertainty, and identifies sources of misunderstanding and recommends improvements in the methods of communication.

Although NRC2006 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 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, weather and climate industry, academic and non-governmental 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.

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 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 and an end-to-end roadmap of tasks for developing and implementing Enterprise systems that generate and communicate forecast certainty information. A method to monitor progress is proposed in Section 6. This monitoring function will be crucial to gaining the resources and nurturing the partnerships necessary to implement the plan.

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 imbedded 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 the probabilities of potential outcomes (see Figure 4). Since weather- and other hydrometeorological-based decisions can be consequential (e.g., Hurricane Katrina), 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. 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 90F”), as is commonly used in decision theory and risk-management models (see Appendix D). Others may prefer the information to be conveyed in a less formal, more qualitative fashion, adapted to typical psychological, behavioral, and communication norms (e.g., slight chance of rain). If nothing else, service providers with customers who only want a single-value 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 benefits of using hydrometeorological forecast uncertainty information, but also to learn how to maximize these benefits through better use of the information in decision making. However, the existing literature on the socio-economic impacts of hydrometeorological forecast uncertainty information documented in NRC2006, AMS2008, and other published reports, provide evidence of the needs and benefits of probabilistic information.

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) to the United States causing on average 500 deaths, 5000 injuries, and approximately $14 billion in losses each year. 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” (or “warn on probability”) capability, 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 ~$28 billion per year, and about 2/3 of these

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13 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 and climate industry.

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

delays could be avoided with better weather information\textsuperscript{16}. 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 Traffic Control System\textsuperscript{17} (NextGen)
is to reduce these delays by improving weather information and the use of weather information in
air traffic management decision-making. Documented NextGen requirements\textsuperscript{18} for improved
weather information already include probabilistic weather forecasts. One study\textsuperscript{19}, showed how
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. 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\textsuperscript{20},” (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\textsuperscript{21}. 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 Examples 5).

In the U.S., floods and droughts kill more people (approximately 90 per year) and cause more
economic losses (approximately $10B per year) than any other type of natural disaster\textsuperscript{22}.
Population growth and economic development will continue to increase the demands on our water
resources, especially though climate change altering the water cycle, affecting where, when, and how
much water is available\textsuperscript{23}. NOAA’s Integrated Water Forecasting program will reduce 1-7 day

\textsuperscript{16} Abelman, S., C. Miner, and C. Neidhart (2009): The NOAA forecast process in the NextGen era. 25th Conference
on International Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and
Hydrology. Amer. Meteor. Soc., Phoenix, AZ. 4A.2, 7 pp,
\textsuperscript{17} See http://www.faa.gov/about/initiatives/nextgen/
\textsuperscript{18} Concept of Operations for the Next Generation Air Transportation System, v2.0, 2007: Joint Planning and
Development Office, 1500 K St. NW, Suite 500, Washington, DC
\textsuperscript{19} Steiner, M., C. K. Mueller, G. Davidson, and J. A. Krozel (2008): Integration of probabilistic weather
information with air traffic management decision support tools. A conceptual vision for the future. 13\textsuperscript{th} Conference
\textsuperscript{20} See OPNAV Instruction 3500.39B
\textsuperscript{21} 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.
\textsuperscript{22} http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts
\textsuperscript{23} http://www.nature.com/nature/journal/v452/n7185/full/452285a.html
river forecast errors by 50% and quantify uncertainty which will allow for optimizing water
availability allocations for growing communities, support productive agriculture / aquaculture,
expand industry and river commerce, maximize 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. 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 to predict electricity consumption and
peak load.

Another area that could benefit from probabilistic information are sustaining ecosystem
health. Ecological forecasts are the prediction of the impacts of physical, chemical, biological,
and human-induced change on ecosystems and their components.24 Harmful algal blooms
(HABs), water quality and beach closures, as well as coral bleaching are all examples of
ecological health concerns. Ecological forecasts, including the characterization of uncertainty
contained in those forecasts, will assist with decision making and stewardship of the oceans,
coastal zones, and the Great Lakes. Imagine the economic savings that could be had by the
tourism and fishing industries by providing decision-makers strong justification for taking
specific actions that balance the multiple demands on these environments.

Probabilistic hydrometeorological 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, the cost of poor air quality to the U.S. from air pollution-related
illness alone has been estimated at $150 billion per year. 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 saves lives. For each 1 percent reduction in adverse health impacts
that air quality forecasts could provide, over $1 billion would be saved every year.25 Similarly,
probabilistic forecasts and warnings for potential hazardous weather events (such as winter
storms when there are more accidents and injuries owing to people falling26), could help hospitals
and other health care facilities better assess risks and prepare for patient surges and related
transportation, staffing, and other issues.

3. Vision and Strategic Goals

In this section, strategic goals are defined to guide the Enterprise toward a future where

26 The U.S. currently spends $41, 636 per fracture or dislocation of the hip and averages 930 discharges and average
hospital stays of 5.7 days per fracture or dislocation of hip. See   http://hcupnet.ahrq.gov/HCUPnet.jsp
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, marine and surface transportation efficiency
- Strengthen national defense and homeland security;
- Improve water resources management;
- Sustain ecosystem health;
- Improve energy production and management;
- Increase business and agricultural productivity and competitiveness; and
- Enhance public well being.

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.

However, despite this progress, the Enterprise is not yet positioned to achieve the tantalizing
benefits of employing forecast uncertainty information described in Section 2. Substantial
scientific and technological challenges remain that need to be solved in order to make ensemble
prediction and associated post-processing 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. For example, in situations when an ensemble
estimates a 30 percent probability of greater than 3 cm rainfall, the event may happen only 15
percent of the time (see Figure 5). Additionally, a comprehensive understanding of the best ways
to communicate uncertainty and a broad program of training and education are needed to enable
forecasters and other service providers the ability to interpret, manage, and add value to ensemble
prediction system output so users have the ability to understand and apply probabilistic forecasts
and other forecast uncertainty information in their decision making (see Figure 6). 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.

In order to meet the scientific and cultural challenges associated with a greater focus on

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27 For example, NWS Storm Prediction Center forecasters have begun using output from the National Centers for
Environmental Prediction (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.”
probabilistic forecasting, the Enterprise must build capabilities in four key, interrelated areas:

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

2) **Generating** uncertainty data, products, services, and information needed by user communities;

3) **Communicating** uncertainty information effectively, and **Assisting** users in interpreting and applying the information in their decision making;

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

Descriptions of these strategic goals are discussed next.

**Strategic Goal 1: Understand Forecast Uncertainty**

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

Before the pioneering works on atmospheric predictability of Ed Lorenz, Ed Epstein, Phil Thompson, and others became widely appreciated, the task of numerical weather prediction and improving weather (hydrometeorological) forecasts appeared more straightforward. Near-perfect numerical weather predications at extended lead times were contemplated with 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 tornado outlook products days in advance, there needs to be greater understanding about whether these small-scale features have any predictable signal at all. If it is concluded that such a project is unlikely to succeed, what other approaches might work effectively. Could ensemble forecasts improve the identification of areas where severe weather is most likely? What about further work with conditional probabilities (if A happens, what is the likelihood of B happening?) There is also much yet to learn about ensemble prediction systems such as what numerical and statistical post-processing techniques provide reliable and skillful estimates of forecast uncertainty.

Additionally, much of the Enterprise’s customer base is accustomed to receiving and making decisions based on deterministic hydrometeorological forecast information. There is much to understand about how various types of users currently perceive, synthesize, and use uncertainty information to make decisions; and what types of uncertainty information is needed; and what formats will most effectively improve their decision-making.

*Success Criteria: The Enterprise will have achieved this goal when there is a community...*
consensus on theoretical predictability estimates (what phenomena are predictable out to what lead time); when the academic and research community is actively producing new ideas for enhancing ensemble prediction systems and transitioning these ideas to operational ensemble system developers; and when product developers and service providers have an understanding of how to design and communicate products that will be of greatest use to customers.

Strategic Goal 2: 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 (the “deterministic” paradigm) to also providing reliable uncertainty information (a probabilistic paradigm). Currently, the Enterprise provides a limited set of forecast uncertainty products, including probability of precipitation forecasts (POP) and hurricane track forecasts (e.g., the “cone of uncertainty”). An integrated, comprehensive, sharp and reliable suite of widely disseminated uncertainty forecast products does not yet exist. In accordance with 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 it to their particular applications and decisions tools. Derived products, post-processed 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 will 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), 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 3: Communicate forecast uncertainty information effectively, and Assist users 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, 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 engage 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
In addition, mutual awareness and education is needed between the Enterprise and user communities to understand how uncertainty information should be presented to maximize its usefulness. 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 forms of communication (e.g., Internet, PDAs, 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 to increase 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 product, service, and information 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 evidence that uncertainty information is resulting in better decisions.

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. Currently, the European Centre for Medium Range Weather Forecasts (ECMWF) 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. That is, a 3.5-day ECMWF forecast is as skillful as a 2-day NWS forecast. The ECMWF system is currently approximately double the resolution of the NWS system (~30 km vs., ~60 km), and they plan to upgrade to approximately ~15 km in 2010. All told, ECMWF dedicates approximately 50 times more computer resources for the computation of their ensemble predictions (including real-time reforecasting and statistical post-processing) than does the NWS. A comparable U.S. investment will be needed to provide the highly skillful, reliable probabilistic forecast products required to support Enterprise partners and customers. This will require a commensurate increase in disk storage, an archive facility to save old forecasts or preferably to store reforecasts for statistical post-processing 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 application. These resources are essential to maximize the life and property saving potential and the potential economic benefits of uncertainty information.

Success Criteria: The Enterprise will have achieved this goal when the Enterprise has (or has access to on a continuing basis\textsuperscript{29}) facilities to run state-of-the-art ensemble prediction systems and when the data from these advanced systems is 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 the probabilistic forecasting paradigm 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) Government sector, which includes local, state, and federal governments, (but is predominately the U.S. Federal government); 2) America’s Weather and Climate Industry (Industry), which includes two components – consulting/service companies (companies) and media; 3) Academia, which includes associated research institutions; and 4) Non-Government 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 probabilistic forecasts into decision making. Increasingly, the missions, strengths, and capabilities among these sectors can overlap, making distinct delineations difficult. Nevertheless, there are 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 large corporations\textsuperscript{30}. 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 America’s weather and climate industry and the government. However, the boundary between the academic sector and private sector for delivering information is changing and must be taken into consideration, as academia is increasingly providing services normally considered a commercial role.

Government Sector

One role of the Government sector is to generate and sustain a foundational or baseline suite of forecast uncertainty data, products, services, and information in response to user and partner

\textsuperscript{29} This goal in particular requires continuous improvements in hardware capabilities, which typically double approximately every two years following Moore’s law.

\textsuperscript{30} 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.
requirements. The Government should also ensure this foundation 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. As appropriate, the Government should collaborate on new and emerging information needs with Enterprise partners on leading edge, high-risk product development and/or resource-intensive products, where appropriate.

The Government should develop, maintain, and execute the nation’s baseline probabilistic forecast machinery. The Government will 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 post-processing 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 will, of course, use that ensemble information for their forecasts and warnings, while the America’s weather and climate industry will 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 the critical decision makers, such as the emergency management community, in fulfilling the protection of life and property role of government. The Government will 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 and communicating uncertainty forecast information. NWS training to date has occurred primarily through COMET, the Cooperative Program for Operational Meteorology and Training, operated by UCAR. COMET offers both on-site and web-based training, including a number of uncertainty-related training modules. 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.

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**

This sector has two components, weather and climate companies that provide weather and
climate products/information for a fee and/or through advertising revenue, and the media. Each of these components has particular roles and responsibilities. Some private companies span both categories.

Weather and Climate Companies

Weather and climate companies 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 and climate companies will also lead in developing specific tools to interpret and understand uncertainty as well as develop the tools to educate clients and public audiences on the best way to use that information.

The Weather and Climate Industry should extend and tailor forecast uncertainty information provided by the Government sector and information originated within the industry to meet their clients’ specific needs. The Industry should provide interpretive support educating clients about uncertainty, its socioeconomic value, and how to use it to benefit their business. An emphasis on developing uncertainty decision support tools geared to individual clients’ needs will leverage uncertainty products produced by the government and within the Industry.

Media

Today the media plays a critical role in providing forecast and warning information to the public. This role will expand to providing forecast uncertainty information as the Enterprise moves in that direction. The media is uniquely positioned to help determine what forecast uncertainty products and services the public wants (via surveys and other methods) and to 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 private-sector media cannot be equaled by the government or any other component of the Enterprise. Even so, for potentially life saving decisions based on warnings, all components of the Enterprise will need to be involved.

Academic Sector

Academia continues to provide the basic education in meteorology, hydrology, and climatology necessary to begin a career in the atmospheric sciences. As the weather, water and climate community shifts to providing more uncertainty information to users, educational institutions will need to incorporate uncertainty education into standard curriculums. In particular, curriculum will need to broaden to expose students more 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 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.

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

Last, but not least, Academia will 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 quasi-operational environment have demonstrated the usefulness of iterative technique refinement to maximize the development of new techniques before they are integrated into operations and/or provided to end users.

Non Government Organizations Sector

NGOs, such as the American Meteorological Society (AMS), National Weather Association (NWA), and National Center for Atmospheric Research (NCAR), have a critical role in uniting the Weather and Climate Enterprise to address common goals and setting the vision of uncertainty for the Enterprise as a whole. Annual meetings of these NGOs provide essential venues to discuss the direction, pace, and implementation of the effort to pursue this vision. NGOs have 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 that consensus. One of their focus areas is on information exchange and consensus leadership.

NGOs also have a critical role in education – first to educate their members (AMS and NWA) 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, the AMS in particular, also play an important role in helping the academic community define the educational requirements and skills needed for the field of meteorology. The AMS could help guide the curricula to address understanding and integrating ensemble information into the forecast process, and then how to communicate that 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 reach the vision of transitioning the Nation to a probabilistic forecasting paradigm. 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. The write-up for each objective provides background information; the need for this specific objective; current capabilities and gaps; performance measures and targets; overall proposed solution strategy, and specific tasks that must be accomplished to fulfill the objective. Within this section, briefer 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\(^{31}\) 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.

\(^{31}\) 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, a government agency program might end up supporting a research task recommended in this plan with academia in the lead.
### Table 1. Objectives supporting each Strategic Goal

<table>
<thead>
<tr>
<th>Strategic Goal 1</th>
<th>Strategic Goal 2</th>
<th>Strategic Goal 3</th>
<th>Strategic Goal 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understand forecast uncertainty</td>
<td>Generate a fundamental set of operational forecast uncertainty data and information</td>
<td>Communicate forecast uncertainty information effectively, and assist users in interpreting and applying the information in their decision making</td>
<td>Enable forecast uncertainty research, development, operations, and communications with supporting infrastructure</td>
</tr>
<tr>
<td>Obj. 1.1 Understand and quantify predictability.</td>
<td>Obj. 2.1 Improve the initialization of ensemble prediction systems.</td>
<td>Obj. 3.1 Prepare the next generation for using uncertainty forecasts through enhanced K-12 Education.</td>
<td>Obj 4.1 Acquire necessary high performance computing.</td>
</tr>
<tr>
<td>Obj. 1.2 Develop the theoretical basis for and optimal design of uncertainty prediction systems.</td>
<td>Obj. 2.2 Improve forecasts from operational ensemble prediction systems</td>
<td>Obj. 3.2 Revise undergraduate and graduate education to include uncertainty training.</td>
<td>Obj 4.2 Establish a comprehensive archive.</td>
</tr>
<tr>
<td>Obj. 1.3 Identify societal needs and best methods for communicating forecast uncertainty</td>
<td>Obj. 2.3 Develop probabilistic nowcasting systems.</td>
<td>Obj. 3.3 Reach out to and educate users.</td>
<td>Obj 4.3 Ensure easy data access.</td>
</tr>
<tr>
<td></td>
<td>Obj. 2.4 Improve statistical post-processing techniques.</td>
<td>Obj. 3.4: Improve the presentation of government-supplied uncertainty forecast products.</td>
<td>Obj 4.4 Establish a forecast uncertainty test bed(s)</td>
</tr>
<tr>
<td></td>
<td>Obj. 2.5 Develop non-statistical post-processing techniques.</td>
<td>Obj. 3.5: Tailor data, products, services, and information for private-sector customers.</td>
<td>Obj 4.5 Work with users’ to define their infrastructure needs</td>
</tr>
<tr>
<td></td>
<td>Obj. 2.6 Develop probabilistic forecast preparation and management systems.</td>
<td>Obj. 3.6 Develop and provide decision support tools and services.</td>
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<td></td>
<td>Obj. 2.7 Train forecasters</td>
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<td></td>
<td>Obj. 2.8 Develop probabilistic verification systems.</td>
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<tr>
<td></td>
<td>Obj. 2.9 Include digital probabilistic forecasts in the Weather Information Database.</td>
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</table>

### 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 improving operational probabilistic prediction systems (Strategic Goal 2) and communicating this information to users (Strategic Goal 3). Specifically, in order to improve operational probabilistic prediction systems, an increased understanding of the nature of atmospheric predictability is needed (Objective 1.1) to set reasonable forecast accuracy and reliability goals and to 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\(^ {32}\) (predictability usually increase with the scale of 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 the forecast model are in greatest need of improvement.

A fuller understanding of the sources of forecast uncertainty as well as efficient numerical methods for estimating uncertainty in prediction systems (Objective 1.2) are also needed. 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. However, 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. increasing model horizontal resolution vs. improving model numerics is not well understood.

Last, but not least, an understanding of the best ways for communicating forecast uncertainty information to users (Objective 1.3) is needed in order to put in place effective ways to communicate uncertainty information with users and assist them in using it in their decision making under Strategic Goal 3. Specifically, 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. A few preliminary studies\(^ {33}\) exist on the effective ways for communicating probabilistic information. However, 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.

\(^ {32}\) See for example, [http://tinyurl.com/dfegwl](http://tinyurl.com/dfegwl).

\(^ {33}\) See for example, WMO publication [http://tinyurl.com/676dyd](http://tinyurl.com/676dyd).
Table 2. Summary of the implementation roadmap for Strategic Goal 1, Understand Forecast Uncertainty, 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 31). GOV, ACA, COM, and NGO stand for the government, academia, commercial sector and non governmental organization sector, respectively.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Solution Strategy</th>
<th>Tasks</th>
</tr>
</thead>
</table>
| **(1.1) 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. *(Lead: ACA,)*  
• Sustain current funding of ensemble and predictability research through programs such as THORPEX. *(Lead: ACA, GOV)*  
• Develop funding programs/requests for proposals focusing on quantifying estimates of the limits of predictability. *(Lead: ACA)* |
| | | • Perform research with higher-resolution models that better quantify estimates of the limits of predictability. Studies should be prioritized based on societal impact, e.g., position and intensity of land-falling hurricanes, and overall predictability. *(Lead: ACA)* |
| | | • Sustain predictability studies using improved, higher-resolution models that increasingly incorporate stochastic elements. *(Lead: ACA)* |
| **(1.2) 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. | • Continues research supported by existing research grants programs. *(Lead: ACA)* |
| | | • Expand research program on improved numerical techniques for estimating analysis and forecast uncertainty, especially at the mesoscale *(Lead: ACA).*  
• Work with operational model developers (see Obj 2.2) to implement proven superior research techniques. *(Lead: ACA)* |
| | | • Sustain uncertainty prediction system research. *(Lead: ACA)* |
| **(1.3) Identify societal needs and best methods for communicating forecast uncertainty** | Conduct basic research to determine the best methods of conveying hydrometeorological forecast uncertainty guidance to the public. | • Host a special forum for the social science (including economists to determine economic benefits of uncertainty information), behavioral and related research community to interact with hydrometeorological forecasters and service providers. *(Lead: NGO)*  
• Begin grants-driven projects to perform basic research on optimal methods for communicating uncertainty *(Lead: ACA).*  
• Hold workshop(s) to entrain new social science and interdisciplinary researchers into field of hydrometeorological forecast uncertainty. *(Lead: NGO)* |
| | | • Fund proposals to examine most effective ways to communicate uncertainty to different audiences in different contexts and include communication of weather forecast uncertainty as a topic in existing calls for research. *(Lead: 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.) *(Lead: ACA)*  
• AMS or universities facilitate building public/private consortiums for funding research on communication of forecast uncertainty. *(Lead: NGO, ACA)* |
| | | • Ongoing maintenance of organization to facilitate further research based on 2-6 year results. *(Lead: NGO)* |
Implementation Roadmap for Strategic Goal 2: Generate Forecast Uncertainty Data, Products, Services, and Information

The implementation roadmap for Strategic Goal 2 is summarized in Table 3 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 the observations 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, forecasts, and warning data and information, which, for the most part, are all made available to Enterprise partners. The Enterprise partners, including the NWS and similar 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 2 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 mostly the responsibility of the government sector, owing to the resources and infrastructure required to support this activity.

This foundational forecast uncertainty data set will include observation and analysis uncertainty information, raw and post-processed ensemble model output, and human value-added information for forecast leads out to several weeks (see Table 2 for examples). 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, 50, 90 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 below. The 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 3. Enhancements to IT and other infrastructure improvement objectives will also be necessary to achieve these objectives; such supporting improvements are covered under Strategic Goal 4.

Objectives 2.1 – 2.9 focus on improving the steps by which forecasts are produced and uncertainty data and information are generated and made available to Enterprise partners. Note

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34 The 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 sensitivity of the information.
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 this is already handled adequately by instrument designers and data assimilation scientists.

Table 3. A sample of the types of forecast uncertainty information that should be generated and made freely available as part of the foundational set.

<table>
<thead>
<tr>
<th>(1) Continuous variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature and dew point</td>
</tr>
<tr>
<td>o Hourly, daytime maximum, nighttime minimum temperatures mean and range of uncertainty (e.g., 10/50/90th percentile of forecast distribution).</td>
</tr>
<tr>
<td>o Extreme temperature probability of exceedance.</td>
</tr>
<tr>
<td>o User-specific probability of exceedance (e.g., sub-freezing thresholds for crop growers, materials applications thresholds for concrete pourers)</td>
</tr>
<tr>
<td>Wind speed</td>
</tr>
<tr>
<td>o Exceedance values for pre-defined thresholds (e.g., gale, hurricane force, etc.)</td>
</tr>
<tr>
<td>o User-specific probability of exceedance (e.g., wind-energy industry)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(2) Quasi-continuous variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind direction and wind gusts PDFs (critical for aviation, wind energy industry, temperature forecasts)</td>
</tr>
<tr>
<td>Sky cover and cloud optical depth PDFs (critical for solar energy industry, aviation/transportation sector)</td>
</tr>
<tr>
<td>Ceiling height PDFs (critical for aviation)</td>
</tr>
<tr>
<td>Visibility PDFs (critical for aviation)</td>
</tr>
<tr>
<td>Precipitation (PQPF, timing, precipitation type)</td>
</tr>
<tr>
<td>o PQPF probability of exceedance values such as 0.1&quot;, 0.25&quot;, 0.5&quot;, 1&quot;, 2&quot;, etc. including flooding exceedance values</td>
</tr>
<tr>
<td>o Probability of precipitation shortfalls (e.g., drought and water availability)</td>
</tr>
<tr>
<td>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)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(3) Discrete weather elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe weather</td>
</tr>
<tr>
<td>o Probability of tornado occurrence within 25-mi of a point</td>
</tr>
<tr>
<td>o Probability of extreme tornado</td>
</tr>
<tr>
<td>o Probability of any severe (tornado, winds, hail)</td>
</tr>
<tr>
<td>Tropical cyclones (current products at <a href="http://www.nhc.noaa.gov">www.nhc.noaa.gov</a>)</td>
</tr>
<tr>
<td>o Probabilistic intensity values (e.g., 50% chance of category 1 at landfall)</td>
</tr>
<tr>
<td>o Probabilistic storm surge values with inundation mapping of each probability</td>
</tr>
<tr>
<td>o Probabilistic storm track (e.g., probabilistic information within “cone of uncertainty”)</td>
</tr>
<tr>
<td>Flooding (current products at <a href="http://www.hpc.ncep.noaa.gov/nationalfloodoutlook/index.html">www.hpc.ncep.noaa.gov/nationalfloodoutlook/index.html</a>)</td>
</tr>
<tr>
<td>o Probability of exceeding stream flow heights (focusing on location-specific levee heights, inundation mapping)</td>
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<tr>
<th>(4) Earth-system elements</th>
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<tr>
<td>Avalanche probability for a given area</td>
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<tr>
<td>Mudslides/debris flows probability for a given area</td>
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<tr>
<td>Tsunamis</td>
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<tr>
<td>Space Weather (e.g., solar storms)</td>
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<th>(5) Multi-variable probabilities</th>
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<td>Heat Index (e.g., combining temperature and dew point)</td>
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<td>Wind chill (e.g., combining temperature and wind speed)</td>
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<tr>
<td>Fire weather (e.g., combining temperature, dew point, wind speeds, POP)</td>
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<th>(6) Multiple weather scenarios</th>
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<tr>
<td>Aviation applications (individual gridded scenarios from an ensemble input into flight routing software).</td>
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<tr>
<td>Hydrologic forecast chains (individual time series of possible rainfall/temperature scenarios fed into ensemble of hydrologic forecast models to produce ensemble of streamflow estimates)</td>
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</table>
New and improved data assimilation techniques are needed (Objective 2.1) that can produce an ensemble of initial conditions that are accurate, sample the range of possible true analysis, 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 forecasts become higher-resolution, these techniques must be able to estimate uncertainty at the meso- as well as the synoptic and planetary scales.

Improved ensemble prediction methods (Objective 2.2) 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. 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 2.3) 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 post-processing (Objective 2.4) of raw ensemble model output to ameliorate bias and other deficiencies will likely never be completely eliminated despite improvements in ensemble prediction methods (Objective 2.2). Additionally, statistical post-processing 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. For every-day weather such as surface temperature at short forecast leads, a variety of new ensemble model-based calibration techniques appear to perform relatively competitively. However, for rare events and long-lead forecasts the calibration technique of choice may depend upon particular applications. In addition, many statistical post-processing techniques need large past “training” forecast data sets from a stable operational model to properly adjust current forecasts. With limited computational resources, this requirement often conflicts with the desire to rapidly implement improvements in operational ensemble forecast systems.

Non-statistical post-processing techniques (Objective 2.5) 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 post-processing techniques discussed under Objective 2.4). 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 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. But, little has been done to develop, test, and verify algorithms that produce skillful and reliable probabilistic forecasts of such non-observed 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 post-processed 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 2.6) 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 to be trained (Objective 2.7). While some basic training on the theoretical basis for ensemble prediction systems has been developed,35 more is needed to provide knowledge of the general underlying theory behind and of the performance of ensemble prediction and other probabilistic systems, the weaknesses in current operational systems, and what can and can not be corrected with statistical post-processing. Forecasters will also need to be trained in the new uncertainty forecast preparation tools they will use.

The enterprise also needs a comprehensive, agreed-upon set of standards and software algorithms for uncertainty verification (Objective 2.8). 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 2 (Objective 2.9) 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

35 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].
“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’ 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. 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 other information for users to access. Comprehensive forecast uncertainty data and information will need to be included in the planning and deployment of these database and access systems as they evolve.
Table 4. Summary of the implementation roadmap for Strategic Goal 2 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 31). GOV, ACA, COM, and NGO stand for the government, academia, commercial sector and non governmental organization sector, respectively.

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<tr>
<th>Objective</th>
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<th>Tasks</th>
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| (2.1) 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 quasi-real time tests during hurricane season and other high-impact events of an EnKF using a global forecast model. *(Lead: GOV)*  
- Continue R&D on the treatment of model error and sampling error in ensemble filters. *(Lead: GOV)*  
- Evaluate EnKF relative to 4D-Var for its ability to produce reduced-error initial conditions. *(Lead: GOV; ACA)*  
- Explore hybridization methods of variational and EnKF methods. *(Lead: GOV; ACA)* | - Transition EnKF into parallel testing/operations at NWP facilities. *(Lead: GOV)*  
- Further develop and implement hybrid 4D-Var / EnKF methods. *(Lead: GOV; ACA)* | - Develop improved methods for the initialization of ensembles at the mesoscale, with perturbations that grow appropriately quickly and are consistent with analysis error *(Lead: GOV, utilizing ACA from Obj. 1.2)* |
| (2.2) Improve forecasts from operational ensemble prediction systems | Increase ensemble model grid resolution incorporating research results from Obj. 1.2; 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 *(Lead: GOV)*  
- Develop higher-resolution global ensemble prediction systems. *(Lead: GOV)*  
- Develop higher-resolution, short-range, limited-area ensembles *(Lead: GOV, ACA)*  
- Test promising experimental ensemble forecast system techniques developed in academia (see Obj. 1.2) *(Lead: GOV)*  
- Develop improved hydrologic ensemble forecast system models *(Lead: GOV; ACA)*  
- Develop hourly lagged ensemble forecast techniques for mesoscale models. *(Lead: GOV, ACA)* | - Implement three-fold higher-resolution ensemble model systems. (SREF to ~10 km) by 2012. *(Lead: GOV)*  
- Develop relocatable, 4-km high-resolution, explicit convection, limited-area ensemble forecast system for hurricanes, severe and fire weather *(Lead: GOV, ACA)*  
- Continue to test promising experimental ensemble forecast system techniques developed in academia and implement best methods into operations. (see Obj. 1.2) *(Lead: GOV)*  
- Compare performance of mesoscale lagged ensemble forecast systems to more conventional ensemble system designs. *(Lead: GOV, ACA)*  
- Upgrade hydrologic forecast models, to produce reliable streamflow forecasts. *(Lead: GOV, ACA)* | - Enterprise should double its ensemble forecast systems horizontal resolution approximately every 8 years, consistent with Moore’s Law. *(Lead: GOV)*  
- Continue to test promising experimental ensemble forecast system techniques developed in academia, and implement best methods into operations. (see Obj. 1.2) *(Lead: GOV)* |
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| **(2.3)** 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 the dressing of existing deterministic forecast with uncertainty information. (*Lead: GOV, ACA*)  
- Begin to develop new techniques for generating probabilistic nowcasts (*Lead: GOV, ACA*)  
- Perform intercomparisons of nowcast algorithms to determine which are most suitable for applications. (*Lead: GOV, ACA*)  
- Based on the performance of these, implement the most appropriate probabilistic nowcast algorithms. (*Lead: GOV, ACA, Com*)  
- Develop tools for blending together observationally-based nowcast and NWP-based guidance as forecast lead increases. (*Lead: GOV, ACA*)  
- Implement techniques for blending together nowcast and NWP based guidance (*Lead: GOV*)  
- Based on improvement of data assimilation and numerical weather prediction systems, decrease emphasis on separate nowcasting tools, and develop more NWP based approaches. (*Lead: GOV, ACA*) |
| **(2.4)** Improve statistical post-processing techniques | Develop supporting observational and reforecast data sets needed for post-processing, and develop and implement improved statistical post-processing techniques to improve the objective probabilistic forecast guidance. | - Develop a comprehensive implementation plan for statistical post-processing, including defining requirements. (*Lead: GOV*)  
- Define which observational / reanalysis data set(s) will be used for testing techniques. (*Lead: GOV*)  
- Develop a robust reforecast data set, and observations/analyses as needed, and make this readily available to researchers (*Lead: GOV*)  
- Determine the optimum reforecast training sample size, a compromise between post-processing skill improvements (favors a large sample) and computational cost (favors a limited sample). (*Lead: GOV*)  
- Test, refine, and compare post-processing algorithms. (*Lead: GOV, ACA*)  
- Begin the regular generation of reforecast data sets corresponding to current operational models, based on previously determined optimal reforecast configuration. (*Lead: GOV*)  
- Implement most promising post-processing techniques for common variables. (*Lead: GOV, ACA*)  
- Continue to test, refine, and compare post-processing algorithms, but now using emerging standard verification techniques (see Obj. 2.8). (*Lead: GOV, ACA*)  
- Develop new post-processing techniques for more specialized variables.  
- Compare objectively produced post-processed forecast products to those modified by human forecasters (see Obj 2.6) using standard verification techniques (see Obj 2.8). (*Lead: GOV*)  
- Begin regularly monitoring the quality of post-processed vs. raw numerical guidance. (*Lead: GOV*)  
- Continue the regular generation of reforecast data sets corresponding to current operational models (*GOV*)  
- Implement most promising post-processing techniques for more specialized variables. (*Lead: GOV, ACA*)  
- Develop specific post-processing techniques for more specialized products with less standard variables and appropriateness of existing approaches. (*Lead: GOV*) |
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| (2.5) Develop Non-statistical Post-processing Techniques | Convert to probabilistic current deterministic forecast products that diagnose specialized forecast variables from model output. Determine best methods for dealing with ensemble system bias with these algorithms, and implement best methods. | • Test the simple method of forming an ensemble of diagnosed values from ensemble model outputs. *(Lead: GOV)*  
• If bias-corrected members are available (see Objective 2.4 above), determine whether the input bias-corrected data produces a more reliable and skillful diagnosed ensemble. *(Lead: GOV)*  
• Develop new techniques that produce appropriate sub-gridscale probabilistic forecast information based on the calibrated grid-scale information. *(Lead: GOV)*  
• Implement the most promising techniques. *(Lead: GOV, ACA)* |
| (2.6) 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 in how they use prob. forecast information. *(Lead: GOV; NGO; ACA)*  
• Complete plan to include ensemble information in AWIPS *(Lead: GOV)*  
• Develop experimental tools that allow the graphical editing of probabilistic forecasts *(Lead: GOV)*  
• Gather forecast feedback on workstation requirements *(Lead: GOV)*  
• Implement new gridded ensemble products on the NDFD *(Lead: GOV)*  
• Evaluate forecaster-modified guidance produced with experimental forecast tools relative to objective guidance (see Obj. 2.4).  
• If warranted based on forecast evaluation, implement forecast editing tools in AWIPS. *(Lead: GOV)*  
• Refine ensemble display and graphical editing tools as necessary. *(Lead: GOV)* |
### (2.7) 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 collaborators, within and outside the NWS (Lead: GOV)
- Identify existing web-based training on uncertainty NWP. (Lead: GOV)
- Identify best practices in other disciplines using uncertainty. (Lead: GOV; ACA)
- Develop in-person and online training materials. (Lead: GOV)
- Obtain operational reviewer feedback on training. (Lead: GOV; ACA)
- Develop training courses and position description requirements for training and hiring proper support personnel. (Lead: GOV)
- Run uncertainty training courses for forecasters including Weather Event Simulator (WES) cases. (Lead: GOV)
- Identify good cases for future training material (Lead: GOV; ACA; NGO)
- Maintain training developed over the mid-term so that continues to be current and relevant to forecast operations. (Lead: GOV)

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<td>(2.7) Train Forecasters</td>
<td>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.</td>
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<tr>
<td><strong>Tasks</strong></td>
<td><strong>Short-term (0-2 years)</strong></td>
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<td></td>
<td>• Develop forecast uncertainty verification standards and best practices. (Lead: NGO)</td>
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<td>• Continue research into new verification methods. (Lead: GOV; ACA)</td>
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<td>• Develop prototype probabilistic verification packages for particular applications, such as for aviation forecasts. (Lead: GOV)</td>
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| (2.9) 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) (Lead: GOV).  
• Add forecast probability grids to NDFD. (Lead: GOV)  
• Develop specification and implementation plan for probabilistic information in WIDB, indicating variables, spatial/temporal resolution, etc. (Lead: GOV)  
• Develop techniques to synthesize probabilistic forecast information from various sources (different forecast systems, obs., human-modified guidance, etc.) (Lead: GOV) | • Implement preliminary techniques for synthesizing probabilistic forecast information from various sources (Lead: GOV)  
• Integrate WIDB probabilistic information into Air Traffic Management Systems. (Lead: GOV)  
• Meet all probabilistic NextGen requirements. (Lead: GOV)  
• Provide full network connectivity ensuring consistent information use across service areas and user groups. (Lead: GOV)  
• Upgrade techniques for synthesizing information from various sources. Upgrade spatial / temporal resolution of WIDB as warranted by user requirements.  
• Migrate to Environmental Information Database. (Lead: GOV) |
Implementation Roadmap for Strategic Goal 3: Communicate forecast uncertainty information effectively, and assist users in interpreting and applying the information in their decision making

The implementation roadmap for Strategic Goal 3 is summarized in Table 4 and detailed in Appendix F. All of the capabilities developed under the Strategic Goal 2 objectives to generate forecast uncertainty information will be wasted if customers and users don’t see the value of the information and know how to use it to help them in their decision making. The following set of objectives support Strategic Goal 3 by sensitizing and educating students, users and the public about uncertainty and probability and hydrometeorological students about the underlying physical theory and social science aspects of uncertainty; improving the general presentation of forecast uncertainty information and tailoring it for users and customers based on social science and user feedback; and providing decision support tools and services to assist users interpret and apply forecast uncertainty information in their decision making.

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 3.1) to illustrate and embed the concepts of probability and statistics in meteorology and weather forecasting in our Nation’s youth.

Hydrometeorological science undergraduate and graduate students need to have a better basic understanding of chaos theory, the fundamentals of ensemble prediction, probabilistic forecasting and the use of uncertainty guidance for decision making, as well as a broad understanding in the social sciences and effective communication techniques (Objective 3.2). Currently, the course standards for meteorological education, for example), does not include the necessary education in the theoretical and practical aspects of uncertainty, no less education in related social science aspects.

Generations of hydrometeorological users and the general public have grown accustomed to single-value deterministic forecasts. Inaccurate weather forecasts are disparaged and are often the butt of jokes. New information and products that include forecast uncertainty could be viewed as a hedge against poor science and forecasts. However, some social scientists argue that acknowledging uncertainties and unknowns builds credibility. Regardless, outreach and education are needed to inform users and the public that forecast uncertainty is part of nature, and that comprehending and using uncertainty information will improve their decision making (Objective 3.3). Users will also need to educate the hydrometeorological and social-science community about how the data should be formatted so they can best use the information.

Improving the effectiveness of the day-to-day communication of forecast uncertainty will involve both improving the presentation (e.g., formats) of government-supplied uncertainty forecast products and services (Objective 3.4) and tailoring uncertainty information by the commercial sector for specific customers (Objective 3.5). 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 2.8), but rather through regularly available products. By leveraging social science research results and user feedback (see Objectives 1.3 and 4.6), these products will need to be in formats that do the best job possible of conveying the breadth of uncertainty information iconically, graphically, textually, and/or numerically. There is virtually no established capability in standard graphical products for uncertainty in the Enterprise. 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 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 3.6) to provide a link between forecast uncertainty information and direct user impacts and applications. Single-value deterministic forecasts severely limit the utility of weather, water, and climate forecast information because they don’t allow users to take their own probabilistic thresholds for uncertainty into account 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. This availability of forecast uncertainty information for decision support will require extensive understanding and interpretation for different levels of decision makers.
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. Lead refers to sector(s) recommended to take leadership in performing the task, not necessarily funding it (See Footnote 31). GOV, ACA, COM, and NGO stand for the government, academia, commercial sector and non governmental organization sector, respectively.

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<td>(3.1) Prepare the next generation for using uncertainty forecasts through enhanced K-12 Education</td>
<td>Prepare supplementary material on probability and statistics related to weather than can be incorporated into K-12 curricula so future students are better prepared to use and interpret probabilistic forecast information.</td>
<td>• Sponsor a committee that will develop sample problems that illustrate the concepts of probability and statistics in hydrometeorological forecasting. Develop an on-line repository. <em>(Lead: NGO)</em></td>
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<td>• Work with other statistical organizations (e.g. American Statistical Association) and school textbook manufacturers to incorporate uncertainty information. Encourage use of examples contained in the repository mentioned in 1). <em>(Lead: NGO)</em></td>
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<td>• Contact state depts. of education and school boards on desired changes in forecast uncertainty products/services <em>(Lead: NGO)</em>.</td>
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<td>• 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. <em>(Lead: NGO; ACA)</em></td>
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<td>(3.2) Revise Undergraduate and Graduate Education to Include Uncertainty Training</td>
<td>Change hydrometeorological science courses to include material necessary to understand forecast uncertainty. Stress cross-disciplinary studies in the social sciences on use of forecasts.</td>
<td>• 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. <em>(Lead: ACA)</em></td>
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<td>• Post materials and lectures (e.g., at The COMET Program (<a href="http://www.comet.ucar.edu">http://www.comet.ucar.edu</a>). <em>(Lead: NGO, ACA)</em></td>
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<td>• Develop recommendations for curriculum changes, e.g., students to take basic probability and statistics course, statistical meteorology, and modify synoptic/dynamic courses to discuss chaos theory, ensemble prediction methods. <em>(Lead: NGO)</em></td>
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<td>• Assimilate recommended uncertainty material into courses currently offered. <em>(Lead: ACA)</em></td>
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<td>• Develop a mechanism to maintain contact with institutions involved in post-secondary education, and update these institutions on new developments in hydrometeorological uncertainty at a level appropriate to undergraduate and graduate education. <em>(Lead: ACA)</em></td>
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<tr>
<td>Objective</td>
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<td>(3.3) Reach Out To and Educate Users</td>
<td>Through, e.g., broadcast meteorologists and educational information and feedback forms on NWS web pages, educate the user on probabilistic forecast products; find out what they don’t understand, and develop mechanisms for correcting the product development to make forecast products more useful.</td>
<td><strong>Short-term (0-2 years)</strong>&lt;br&gt;• As NWS web pages are modified to include probabilistic forecast information (see Obj. 3.4), develop training material and user feedback capabilities.&lt;br&gt;• Develop material to train broadcast meteorologists (e.g., adapt material from Obj. 2.7) to communicate forecast uncertainty (<em>Lead: NGO</em>)&lt;br&gt;• As TV meteorologists begin to incorporate uncertainty elements into their broadcasts, they begin to educate the public. (<em>Lead: Com</em>)</td>
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<td>(3.4) Improve the Presentation of Government-supplied Forecast Uncertainty Products and Services</td>
<td>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.</td>
<td><strong>Short-term (0-2 years)</strong>&lt;br&gt;• Conduct social-science studies (see also Obj. 1.3) focused on the NWS “Point-and-Click” public weather web pages to determine how best to convey additional uncertainty information. (<em>Lead: GOV</em>)&lt;br&gt;• In consultation with social scientists, develop some prototypes of possible presentation formats for uncertainty information on government web pages (<em>Lead: GOV</em>)</td>
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| **(3.5)** Tailor Data, Products, Services, and Information for Private-Sector Customers | Solutions will require close communication. Education, training and outreach will highly factor in the effectiveness of communicating forecast uncertainty. Social science can help minimize confusion, and dismissal of uncertainty information. | • Improve visualization techniques (i.e., time series) to communicate changes in weather *(Lead: COM)*.  
• Improve graphics to depict decreasing forecast accuracy as the time period lengthens. *(Lead: COM)*.  
• Educate customers who receive products about the meaning of probability *(Lead: COM)*.  
• Certain technologies that make ‘steady state’ assumptions in storm path (e.g., StormTracker radar) need to be stated as such. *(Lead: COM)*.  
• Broadcast meteorologists re-evaluate how they present raw model output. *(Lead: COM)*.  
• Depict ensemble products as the range of possibilities and that a ‘best fit’ solution is made from these possibilities *(Lead: COM)*.  
• The AMS or other NGOs can facilitate the more rapid development of tailored products by gathering and promoting the publication of best practices. *(Lead: NGO)*.  
• Private-sector products will continue to be based upon numerical model and ensemble forecast information provided by the NWS. Since private customers may want products that do not change radically in characteristics from one day to the next, the NWS will need to provide advanced warning of modeling system changes. Ideally the NWS would make available training data such as reforecasts in advance of implementation. *(Lead: GOV)*.  
• Reconciliation of numerical model forecasts to actual occurrences (e.g., radar showing precipitation where there is none depicted in a numerical model). Rapid updates of mesoscale models and the distribution of these government products to the private sector will improve the accuracy of forecasts. *(Lead: GOV)*. |
| **(3.6)** Develop and Provide Decision Support Tools and Services | Develop forecaster tools that help forecasters provide critical users with optimally effective decision support. | • Make a list of customers and the decisions they make with weather information. Determine which users/decisions can potentially benefit the most from probabilistic forecast information. *(Lead: GOV)*.  
• Develop decision-support tools for forecasters and their most critical customers, including impact-based, graphical information (see also Obj. 3.4). *(Lead: GOV, ACA)*.  
• Evaluate decision support tools (see Obj. 4.4) *(Lead: GOV)*.  
• Implement decision support tools operationally for most critical customers *(Lead: GOV)*.  
• Develop decision-support tools secondary customers, and evaluate (see Obj. 4.4) *(Lead: GOV)*.  
• Continue to survey for important new customers and determine whether new decision support tools should be created *(Lead: GOV)*.  
• Implement decision support tools operationally for secondary customers *(Lead: GOV)*.  
• Continue to survey for important new customers and determine whether new decision support tools should be created *(Lead: GOV)*.  
• Intelligent information services to anticipate user needs/thresholds *(Lead: GOV)*. |
Implementation Roadmap Strategic Goal 4: Enabling forecast uncertainty research, development, and operations with supporting infrastructure.

The implementation roadmap for Strategic Goal 4 is summarized in Table 5 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 1.1), ensemble design (Objective 1.2), operational ensemble initialization and prediction (Objectives 2.1 and 2.2), and statistical post-processing (Objective 2.4) will require increases in high-performance computing. Despite advances that may be possible by sharing multi-model ensemble forecast data among U.S. and international centers, the production of skillful, reliable probability products cannot be achieved fully without a large increase in computational resources dedicated to the production of improved uncertainty forecasts. 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, ECMWF still dedicates approximately 50 times more computational resources to the production of its global medium-range ensemble compared to NCEP.

A readily accessible public archive of past operational ensemble forecasts and verification statistics is also needed (Objective 4.2) to facilitate research (Objectives 1.1 and 1.2), the calibration (statistical adjustment) of ensemble forecasts (Objective 2.4), the ensemble technique development process, and for 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 US 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, very large 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 private sector 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

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, private sector meteorologists, and consumers all have made significant and continuing investments in infrastructure. Technological advances keep increasing capabilities for the same price. Current user software systems are mostly oriented towards a single deterministic forecast. Software systems and decision aids that deal with a single forecast and no probabilistic information will ignore the new data streams. Post-processing requirements will add another dimension to the problem
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 31). GOV, ACA, COM, and NGO stand for the government, academia, commercial sector and non governmental organization sector, respectively.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Solution Strategy</th>
<th>Tasks</th>
</tr>
</thead>
</table>
| **(4.1) Acquire Necessary High Performance Computing Capability (HPC)** | Acquire more computer resources | • Determine CPU cycles necessary to run global, regional, and extreme-event systems envisioned in objectives 2.1, 2.2, as well as the reforecasts necessary for calibration in Objective 2.4. (Lead: GOV)  
• Procure and install HPC sufficient to carry out Objectives 2.2 and 2.3. (Lead: GOV)  
• Regularly upgrade HPC roughly in accordance with Moore's Law (a doubling of CPU power approximately every 2 years). (Lead: GOV) |
| **(4.2) Establish a Comprehensive Archive** | Expand NOAA’s “NOMADS” system so it provides ready access to ensemble predictions, post-processed 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. (Lead: GOV)  
• (Ideal) Archive full model output at high temporal resolution. (Practical) Since it is likely that the full archive cannot be maintained on fast storage, query relevant members of the community (see Obj 2.1, 2.2, 2.7) to determine what subset of data must be kept on fast storage. Archive this subset on fast storage, the rest on slow storage. (Lead: GOV)  
• Upgrade NOMADS system to accommodate higher-resolution output. (Lead: GOV)  
• Expand user interface to archive to allow more analytic services, e.g., ability to derive results using archived data. (Lead: 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. (Lead: GOV)  
• Implement requirements defined in short-term and begin continued requirements definition. (Lead: GOV)  
• Archive and user interface must keep pace with model and usage growth.  
• Build robust, flexible, and extensible system, and include analytic services (i.e., results derived from the archive) (Lead: GOV) |
| **(4.4) Establish Forecast Uncertainty Test Bed(s)** | Establish capabilities for model developers, forecasters, and users to interact prior to product implementation | • Explore possibilities for test bed(s) including expanding existing test beds, establishing new on-site facilities or virtual capabilities. (Lead: GOV)  
• Establish test bed(s) and processes for testing/evaluating experimental techniques and products well before implementation; and for easy transition to operations. (Lead: GOV)  
• Operation testbed(s) and continue to refine/improve approach. |
<table>
<thead>
<tr>
<th>(4.5) Work with Users to Define their Infrastructure Needs</th>
<th><strong>Short-term (0-2 years)</strong></th>
<th><strong>Medium-term (2-6 years)</strong></th>
<th><strong>Long-term (&gt; 6 years)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Educate users on size of problem early so planning processes can accommodate infrastructure commensurate with future needs.</td>
<td>• Publication and dissemination of ACUF report to educate users on requirements for ensemble data. <em>(Lead: NGO)</em></td>
<td>• Add sessions on this topic to appropriate AMS conferences. <em>(Lead: NGO)</em></td>
<td>• Encourage development of user community to exchange ideas, methods, and applications. <em>(Lead: NGO)</em></td>
</tr>
</tbody>
</table>
6. Summary and Monitoring Progress

The ACUF Weather and Climate Enterprise Strategic Implementation Plan for Generating and Communicating Forecast Uncertainty Information defines a vision, strategic goals, roles and responsibilities, and an implementation 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.

The plan is based on, and intended to provide a foundation for, implementing recent recommendations regarding forecast uncertainty by the National Research Council, AMS, and World Meteorological Organization. It leverages emerging results from The Observing System Research and Predictability Experiment (THORPEX), other scientific and socio-economic studies, and the best practices of hydrometeorological 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 socio-economic 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, marine and surface transportation efficiency
- Strengthen national defense and homeland security;
- Improve water resources management;
- Sustain ecosystem health;
- Improve energy production 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 in four key, interrelated strategic areas: 1) Understanding; 2) Generating; 3) Communicating and Assisting; 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 non-governmental organizations) should work in partnership over the next decade to meet the 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. While the implementation roadmap suggests sector roles and responsibilities and sector leadership for the various tasks, it is not programmatic in the sense of defining program plan with accompanying cost, schedule, and performance information. These important details are beyond the scope of this plan and are the purview and responsibility of
Enterprise decision makers throughout the partnership.

The ACUF recommends that the AMS Commission Steering Committee (CSC) as part of the CWCE monitor the progress of the ACUF Weather and Climate Enterprise Strategic Implementation plan for executive level oversight since that entity is representative of the Enterprise.
Figure 1: 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.
Figure 2. In December 1999, France and central Europe were battered by a rapidly developing
storm with wind gusts of up to one-hundred and fifty miles per hour. The storm caused one-
hundred and forty fatalities and damages exceeding an estimated 100 billion Euros. The
deterministic numerical weather prediction model operational at the time had no hint of the storm
at least 42 hours in advance. Without long-lead model guidance indicating the potential for a
storm, no advanced alerts were issued to raise public awareness and preparation activities until
closer to the time of the storm when the model finally began to indicate a storm. A comparison
between the single-value forecast and an ensemble forecast of the storm period (run
retrospectively) illustrates how forecast uncertainty information may have helped alert for the
possibility of the storm with longer lead time and thus improved public awareness and
preparation. In particular, as shown in the figure below, while the storm was not forecasted by
the operational deterministic prediction system 42-hours in advance, the post-event ensemble
prediction shows a large amount of forecast uncertainty, with 15 of 50 (30%) of ensemble model
members indicating the formation of an intense storm. If this ensemble information had been
available in real time, forecasters would have been aware of the possibility of a major storm given
that 30% of the ensemble members were predicting it, and may have raised a red flag and issued
alerts sooner.

Stamp map of the “Lothar” storm over France. Upper-left panel shows the sea-level pressure
contours from the deterministic prediction of the ECMWF system valid at 0600 UTC 26
December 1999. The panel just to the right shows the sea-level pressure analysis valid at the
same time. Fifty ensemble predictions are shown below, with many of the members forecasting
an intense storm similar to the one that verified (occurred, see chart labeled “Verification” on top
left). Reprinted with permission from Tim Palmer and ECMWF.
Figure 3: International efforts to express forecast uncertainty are available via the Internet. The following two weather forecast graphics are provided for Trondheim, Norway from the Norwegian Meteorological Institute Web site (see http://www.yr.no/). Figure A indicates the degree of “trust” or certainty that can be placed in each of three elements of the forecast: weather condition, temperature, and wind direction and speed. Figure B indicates numerical probabilities for different possible temperature and precipitation occurrences.

Probability forecast

The long term forecast in the table above contains the most predictable weather information, and how certain we are that the forecast is correct.

The probability forecast in the diagram below indicates the probabilities for different possible developments of the temperature and precipitation. The long term forecast is given by black lines.

The grey fields (for temperature) and the blue fields (for precipitation) indicate the range of possible weather developments which are predominantly probable (80 percent). The width of the fields is proportional to the degree of uncertainty of the forecast.

Within these fields, it is considered most probable (50 percent) that the development hits the dark part. Still it is somewhat probable (30 percent) that it hits the lighter part outside the dark.

Tips, advice and facts about the probability forecast (in Norwegian)

What is the probability for different weather?

The long term forecast (from the above table) is indicated with a black line.

Temperature:
- 60% probability
- 30% probability

Precipitation:
- 60% probability
- 30% probability
Figure 4. An illustrative probabilistic forecast for temperature. A distribution (blue curve) of probabilities (called a probability distribution function) defines the probability of occurrence for each degree increment within the range of possible temperatures. In this example, the range of possible temperatures in the probability distribution function is from 50°F to 60°F, with the largest probability (about 0.38) for a temperature of 55°F. The deterministic forecast (red line), on the other hand, expresses only the most likely single forecast value for the temperature, which is 55°F. What is missing from such a single-value forecast is the range of possible temperatures and their likelihood.
Figure 5. Ensemble forecast systems may be biased and/or deficient in spread resulting in misestimated probabilities.
Figure 6. Sample Product: Day 4-8 Convective Outlook from the NWS Storm Prediction Center. It is not clear what “Predictability Too Low” means.
List of Acronyms

Ad-Hoc Committee on Uncertainty in Forecasts (ACUF)
American Meteorological Society (AMS)
AMS Commission Steering Committee (CSC)
Commission on the Weather and Climate Enterprise (CWCE)
Cooperative Program for Operational Meteorology and Training (COMET)
European Centre for Medium Range Weather Forecasts (ECMWF)
Meteorological Service of Canada (MSC)
Model Output Statistics (MOS)
National Air Space System (NAS)
National Centers for Environmental Predication (NCEP)
National Digital Forecast Database (NDFD)
National Oceanic and Atmospheric Administration (NOAA)
NOAA Operational Model Archive and Distribution System (NOMADS)
National Research Council (NRC)
Next Generation Aviation Traffic Management System (NextGen)
Non-Government Organizations (NGOs)
Numerical Weather Prediction (NWP)
Operational Risk Management (ORM)
Probability Density Function (PDF)
Probability of Precipitation forecasts (POP)
The Observing System Research and Predictability Experiment (THORPEX)
THORPEX Interactive Grand Global Ensemble (TIGGE)
4-Dimensional Weather Information Database (WIDB)
World Meteorological Organization (WMO)
Appendix A
List of ACUF Members

Co-Chairs:
- Elliot Abrams, CCM
  AccuWeather, Inc.
- Steve Abelman
  NOAA/National Weather Service
- Dr. Jon Ahlquist
  Florida State University
- Jordan Alpert
  NOAA/National Weather Service
- Dan Bickford
  Meteorologist - WSPA-TV
- Matthew Biddle, Ph.D.
  The University of Oklahoma
- Andrea Bleistein
  NOAA/National Weather Service
- Phil Breuser
  Professional Consulting Meteorologist, Issaqu, WA
- David Bright
  NOAA/National Weather Service
- Peter Browning
  NOAA/National Weather Service
- Gordon Brooks
  Air Force Weather Agency
- Barbara G. Brown
  National Center for Atmospheric Research
- Bill Bua
  UCAR/COMET
- J.D. CETOLA, Lt Col, PhD
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- Dr Dan C Collins
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- Julie Demuth
  National Center for Atmospheric Research (NCAR)
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- Dr. Charles A. Doswell III, CCM
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- Dr. Jun Du
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- Tom Dulong
  Meteorologist in Charge
  NWS FAA Academy
- Gina Eosco
  American Meteorological Society, Policy Program
- Paul A. Hirschberg
  NOAA/National Weather Service
- Mary Erickson
  NOAA/National Ocean Service
- John Ferree
  NOAA/National Weather Service
- Greg Fishel
  Chief Meteorologist - WRAL-TV
- John Gaynor
  NOAA - Office of Weather and Air Quality
- Bob (aka Harry) Glahn
  NOAA/National Weather Service
- Thomas M. Hamill
  NOAA/ESRL
- John Hannan
  Defense Threat Reduction Agency
- Jim Hansen
  Naval Research Laboratory
- Pat Hayes
  Northrop Grumman Corp
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- Eddie Holmes, CBM (tentative),
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- Michael Johnson
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- Chris Kiley
  Advisory and Assistance Services (A&AS)
  Defense Threat Reduction Agency
  Chemical Biological Technologies Directorate
- Evan Kuchera
  Air Force Weather Agency
- Carlie Lawson
  Natural Hazards Consulting
- Jenifer Clare Martin
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• Chris Maier
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• Bernard N. Meisner, Ph.D. CCM
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• Brenda Philips
Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA)
University of Massachusetts
• Carla Roncoli, PhD
Department of Biological and Agricultural Engineering
The University of Georgia
• Dan Satterfield
Chief Meteorologist - WHNT TV
• John Schaake
Retired NOAA
• Paul Schultz
NOAA/GSD
• Prof Leonard A. Smith
London School of Economics
• John Sokich
NOAA/National Weather Service
• Alan E. Stewart, Ph. D.
The University of Georgia
• Dan Stillman
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• Neil Stuart
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• Zolton Toth
NOAA/National Weather Service
• Steve Tracton
Retired NOAA
• Robyn L. Weeks
The Weather Channel
• Dick Westergard, CCM
Shade Tree Meteorology, LLC
• Bernadette Woods
WJZ-TV
• Chris Elfing, Director
Board on Atmospheric Sciences and Climate
The National Academies (K-636)
• Scott Sandgathe
Principal Meteorologist
APL-UW
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: 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: 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 post-processed 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: 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:** NWS should dedicate executive attention to coordinating the estimation
and communication of uncertainty information within NWS and with Enterprise partners.

**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:** 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.

**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 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 National Centers for Environmental Prediction 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 nested
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) re-forecast datasets to
facilitate post-processing.

**Recommendation 3.5:** The National Center for Environmental Prediction, in collaboration with appropriate NOAA offices, should identify the length of re-forecast product necessary for time-scales and forecasts of interest, and produce a re-forecast 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 should investigate methods to use the full distribution of the Climate Forecast System ensemble members (e.g., through a post-processing 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 Climate Prediction Center should develop more effective objective methods for combining forecast components to improve forecast performance.

**Recommendation 3.10:** The Climate Prediction Center 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 National Weather Service and the National Centers for Environmental Prediction 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 should implement operational hydrology databases that span a large range of scales in space and time. The contribution of remotely-sensed and on-site data and the associated error measures to the production of such databases should be delineated.

**Recommendation 3.13:** The Office of Hydrologic Development 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 Office of Hydrologic Development 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: 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.

Communicating Forecast Uncertainty Recommendations:

Recommendation 4.1: The National Weather Service 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 post-processed 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 National Weather Service 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 Climate Prediction Center 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: 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

Formally, there are two primary interpretations of probability\(^4\) – 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 one to appear \(1/6\) of the time; that would be our forecast of a one occurring–\(1/6\). That would be a better forecast than saying “a one will happen,” or “a one will not happen.” After many tosses, a calculation of the number of ones 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 non-repeatable, 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, 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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\(^4\) 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 2. While such a distribution may not be definable analytically, in practice it is a rather smooth, non-decreasing 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 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

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 full use of the decision theory required. 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 and 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 [It is much more than reliability, it is the value they provide, which includes the level of definition they provide.], 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 unbiased probabilities.
Appendix E
Forecast Uncertainty Application Examples

Application Example 1:
Protecting Life and Property (Andrea Bleistein, NOAA/NWS)

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.37

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 like 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 WOD38. Further, those locations where a tornado first develops may receive very little or no lead time. So, an 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” (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). 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 times39, which would help lower yearly average losses nationwide owing to hazardous storms. Imagine having appropriately worded statements warning the public 1 hour ahead of tornadoes and 2 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.

37 See http://www.economics.noaa.gov/?goal=climate&file=users/government/nws
39 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 E1: Adapted from Stensrud, David J. et al., 2009. Figure E1a is radar reflectivity of a developing thunderstorm; b is radar reflectivity of a mature mesocyclone with polygon warning; c is radar reflectivity of a developing thunderstorm with a conceptual probabilistic path; and d is radar reflectivity of a mature mesocyclone with validated conceptual probabilistic path from image c. [Disclaimer: The images shown above are meant to illustrate a hypothetical application of “warn-on-probability” technology). Dissemination of a graphic with this sort of probabilistic path needs to take into account societal understanding of the message it is trying to communicate and false-alarm rates.]
Application Example 2:
Optimizing Tropical Cyclone Evacuations (Tom Hamill, NOAA/OAR)

Imagine yourself as a state emergency manager, responsible for ordering the evacuation of coastlines when a hurricane threatens. You must decide 48-h prior to the hurricane landfall to either evacuate, 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. You have available the expected number of lives that will be lost for every possible hurricane scenario (Table 1), with evacuation and with no evacuation. Envision three forecast scenarios:

**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. From this they have generated a table of the probabilities for storms of various intensity (tropical storm, hurricane Saffir-Simpson Category 1, 2, 3, 4, or 5) hitting your county. The data is also stratified according to whether the eye was to the east or west. A category-1 storm is the most likely, but there is still significant probability of a greater intensity storm.

**Scenario 2**: Your meteorologist provides you with a probability forecast that has the same mode (the most likely event is some category-1 storm), but there is much greater confidence in this outcome or a lesser tropical storm than in scenario 1. There is no probability of a major category-4 or -5 storm.

**Scenario 3**: Your meteorologist provides you with yet another probability forecast with the same mode (category 1), but now the uncertainty is very large, and the probability of a catastrophic category-5 storm is not that much less than the probability of a category-2 storm.

Scenario 1 approximates what is available currently. Ensemble predictions applied to hurricane forecasting is still an emerging science, and the ability to predict intensity and the situation-dependent uncertainty is limited, so climatological statistics are still commonly used. As a result, as shown in Table 1, you face a very tough choice: there is a nonzero chance of a catastrophic storm, and if you don’t evacuate, a major loss of life will occur. Then again, the probability is not especially high, and some lives will be lost in the evacuation, and people may not evacuate as readily next time with a false alarm.

The choices under the lower uncertainty and higher uncertainty forecasts are much more clear. The lower uncertainty forecast indicates little chance of a major hurricane, so the decision, at least for now, would likely be to not evacuate (this could be re-evaluated 6 or 12 h hence with new information). In the high-uncertainty scenario, the possibility of a major hurricane is in fact quite large, so the cost of a false alarm are more than overwhelmed by concerns that a complete evacuation could not be accomplished in time. This illustrates the case-to-case potential of uncertainty forecasting; the varying uncertainty in this case around the unvarying most likely event is enough to greatly affect a major decision.
<table>
<thead>
<tr>
<th>Tropica l storm</th>
<th>Cat 1 (east)</th>
<th>Cat 1 (west )</th>
<th>Cat 2 (east)</th>
<th>Cat 2 (west )</th>
<th>Cat 3 (east)</th>
<th>Cat 3 (west )</th>
<th>Cat 4 (east)</th>
<th>Cat 4 (west )</th>
<th>Cat 5 (east)</th>
<th>Cat 5 (west )</th>
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</thead>
<tbody>
<tr>
<td>Lives lost without evacuation</td>
<td>1</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>20</td>
<td>50</td>
<td>20</td>
<td>250</td>
<td>400</td>
<td>1300</td>
</tr>
<tr>
<td>Lives lost with evacuation</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>Probability, deterministic +climatology</td>
<td>0.1</td>
<td>0.17</td>
<td>0.17</td>
<td>0.13</td>
<td>0.13</td>
<td>0.08</td>
<td>0.08</td>
<td>0.05</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Probability, low uncertainty</td>
<td>0.35</td>
<td>0.25</td>
<td>0.22</td>
<td>0.09</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Probability high uncertainty</td>
<td>0.02</td>
<td>0.13</td>
<td>0.14</td>
<td>0.10</td>
<td>0.11</td>
<td>0.10</td>
<td>0.11</td>
<td>0.06</td>
<td>0.10</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Table 1**: An example of the use of probabilistic information for deciding on coastal evacuation in the case of an approaching hurricane for a particular county along an east-west oriented coast. Columns denote the possible category for the hurricane intensity *in this county*, and whether the eye will be to the west or to the east. The first row denotes the expected number of deaths as a function of storm type and eye position when no evacuation is ordered. The second row denotes the lives lost with evacuation (some are inevitable due to stress-related heart attacks, traffic accidents, and people disregarding evacuation orders). The third row denotes the probability of each possible event given a deterministic forecast and the statistics of errors from past deterministic forecasts. The fourth row denotes a possible probability forecast in a situation where the mode is the same (a category-2 storm) but where there is little uncertainty due to the use of ensemble prediction tools. The fifth row denotes another scenario where the mode is the same but now the uncertainty in the storm strength and position are larger.
Application Example 3:
Using Probabilistic Information to Fight Wildfires (Douglas Hilderbrand, NOAA/NWS)

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. 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 dominate 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 photo below), 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 E2. 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.

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 maximize resource effectiveness. Tactical efficiency improvements reduce cost for most severe fires (Type-1 fires) 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% 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 pre-deployed firefighters to respond to any shift in the winds to the west. Diurnal thunderstorms developing to the northeast has indeed caused this westerly shift in winds. However, because of the pre-deployment 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, NOAA/NWS)

In 2007, flight delays associated with increasing traffic within the national airspace system (NAS) accounted for almost 20% of total flight time equating to a cost of $41 billion. 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. Consequently, one key NextGen goal is to improve weather information and the use of weather information in ATM decision-making. The NextGen Network 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 space and 1 time) database so-called the Weather Information Database (WIDB), which will include global, regional, and local observations and forecasts.

Traditionally, aviation weather forecasts, such as Terminal Aerodrome Forecasts (TAFs), have been deterministic. However, already recognizing the value of forecast uncertainty information, documented requirements for the WIDB currently include probabilistic forecast information. For example, recent studies have shown how probability information can be used to reap considerable fuel carriage savings and be translated into anticipated air space capacity reductions.

One study 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 E3), the airline industry could collectively save hundreds of millions of dollars annually by incorporating such information into decision making.

Another study examined the value of applying probabilistic thunderstorm forecasts to enroute operations. Currently, air traffic managers utilize radar and deterministic forecast

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40 Joint Economic Committee of the House and Senate, May 22, 2008, Your Flight Has Been Delayed Again, Available at: http://www.jec.senate.gov/
42 Concept of Operations for the Next Generation Air Transportation System, v2.0, 2007: Joint Planning and Development Office, 1500 K St. NW, Suite 500, Washington, DC
products to issue so-called “playbook routes” as a method of directing traffic flow. Playbook routes are pre-determined 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. As shown in Figure E4, 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 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 ratio. Per the example in Figure E5, individual aircraft could be progressively routed from east to west through the boxes that have the lowest forecast likelihood of capacity reduction below the flow capacity ratio threshold (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 versus following a playbook route. Projected savings from this method have yet to be quantified in dollars, but they should be substantial.

Figure E5. Example of predicted probabilistic available flow capacity ratio based on expected weather hazards.

Application Example 5:
Strengthening Security (Jim Hansen, Naval Research Laboratory)

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 E6). 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 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.

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 Horn of Africa. 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 E7 is an example risk surface\(^{51}\) for an 84-hour forecast initialized at 00Z, November 14, 2008. At each point in the domain the probability of exceeding the four severity thresholds for surface winds and seas were estimated from the ensemble and used to populate the RMM. The maximum risk (lowest value) is then extracted and plotted in Figure E7 (low values are high risk, high values are low risk). At a glance an operator can see that the meteorological risk to pirates in

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\(^{47}\) OPNAV Instruction 3500.39B
\(^{48}\) [http://safetycenter.navy.mil/presentations/orm/5yearvision.htm](http://safetycenter.navy.mil/presentations/orm/5yearvision.htm)
\(^{49}\) [Economic Impact of Piracy in the Gulf of Aden on Global Trade](http://www.marad.dot.gov/documents/hoapiracy.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.
\(^{51}\) Note that this is risk from the point of view of the pirate; the risk associated with small boat operations.
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.

The 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.

<table>
<thead>
<tr>
<th>Severity</th>
<th>Probability</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death, Loss of Asset</td>
<td>Likely</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Severe Injury, Damage</td>
<td>Probable</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Minor Injury, Damage</td>
<td>May</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Minimal Threat</td>
<td>Unlikely</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure E6: Risk Management Matrix

Figure E7: Maximum risk for pirate activity
Appendix F

Detailed Description of Objectives

NOTE: TABLES ARE STILL UNDER CONSTRUCTION. EDITING PROCESS TO DATE MAY HAVE RESULTED IN SOME INCONSISTANCIES AMONG TABLES WITHIN THIS APPENDIX AND SECTION 5.

The objectives are organized under the strategic goals as follows:

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

Strategic Goal 2. Generate a fundamental set of operational forecast uncertainty data and information.
- Obj. 2.1 Improve the initialization of ensemble prediction systems.
- Obj. 2.2 Improve forecasts from operational ensemble prediction systems.
- Obj. 2.3 Develop and implement probabilistic nowcasting systems.
- Obj. 2.4 Improve statistical post-processing techniques.
- Obj. 2.5 Develop and implement non-statistical post-processing techniques.
- Obj. 2.6 Develop and implement probabilistic forecast preparation and management systems.
- Obj. 2.7 Train forecasters.
- Obj. 2.8 Develop and implement probabilistic verification systems.
- Obj. 2.9 Include digital probabilistic forecasts in the Weather Information Database.

Strategic Goal 3. Communicate forecast uncertainty information effectively, and assist users in interpreting and applying the information in their decision making.
- Obj. 3.1 Prepare the next generation for using uncertainty forecasts.
- Obj. 3.2 Revise undergraduate and graduate education to include uncertainty training.
- Obj. 3.3 Reach out to and educate users.
- Obj. 3.4: Improve the presentation of government-supplied uncertainty forecast products.
- Obj. 3.5: Tailor data, products, services, and information for private-sector customers.
- Obj. 3.6: Develop and provide decision assistance tools and services.

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 a forecast uncertainty test bed.
- Obj. 4.5: Work with users’ to define their infrastructure needs.

The information below includes: background; need; current capabilities and gaps; performance measures and targets; and proposed solution strategy, and tasks. The tasks include specific actions for the short-, mid-, and long-term periods of the next decade, with the short-term tasks generally focusing on those that can be performed within existing resources; and suggested Enterprise partner(s) leads based on the roles and responsibilities proposed in Section 4.
**Objective 1.1 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 basic research to determine quantitatively the limits of predictability for various scales of motion, flow regimes, a range of phenomena, and for various predictability metrics.

**Short-term (0-2 years):**
- Synthesize and publish the results of previous studies to document current understanding of the limits of predictability and how the limit is dependant on phenomena, scale, and metrics. *(Lead: academia)*
- Sustain current funding of ensemble and predictability research through programs such as THORPEX. *(Lead: academia, under government funding)*
- Develop funding programs/requests for proposals that focus on quantifying estimates of the limits of predictability. *(Lead: Government)*

**Medium-term (2-6 years):**
- Perform research with higher-resolution models that better quantify estimates of the limits of predictability. Prioritize studies based on phenomena based on societal impact, e.g., position and intensity of land-falling hurricanes, and predictability. *(Lead: academia, under government funding)*

**Long-term steps (6+ years):**
- Sustain predictability studies using improved, higher-resolution models that increasingly incorporate stochastic elements. *(Lead: academia, under government funding)*
### Objective 1.2: 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.

**Solution Strategy:** Perform research on the underlying theory and optimal design of probabilistic prediction systems. Perform systematic studies of the theoretical underpinnings of the treatment of numerical model error in ensembles. Develop and demonstrate techniques that address model error that is consistent with theory.

**Short-term (0-2 years):**
Continued research supported by existing research grants programs, primarily. *(Lead, academia, sponsored by US Navy, NOAA, NSF, and NASA)*

**Medium-term (2-6 years):**
An expanded research program on improved numerical techniques for estimating uncertainty. For improving the generation of ensembles, the basic research may follow a general sequence, such as: (a) identify a particular deficiency in existing ensemble forecast systems; (b) generate a hypothesis for how this deficiency could be ameliorated; (c) develop new techniques in accordance with this hypothesis, (d) perform experiments, comparing the new technique alongside existing techniques to determine if the new technique is superior. (e) If the new technique is superior (i.e., hypothesis confirmed), work with operational model developers (see Obj 2.2) to implement the technique, otherwise refine the hypothesis and repeat. *(Lead, academia, supported by government grants)*

**Long-term (6+ years):**
- Sustain predictability studies using improved, higher-resolution models. *(Lead, academia, supported by government grants)*

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**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.
### Objective 1.3: Identify societal needs and best methods for communicating forecast uncertainty

<table>
<thead>
<tr>
<th>Background:</th>
<th>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, and the private sector can assist the Enterprise effectively communicate forecast uncertainty.</th>
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<tbody>
<tr>
<td>Need:</td>
<td>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.</td>
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<tr>
<td>Current capabilities:</td>
<td>A few preliminary studies exist on the effective ways for communicating probabilistic information, including a WMO publication (<a href="http://tinyurl.com/676dyd">http://tinyurl.com/676dyd</a>).</td>
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<tr>
<td>Capability Gaps:</td>
<td>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.</td>
</tr>
<tr>
<td>Performance Measures and Targets:</td>
<td>Peer-reviewed research publications that provide useful guidance on best practices for communicating forecast uncertainty. Testing (see test bed) 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.</td>
</tr>
<tr>
<td>Solution Strategy:</td>
<td>Design and support research and entrain relevant experts to develop a community of social science, hydrometeorology, and interdisciplinary researchers working in this area. Build partnerships with established social science programs.</td>
</tr>
<tr>
<td>Short-term (0-2 years):</td>
<td>(1) Host a special conference or symposium at an annual meeting for the social science, behavioral and related research community to interact with hydrometeorological forecast providers and cross-fertilize findings. Example venues are the AMS Policy and Socioeconomic Research Symposium and the Board on Societal Impacts. Include broadcasters and private-sector meteorologists, who have experience in outreach to the public. (Lead: NGO) (2) Begin grants-driven projects to perform the basic research on optimal methods for communicating uncertainty and research on its benefits (Lead: academia). (3) Hold a workshop(s) to entrain new social science and interdisciplinary researchers into hydrometeorological forecast uncertainty, providing a forum to discuss existing knowledge and research questions and methods, and to build collaborations (Lead: NGO).</td>
</tr>
<tr>
<td>Medium-term (2-6 years):</td>
<td>(1) NOAA, NSF, Navy, and other government agencies • funding proposals to examine most effective ways to communicate uncertainty to different audiences in different contexts and • including communication of weather forecast uncertainty as a topic in existing calls for research (2) Researchers deliver findings to meteorological community on how users prefer to receive uncertainty information for a spectrum of products (rainfall, severe weather, daily temperatures, etc.) (3) AMS or universities facilitate building public/private consortiums for funding research on communication of forecast uncertainty</td>
</tr>
<tr>
<td>Long-term (6+ years):</td>
<td>Ongoing maintenance of organization to facilitate further research based on 2-6 year results (Lead: NGO, government).</td>
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Objective 2.1: Improve the initialization of ensemble prediction systems.

**Background:** 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.

**Need:** 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.

**Current Capability:** 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.

**Capability Gaps:** 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.

**Performance Measures and Targets:**
(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.

**Solution Strategy:** Develop ensemble data assimilation techniques (e.g., EnKF and potentially 4D-Var/EnKF hybrid, including improved methods for the treatment of model error in ensemble filters.

**Short-term (0-2 years):**
- Quasi-real-time tests during hurricane season of an EnKF using a global forecast model. EnKF data assimilation will be performed with a model with 30-km grid spacing using 60 members, and 10-member forecasts from a 15-km global model will be tested. Data will initially be evaluated for 1-week hurricane track and intensity forecasts and compared with operational GFS ensemble products. After the fact, this ensemble can be evaluated for its skill with other high-impact events, e.g., heavy precipitation.
- Continue R&D on improved methods for the treatment of model error and sampling error in ensemble filters.
- Explore methods for hybridization of variational and EnKF methods.

**Medium-term (2-6 years):**
- Implement EnKF into operations at NWP facilities.
- Evaluate EnKF relative to 4D-Var for its ability to produce reduced-error initial conditions.
- Develop hybrid 4D-Var / EnKF methods.

**Long-term steps (6+ years):**
- Test and implement hybrid 4D-Var/EnKF methods.
Objective 2.2: 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:** An ensemble of future weather scenarios that can directly provide reasonably sharp and reliable probabilistic forecasts, correctly accounting for the uncertainty 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 T126 (approximately 125 km grid spacing) with 20 members; 4x daily. For comparison, ECWMF runs a 50-member global ensemble at T399, 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 University of Washington). Recent results from using the THORPEX Interactive, Grand Global Ensemble also indicates that more skillful, reliable forecasts may be possible through the 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).

**Solution Strategy:** Refine ensemble model grid resolution dramatically in the next few years (followed by regular resolution improvements thereafter); incorporating research results from Objective 1.2 (basic research in ensemble prediction) into the operational systems; increase sharing of forecast data between operational facilities to create multi-model ensemble products; 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 among Federal agencies (e.g., NOAA, Navy, Air Force) and governments (Canada and others) through projects such as the North American Ensemble Forecast System (NAEFS), National Unified Operational Prediction Capability (NUOPC) and TIGGE/GIFS (THORPEX Interactive Grand Global Ensemble/Global Integrated Forecast System). (Lead: Government)
- Develop and test higher-resolution global ensembles, with improved treatments of the uncertainty due to model error. (Lead Government)
- Develop and test higher-resolution, improved physics short-range, limited-area ensembles, with improved treatments of the uncertainty due to model error. (Lead: government and Academia)
- Work with extramural basic researchers and lab partners that have developed improvements in experimental ensemble forecast systems to test these ideas in pseudo-operational environments (Lead Government)
- Develop and test improved hydrologic ensemble forecast system models (Lead: Government and Academia)
- Explore product development from lagged-average ensemble forecasts from the Rapid Update Cycle and the WRF Rapid Refresh (Lead: government and Academia)

**Medium-term (2-6 years):**
- Implement higher-resolution ensemble model systems. To provide state-of-the-art forecasts, U.S. Enterprise (NOAA, DoD) should increase resolution threefold by 2012. (Lead: Government and Academia)
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.

- Increase SREF system resolution threefold, to ~10 km grid spacing by 2011-2012 with hourly output. (Lead: Government and Academia)
- Develop and implement a relocatable, high-resolution, explicit convection (~4-km grid spacing) limited-area ensemble forecast system for hurricanes, severe local storms, and fire weather that can be nested inside the SREF or GEFS systems, and appropriate methods for initialization. (Lead: Government and Academia)
- Explore the usage of a high-resolution, lagged ensemble forecast system based upon a high-resolution WRF Rapid Refresh (the HRRR). (Lead: Government and Academia)
- Upgrade hydrologic forecast models, so that the meteorological weather input into a hydrologic ensemble prediction system will produce more reliable streamflow forecasts with less need of post-processing. (Lead: Government and Academia)

Long-term steps (6+ years):

- Enterprise should double its ensemble forecast system horizontal resolution approximately every 8 years, consistent with Moore’s Law. (Lead: Government and Academia)
Objective 2.3: Develop and Implement 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

**Solution Strategy:** Given probabilistic nowcasting is a relatively immature technology, explore and compare a variety of possible techniques to determine the most appropriate solutions. It is unlikely that there will be any one-size-fits-all nowcast scheme; perhaps different methods will be developed tailored to different customers and different locations. Some avenues for progress include extending the methods discussed in the “current capabilities” section, as well as exploring the “dressing” of deterministic nowcasts with samples of errors to produce an ensemble of realizations from which probabilities can be estimated. For example, Nehrkont and Hoffman (2006) investigate a dressing technique based on phase errors, which might be particularly appropriate for nowcasting applications. Perhaps tools like the AutoNowcaster that rely on recent observed data can be modified to permit other discrete realizations based on realistic changes to the estimated propagation speed or rate of development/dissipation. In this manner, an ensemble of possible future scenarios may be obtained.

For longer leads, develop and refine tools for blending together the observationally based nowcast and numerically based probabilistic NWP guidance as forecast lead increases. At the earliest leads, nowcasts would be heavily weighted, and at longer leads the NWP guidance would receive increasingly larger weight. Weights will be adjusted as NWP improves for short leads and become more useful than observationally based approaches.

**Short-term (0-2 years):**
- Extend and revise existing probabilistic nowcast algorithms.
- Incorporate probabilistic elements into current deterministic nowcast algorithms, including the dressing of existing deterministic forecast with uncertainty information.
- Develop tools for blending together the observationally-based nowcast and numerically-based NWP guidance as forecast lead increases. (Leads: Government, academia)

**Medium-term (2-6 years):**
- Perform intercomparisons of nowcast algorithms to determine which are the most suitable for crucial applications. Based on the performance of these,
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.

<table>
<thead>
<tr>
<th></th>
<th>implement the most appropriate probabilistic nowcast algorithms (Leads: government, academia, commercial sector).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Long-term steps (6+ years):</strong></td>
<td>Based on improved data assimilation and numerical weather prediction systems, decrease emphases on separate nowcasting tools, and develop more NWP based approaches. (Leads: government, academia)</td>
</tr>
</tbody>
</table>
### Objective 2.4: Improve statistical post-processing techniques.

**Background:** Statistical post-processing 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 post-processing 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 post-processing, 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 maximize 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-grid scale 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

### Solution Strategy
Continue ongoing efforts to improve statistical post-processing of ensemble model output and pursue systematic approaches to optimize ensemble calibration techniques.

**Short-term (0-2 years):**
- Define which observational data set(s) or time series of analyses should be used for testing techniques. *(Lead: Government)*
- Continue to test a variety of algorithms for operational correction of ensembles, including Ensemble Kernel Density MOS (EKDMOS) and stepwise calibration through bias correction at the large scales and a downscaling. *(Lead: Government)*
- Continue research into the optimum reforecast training size *(Lead: Government)*
- Develop roadmap for statistical post-processing. *(Lead: Government)*
- Implement a single-member reforecast into real-time ensemble forecast system, with reforecasts calculated over several decades and a temporal frequency of approximately once per week. *(Lead: Government)*

**Medium-term (2-6 years):**
- Develop the robust reforecast and observational/analysis training data sets to perform statistical post-processing studies, including high-resolution analyses. *(Lead: Government)*
- Survey the literature on existing calibration techniques for each of the parameters, as well as requirements the supporting data sets required. *(Lead: Academia)*
- Perform an objective comparison of the techniques for each forecast variable to determine which is the most appropriate. If none of the existing calibration techniques appear to be appropriate, develop and test new, more appropriate calibration techniques. If the performance of the calibration technique strongly depends on the training sample size, determine which compromises in reforecast sample size (e.g., shrinking the number of reforecast members, or skipping days between reforecasts) lead to the least
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 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:**
- **Short-term:**
  1. Develop implementation plan for post-processing (due by Dec 2010)
  2. Improvement of at least 1 day lead time in the skill of probabilistic forecasts of basic variables such as 2-m temperature, 10-m wind components, and degradation. (Lead: Government)
- Evaluate the prototypes of calibrated forecast products (see Obj 2.6) using standard verification tools (see Obj 2.4). (Lead: Government)
- Implement the calibration techniques. (Lead: Government)

**Long-term steps (6+ years):**
- Reforecast data sets will need to be computed regularly with the then operational model (Lead: Government)
- New customers may be expected to request new products for less standard variables, which may require the development of specific calibration approaches. (Lead: Government)
precipitation after the implementation of the 1-member reforecast.
(3) Peer-reviewed publications that clarify the optimal methods for post-
processing for a variety of applications, as well as publications that explore
sample size issues.
Medium-term:
(1) Completion of the computations of a multi-member reforecast data sets
spanning several decades for operational ensemble prediction system models (by
Dec 2012).
(2) Peer-reviewed publications that document the intercomparisons of post-
processing methods for high-impact events (by Dec 2013).
(3) Experimental post-processing methods that deliver at least 1+ additional day
of forecast lead time for basic variables, above and beyond the gain delivered by
the 1-member reforecast (by Dec 2013).
(4) Operational implementation of advanced statistical post-processing techniques
(July 2014).
Long term:
(1) Regular computation of reforecasts for real-time ensemble prediction system
models.
(2) Testing and implementation of post-processing techniques for less standard
variables.
### Objective 2.5: Develop and Implement Non-statistical Post-processing Techniques

**Background:** 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.

**Need:** 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. Post-processing methods will be needed that can produce reliable, skillful forecasts of these uncertainty elements.

**Current capabilities:** 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 in Kansas City.

**Capability Gaps:** 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.

**Solution Strategy:** Test using a statistically postprocessed ensemble forecasts as inputs to the post-processing techniques; determine whether the forecasts for these indirect forecast elements are reliable. If not, engage in research and development to refine techniques.

**Short-term (0-2 years):**
- For a variable where there are some observations, test the simple method of forming an ensemble of diagnosed values from ensemble model outputs. Examine the reliability and skill of these forecasts. If bias-corrected members are available (see Objective 2.4 above), determine whether the input bias-corrected data produces a more reliable and skillful diagnosed ensemble. *(Lead: Government)*

**Medium-term (2-6 years):**
- Presuming that the diagnostic ensembles above are not reliable nor highly skillful, a more wide-ranging set of research objectives should be performed. Perhaps the forecast variables of interest such as icing are inherently sub-grid scale phenomena that cannot be forecast correctly from grid-scale data, even if that grid-scale data is calibrated. Hence, it may be necessary to develop techniques that produce appropriate sub-grid scale probabilistic forecast information based on the calibrated grid-scale information.

**Long-term steps (6+ years):** Unknown at this point, since this field is relatively immature.

**Performance Measures and Targets:**
-
**Objective 2.6 Develop and Implement Probabilistic Forecast Preparation and Management Systems**

**Background:** Automated probabilistic forecast guidance, e.g. from ensembles and statistical post-processing, may be improved through incorporating forecaster judgment. Computer tools are needed that will allow forecasters to modify objective guidance.

**Need:** 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 post-processed 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.

**Current Capability:** 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 on The National Weather Service 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.

**Capability Gaps:** 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

**Solution Strategy:** Forecasters should have access to datasets from past hydrometeorological events, especially those that were of high impact. In anticipation of certain events, the forecaster should be able to review these cases, compute verification statistics relevant to the situation, and then make well-informed decisions on which ensemble members to emphasize or de-emphasize in the blending process. It is expected that the objective model-derived guidance will be of sufficiently high quality that for most benign weather scenarios it will be used without editing by human forecasters. Scientific validation of forecaster skill will have to occur before any operational transition takes place.

**Short-term (0-2 years):**
- Conduct workshop(s) with forecasters and AWIPS developers to determine development priorities
- Conduct workshop(s) with pilot users of probabilistic forecast information.
- Complete plan to include ensemble information in AWIPS
- Identify reforecast situations in small number of WFOs

**Medium-term (2-6 years):**
- Conduct forecast exercises for forecasters to gather feedback on workstation requirements
- Implement basic capabilities, including new gridded products on the National Digital Forecast Database (NDFD)
- On a research basis, reforecast key cases for selected WFOs
- Develop plans to identify and reforecast key cases nationwide

**Long-term steps (6+ years):**
- Add advanced capabilities
- Formalize and implement the approach of reforecasting key cases. This will require coordination with the NCEP, including having a champion of the reforecast approach at the NCEP. *(Lead: Government)*
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.

*Performance Measures and Targets:*
Objective 2.7 Train Forecasters

Background: Operational government and private-sector forecasters are used to producing mostly deterministic products and may be used to thinking 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 can not be corrected with statistical post-processing. Further, this knowledge must be kept fresh—everything potentially changes as the model and post-processing 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 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 public and private 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

Solution Strategy: UCAR/COMET, the NWS Warning Decision Training Branch (WDTB), and the NWS Training Center (NWSTC), along with other interested parties, need to be involved in, and coordinate, the development of operational forecasting-based training on the use of EPS as a tool to be used in the forecast process.

Short-term steps (0-2 years; lead: government):
- Identify collaborators, within and outside the NWS (e.g. at COMET, WTDB, NWSTC, university researchers, private meteorological entities)
- Identify existing web-based training on uncertainty, probabilistic NWP.
- Identify other disciplines using uncertainty and look for relevant methods of training for use in meteorology.
- When and where practical, develop training on best practices to communicate uncertainty to end-users of forecast products.
- Develop training materials, both for an in-person course and on-line.
- Identify reviewers and testers from operational environments, and use them to give feedback on training as it is developed and after it is published for use.

Medium-term (2-6 years; lead: government):
- Run training courses for forecasters.
- Once formats for the expression of uncertainty have decided upon by the NWS and others, probabilistic product training will also need to be developed.
- Access to data will be needed to develop operationally relevant case applications for high-impact weather events, set up to emulate the operational forecast environment.
- Ongoing: Trained personnel in field offices identify good cases for future training material, and participate in the development of new training material.
- Training would include use of the WES and other real-time simulators appropriate to operations.

Long-term steps (6+ years; lead: government):
| COMET (2011). 25 percent of NWS, military forecasters trained by 2012, additional 25 percent each year thereafter. | • Maintain training developed over the mid-term so that continues to be current and relevant to forecast operations. |
Objective 2.8: Develop and implement probabilistic verification systems

**Background:** The weather enterprise is used to evaluating models and weather forecast with deterministic metrics. Once forecasts are expressed with uncertainty information, they will need to be evaluated using metrics that quantify how well they do in making 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:**
- Version 1.0 of uncertainty forecast verification software library (2013)

**Solution Strategy:** Form a group of experts to develop forecast uncertainty verification standards and best practices. Develop and freely disseminate a software library of verification and verification display procedures appropriate to forecast uncertainty products. Implement a “verification clearing house” where forecast uncertainty verification statistics are collated and displayed.

**Short-term (0-2 years):**
- Continue ongoing research into new verification methods.
- Develop prototype probabilistic verification packages for particular applications, such as for aviation forecasts.
- Note: World Meteorological Organization activities may coalesce in the next two years around standards for the verification through its joint working group on verification and THORPEX/TIGGE working groups.

**Medium-term (2-6 years):**
- Form a team of uncertainty verification experts to: (i) identify a standard, scientifically defensible set of methodologies for the evaluation of uncertainty forecast products, (ii) evaluate new metrics and determine whether they should become part of the baseline, and (iii) based on (i) and (ii), develop and publish an “uncertainty verification manual” that specifically indicates how each metric is to be computed.
- Periodically thereafter, this team will meet to review new verification developments and determine whether the manual should be expanded or changed.
- Software developers will build a standardized library of routines based on the specifications in the uncertainty verification manual, as well as software for the convenient display of verification data. This software will be made publicly available as freeware.
- Relevant parts of the weather enterprise (model developers, forecasters, applications developers) use the toolkit for verification, and make the verification data publicly available.
- Institute a verification “clearing house” where the synthesized...
<table>
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<th>First results from verification clearing house (2014).</th>
<th>verification results from various components (raw ensemble guidance, objectively post-processed guidance, official forecasts, and end products) are all gathered in one place and made available. <em>(Lead: Government)</em></th>
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| **Long-term steps (6+ years):**                      | Users are likely to continue to request the development and testing of new uncertainty products. *(Lead: Government)*  
Accordingly, new verification procedures specific to these products will be needed. *(Lead: Government).* |
**Objective 2.9: Include digital probabilistic forecasts in the Weather Information Database:**

**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.

**Solution Strategy:** Figure x illustrates Conceptual model of the Weather Information Database. Ensemble prediction systems, probabilistic statistical post-processing systems, and forecaster value added generation of probabilistic forecasts occur in the forecasting sector of the conceptual model (upper right sector). The probabilistic forecast output is then integrated into Decision Support Systems, as well as into graphical and text products (bottom sector).

[note from Tom: this description isn’t quite clear to me yet. What is stored in the WIDB? Different ensemble prediction system’s outputs, or one synthesized set of uncertainty data, including forecaster manual adjustments? Does the WIDB store the data to make decisions, or does it contain decision information?]

Also, the content of the solution strategy ought to be about what specifically needs to be done to extend the WIDB to contain probabilistic information rather than deterministic.]

**Short-term (0-2 years):**
- integrating probabilistic data into other environmental information sources
- forecaster oversight of probabilistic gridded data,
- developing common data standards and protocols (e.g., lexicon of probabilistic terms),
- initial integration of diverse weather elements into decision support tools. *(Lead: Government)*

[note from Tom: I prefer to have this information expressed as tasks, e.g., 1st bullet becomes “develop techniques for synthesizing uncertainty information from a variety of ensemble prediction systems, and other tools”]

**Medium-term (2-6 years):**
- improving the ensemble model systems (high resolution and accuracy of individual members),
- full network compatibility of environmental information
**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 ensure 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.

{Tom: this information below is useful, but it doesn’t sound like a “gap” description to me. Also: how do we resolve discrepancies between various systems, e.g., SREF versus global model? Is the data stored as ensemble members, as probabilities, or what?}

Specifically, a net-centric (net-enabled) capability is envisioned:

*Information is available, secure, and usable in real time
Information push/pull (two-way sharing)*

Virtual repository with no single physical database or centralized system

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**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) [note from Tom: the above sounds like a metric for a decision support system, not one for a WIDB.]

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.

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- direct integration of probabilistic information into Air Traffic Management Systems.

**Long-term steps (6+ years):**

- meeting all probabilistic NextGen requirements *(Lead: Government)*
- full network connectivity ensuring consistent information use across service areas and user groups. *(Lead: Government)*
### Objective 3.1: Prepare the next generation for using uncertainty forecasts through enhanced K-12 Education

**Description and Purpose:** 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.

**Need:** In order for our society to understand and use probabilistic information, primary and secondary education standards must include basic concepts in statistics and probability.

**Current Capability:** 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:

- NSF National Science Digital Library (http://nsdl.org)
- 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/)

**Capability Gaps:** 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

**Solution Strategy:** This solution presupposes a general acceptance of the ACUF recommendations and that the enterprise is going to follow through.

**Responsibility:** Professional organizations like the AMS provide material.

**Short-term (0-2 years):**
- **Lead:** AMS, NWA, (Teacher Resource Groups?)
- AMS will sponsor an ad-hoc committee to develop sample problems that illustrate the concepts of probability and statistics in meteorology and weather forecasting; these are put into existing libraries like DLESE.

**Medium-term (2-6 years):**
- **Lead:** AMS, NWA, (Teacher Resource Groups?)
- AMS will contact major textbook manufacturers, indicating how weather products are going to change to incorporate uncertainty information. AMS will encourage them to use examples contained in the repository mentioned in 1).
- The AMS will initiate contact with state departments of education and school boards across the country, providing information on how weather products were going to change to incorporate uncertainty information, and suggesting that it would be useful to further emphasize probability and statistics, including meteorological examples, in the high-school math curricula.

**Long-term steps (6+ years):**
- **Lead:** AMS, NWA, (Teacher Resource Groups?)
- Develop a mechanism to maintain contact with institutions involved in K-12 education and update these institutions on new developments in meteorological uncertainty, appropriate to K-12 education.
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.

**Performance Measures and Targets:**

- **AMS Committee produces examples and test question, incorporated into DLESE (2012)**
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## Objective 3.2: 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 prediction, 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 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. Social science courses are not considered “relevant” in the typical meteorology undergraduate course work.

**Solution Strategy:** Undergraduate and graduate meteorology/atmospheric science departments should include material in their courses on understanding and interpreting ensemble, probabilistic and uncertainty forecast products. This will be more difficult to do at the undergraduate than at the graduate level because there is currently no room in the 4-year curriculum for a specific course on these topics. Regardless, the following short- and medium-range steps should be undertaken to add the requisite material to existing coursework. In addition, faculty advisors should stress the value of cross-discipline studies in the social sciences.

**Short-term (0-2 years; Lead: Academic Sector):**
- Build a web site for educators to share resources. This platform will serve as a bridge until textbooks can be updated to cover this material. The COMET Program (http://www.comet.ucar.edu) may be a suitable place that could be used to post materials and lectures. An example of this, using Moodle software, can be found at [http://courses.comet.ucar.edu] and clicking on COMET Faculty Multimedia Workshop. COMET modules could also be developed that are geared directly to students that could be used to support or motivate synoptic meteorology laboratory assignments. Note that prior to publication COMET modules are quality controlled by multiple reviews.

**Medium-term (2-6 years; Lead: Academic Sector):**
- At the undergraduate level, assimilate new uncertainty material into courses that are currently offered. One possibility is a synoptic/weather-forecasting laboratory that includes a brief description of chaos theory and model error, the basics of how ensemble prediction methods allow estimation of uncertainty from these sources, followed by a lab session comparing ensemble guidance from various systems for a particular storm, or storms, with an evaluation of the strengths and weaknesses of...
| Addition of courses at top 15% of meteorological/atmospheric science college/universities |
| Revise AMS standards for Bachelor’s degree |

- At the graduate level, where programs in atmospheric sciences have more flexibility than undergraduate programs:
  - Students should be required to take a basic probability and statistics course because of its broad utility to both forecasting and data analysis.
  - Ideally, the students would also have the opportunity to take a course in statistical meteorology at the level of Wilks’ *Statistical Methods in the Atmospheric Sciences*.
  - Further, if not covered in a statistical meteorology course, a graduate-level course in dynamic meteorology should include a section that covers chaos theory.
  - Numerical weather prediction courses should discuss ensemble prediction methods, including methods for generating ensembles of initial conditions and model error in ensemble forecasts.

*Long-term steps (6+ years):*

- **Lead: Universities and Professional Organizations**
- Develop a mechanism (possibly through the AMS) to maintain contact with institutions involved in post-secondary education, and update these institutions on new developments in meteorological uncertainty, at a level appropriate to undergraduate and graduate education.
**Objective 3.3: Reach Out To and Educate 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), 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:

**Solution Strategy:** Responsibility: Entire Weather Enterprise including 1) America’s weather and climate forecast industry (e.g., TV meteorologists and private-sector meteorologists); 2) Government (NOAA education/outreach programs/materials), 3) Academic sector including Societal Impact Programs (monitor effectiveness and suggest new methods) and 4) NGO (AMS, NWA, etc…)

Social science methodologies, such as group or individual interviews, surveys, workshops, behavioral analysis, etc., can help determine effective ways to communicate uncertainty information (e.g., displays, formats, word choice).

**Short-term(0-2 years):**
- Early versions of government and private-sector uncertainty products should have, incorporated into the web pages, a feedback form that permits users to indicate what they did and did not understand. The providers should institute a process and work with social scientists for gathering this information, analyzing feedback information, and determining whether changes to the products are warranted [lead: social scientists in government/private sector].
- Design government and private-sector uncertainty forecast products to include links to training material on the uncertainty information; how it is generated, how it is to be interpreted, etc. [lead: government, private sector].
- As TV meteorologists begin to incorporate uncertainty elements into their broadcasts, they also include some rudimentary training of how to interpret this. Certified Broadcast Meteorologists (CBMs) should be pivotal in outreach and education to the general public, and provide mechanisms for feedback to the NWS and other members of the meteorological community on uncertainty products. [lead: private-sector].
- Meetings/Conferences/Workshops that specifically focus on forecast uncertainty will be a venue for user evaluation and feedback.
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, 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.

**Performance Measures and Targets:**

- Web hits in a given time period
- Viewership of digital cable channel that displays more detailed probabilistic weather information
- Response/feedback rate within a given time period per new product/service released

**Medium-term (2-6 years):**

- **Lead: Weather Enterprise**
- Certified Broadcast Meteorologists (CBMs), who act as station scientists at TV and radio stations, should be trained to communicate uncertainty in the forecast through the certification continuing education process, using training materials developed in Objective 3.3. Also, perhaps a short course on the use of probabilistic models should be developed through the AMS and then presented at large-venue meetings of the CBMs. The CBMs would then serve as trainers on probabilistic forecasting through their regular outreach to the public.
- For more sophisticated end-users, more comprehensive material and training will be required. Two possible approaches would be
  - To develop a short course or set of short courses addressing the needs of such end-users, such as emergency managers, governmental entities, private corporations (such as utility companies) and the like.
  - Add a requirement for continuing professional education of certified consulting meteorologists to become conversant in uncertainty in the context of energy usage, weather-related travel safety, governmental issues, infrastructure damage mitigation, and so on.

**Long-term steps (6+ years):**

- **Lead: Weather Enterprise**
- Build upon and sustain business practices that include user feedback, social science, and impact-based decision support.
Objective 3.4: Improve the presentation of government-supplied uncertainty forecast products

**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.

**Solution Strategy:** The government, especially the NWS, re-engineers their web products to include uncertainty information with a standard look-and-feel based on collaboration with social scientists. The format follows the best available research on effective ways of communicating forecast uncertainty.

**Short-term (0-2 years):**

- Planning for possible presentation formats proceeds from existing information like that compiled in the NRC and WMO reports. *(Lead: Government)*

**Medium-term (2-6 years):**

- Consider the NWS’s standard weather forecast web page for purposes of illustration; for other government sectors or private industry, envision an analogous process. The process would start by the NWS convening a team of graphical designers, communications experts, and its forecasters to work together. The team would be supplied some a set of requirements on the information that must be presented, e.g., the product must convey information on the 10th/50th/90th percentiles of the probability distribution for all forecast elements currently on the NWS web page. The initial objective of the team would then be to develop several prototypes of redesigned web pages. These formats would be critiqued in a test bed environment (see Obj 4.6), which would indicate which of the prototypes, or which combination of prototypes, is preferred. This information is then conveyed to the NWS web page designers, who redesign the web pages to incorporate the additional information. In addition to some appealing graphical format, the revised web page 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. Since the information is bound to be somewhat difficult to interpret at first for many users, the revised web page should direct the user to some sort of help page to learn about how to interpret the new
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information being conveyed.

The NWS may also wish to have some way of allowing the public to comment on the new products after implementation; the small sample of a focus group on a test bed may not uncover all of the ambiguities the larger public will have. *(Lead: Government)*

**Long-term steps (6+ years):**
- *Lead: Government*
- Incorporate social science into standard research and development of uncertainty products and services.
### Objective 3.5: Tailor Data, Products, and Services for Private-Sector Customers

**Background:** Products and services for private-sector customers must effectively communicate risk and uncertainty. The private sector predicts weather for the general public, as well as many customers seeking more specific uncertainty forecast information and decision-support assistance.

**Need:** 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 the private sector specific to their commercial clients.

**Current Capability:**
Most tailored forecasts are still deterministic, but some probabilistic offerings are now available. For example, at AER, Inc. ensemble forecasts are post-processed 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 the private-sector industry, yet the general public struggles with understanding the meaning of probability. This gap in understanding needs to be bridged (see Objective 3.4).

**Capability Gaps:** 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.

**Solution Strategy:** Solution methods are likely to be tailored to each particular provider and customer, and each will require close communication to define a viable interface for communicating uncertainty. The value of tailored product, data, and service will undoubtedly depend on the end user’s ability to comprehend the meaning of probability and risk. In this respect, education, training and outreach will highly factor in the effectiveness of communicating forecast uncertainty. Objectives 3.1 through 3.4 are cross-correlated here. Social science is essential to minimize misinterpretation, confusion, and dismissal of uncertainty information.

**Short-term (0-2 years):**
- Improve visualization techniques (i.e., use time series) or other methods to communicate trend or changes in weather (Lead: private sector).
- Improve graphics or visualization to deal with the problem of decreasing forecast accuracy as the time period lengthens (long-range forecasts). Day 6 should not be perceived with the same likelihood of occurrence as Day 1 (Lead: private sector).
- Educate customers and general public audience that receive private-sector product about the meaning of probability in the values they see in pictographs (Lead: private sector).
- Certain private-sector technologies that make ‘steady state’ assumptions in storm path (e.g., StormTracker radar) need to be stated as such, and the implications of that assumption need to be expressed to users when convection is rapidly changing or not steady state (Lead: private sector).
- Many television broadcast meteorologists show model forecasts in their presentation. However, TV meteorologists end up having to ‘explain away’ the problems of the model -- whether it will verify or not, if the precipitation shield is overblown, if the precipitation is too fast, etc. This problem detracts from the effectiveness of communication, including forecast uncertainty. Broadcast
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.

**Performance Measures and Targets:**

In the private 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.

Meteorologists may want to re-evaluate how they present raw model output to the public (Lead: private sector)

- Where ensemble products are presented to the public or end-user, it will be up to the provider to explain these are the ranges of possibilities and that a ‘best fit’ solution is made from these possibilities (Lead: private sector)

**Medium-term (2-6 years):**

- The AMS or similar organization can facilitate the more rapid development of tailored products by gathering and promoting the publication of best practices and success stories in this field. (Lead: NGO)

- Private-sector products will continue to be based upon numerical model and ensemble forecast information provided by the NWS. Since private customers may want products that do not change radically in characteristics from one day to the next, the NWS will need to provide advanced warning of modeling system changes. Ideally the NWS would make available training data such as reforecasts in advance of implementation. (Lead: Government)

**Long-term steps (6+ years):**

- Reconciliation of numerical model forecasts to actual occurrences (e.g., radar showing precipitation where there is none depicted in a numerical model). Rapid updates of mesoscale models and the distribution of these government products to the private sector will improve the accuracy of forecasts. (Lead: Government)
### Objective 3.6: Develop and Provide Decision Support Tools and Services

**Description and Purpose:** 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.

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

**Current Capability:**
- Ad hoc services as needed from government agencies during high impact events (i.e. Red River flooding in 2009).
- Ad hoc use of technologies
- On site support to various state, local EOCs and FEMA

**Capability Gaps:**
- 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

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

**Solution Strategy:**
Provide a link between forecast information, interpretation and user applications.

**Short-term (0-2 years):**
- **Lead:** Government
- Fully connect with partner/customer needs: The increased “direct focus” places a higher emphasis on ensuring the information provided and communicated meets user needs
- Develop training courses and position description requirements for training and hiring proper support personnel

**Medium-term (2-6 years):**
- **Lead:** Government
- Leverage New Technology and Data Sets:
  - New tools (4-D cube), improved high resolution models and new decision support tools free up forecaster time formally spent on routine tasks
  - Increase direct focus and customization:
    - Impact-based, graphical information to paint a complete picture quickly and convey uncertainty information
    - On-demand office communications (chat, point-point, & point-multipoint)
- Maximize value to NOAA:
  - Effectively cut across NOAA Lines and engage other federal agencies with highly relevant, useful information.
  - Source for partner decision support as it related to weather, water and climate impacts

**Long-term steps (6+ years):**
- **Lead:** Government
- Intelligent information services to anticipate user needs/thresholds
**Objective 4.1: Acquire Necessary High Performance Computing**

**Background:** 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 post-processing (Objective 2.4) require high-performance computing.

**Need:** Uncertainty forecasts will be based largely upon ensemble predictions and the post-processing 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.

**Current Capability:** 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.

**Capability Gaps:** 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.

**Performance Measures and Targets:**
- 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.

**Solution Strategy:**
- Acquire more compute resources. Operational forecasts require a dedicated facility.

**Short-term (0-2 years):**
- Determine the CPU cycles necessary for NOAA to run the global, regional, and extreme-event systems envisioned in objectives 2.1, 2.2, as well as the reforecasts necessary for calibration in objective 2.4. (Lead: government)

**Medium-term (2-6 years):**
- Procure and install the supercomputers sufficient to carry out Objs 2.2 and 2.3. Also, NOAA’s high-performance research computers will need a similar magnitude upgrade so that they are capable of testing future ensemble forecast systems. (Lead: government)

**Long-term steps (6+ years):**
- The upgrade should also not be considered a one-time-event; after this major upgrade, NOAA should regularly upgrade its computers roughly in accordance with Moore’s Law (a doubling of CPU power approximately every 2 years).
### 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 post-processing (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 post-processing works best if the same systems (observing, modeling, and data assimilation systems) are used to prepare the historical data as in the system.

**Solution Strategy:** It is anticipated that the NOMADS system will be extended to accommodate the extra forecast and reforecast data. Analysis and observation data are available elsewhere, but should be accessible through NOMADS to provide seamless ordering and delivery.

**Short-term (0-2 years):**
- The first step in extending NOMADS will be a requirements definition phase. This will determine the archival size needed to accommodate the anticipated raw numerical guidance and past forecasts and reforecasts, and their anticipated growth in time as model resolution increases. Ideally, the full models states would be archived at high temporal resolution, especially since post-processing depends on the end-users’ definition of what is optimal. Since it is likely that the full archive cannot be maintained on fast storage, relevant members of the community (see Obj 2.1, 2.2, 2.7) provide inputs to determine what subset of data must be kept on fast storage (e.g., what temporal resolution is acceptable – 1, 3 or 6-hourly?, what model fields – 500 hPa but not 550 hPa?). Members of the community should also be queried on the variety of ways they are likely to access the data; some users may want to access time series of horizontal fields; others may want vertical columns of data for a given model grid point. (Lead: )

**Medium-term (2-6 years):**
- Requirements already defined should be implemented and a new phase of requirements definition begun. In the implementation process NOAA will need to determine the hardware and software resources (allowing for anticipated growth), obtain these resources, write software, and install the system. (Lead: )

**Long-term steps (6+ years):**
- As models and uses grow the archive and the user interface to the archive must keep pace. Therefore the archive must be robust, flexible, and extensible. In particular, as it evolves the user interface to the archive will provide more and more analytic services, i.e., results derived from the archive.
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.
**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 post-processing 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 post-processing codes to run

**Solution Strategy:** Data access system requirements are sufficient bandwidth and compute power, and well defined/implemented interfaces for the ordering and delivery of data. Multiple “mirror” sites for redundancy and scalability are desired to make the system robust. The continued evolution of services should help to conserve bandwidth. Depending on the application, data access solutions will be best satisfied by varying combinations of speed and agility.

**Short-term (0-2 years):**
- The requirements definition phase should analyze expected data volume growth and expected data volume requests, and then compare with existing and currently anticipated resources. Existing distributions systems should collect information on data requests to guide future developments. (Lead: Government)

**Medium-term (2-6 years):**
- Requirements already defined should be implemented and a new phase of requirements definition begun. (Lead: Government)

**Long-term steps (6+ years):**
- As models and uses grow the archive and the user interface to the archive must keep pace. Therefore the archive must be robust, flexible, and extensible. In particular, as it evolves the user interface to the archive will provide more and more analytic services, i.e., results derived from the archive. (Lead: Government)
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.
### Objective 4.4: Build Forecast Uncertainty Test Bed(s)

**Description and Purpose:** 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.

**Need:** A “sandbox” is needed for the testing of new techniques and applications before the investments are made to operationally implement a new product.

**Current Capability:** 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.

**Capability Gaps:** 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 private sector 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.

**Short-term (0-2 years):**
- The informal process described in “current capabilities” is continued. (Lead: Government)

**Medium-term (2-6 years):**
- XX (Lead: Government)
- Two general possibilities exist for a test bed: (a) an on-site facility or, (b) a virtual test bed, with users and developers interacting remotely. If the on-site approach is desired, a facility must be maintained that includes fast workstations that have a large amount of storage capacity, a laboratory environment that facilitates interaction, and projection displays. For remote capabilities, meeting software must be procured. For either on-site or remote approaches, software must be developed to access and display the experimental forecasts for a large number of cases. The software should also be able to display verifying observations, verification statistics, and perhaps the underlying data such as the unprocessed ensemble forecasts. For both approaches, a small staff of meteorologists and social scientists will be needed to develop test software, facilitate the interaction between developers, forecasters, and users, and to implement a formalized method for evaluating uncertainty products, collating feedback, and making impartial recommendations.
- A test bed experiment would be initiated several months prior to a product becoming ready for evaluation. Software would be tested on the experimental forecasts, a test date set, and test bed staff would arrange for a suite of users to be available on that date. Experimental products and other data sets would then be made available for a wide variety of cases. The technique developer would begin by making a presentation on the experimental product, providing some comparison against existing baseline products, if available. Users would then have the chance to examine experimental forecast products over a large number of cases, e.g., across a representative sample of synoptic situations and times of the year. The users would be asked to provide formalized feedback (e.g., a
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<th>1-5 rating of the product) and less formal feedback, such as written comments on what was liked/disliked, and suggestions for improvement. The test bed would conclude with a discussion between users and developers and the issuance of a formal recommendation.</th>
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<td><strong>Long-term steps (6+ years):</strong></td>
<td>• Continuation and refinement of test bed approach developed in medium term. <em>(Lead: Government)</em></td>
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Objective 4.5: Work with Users to Define their Infrastructure Needs

**Description and Purpose:** 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).

**Need:** 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.

**Current Capability:** Universities, private sector 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.

**Capability Gaps:** 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. Post-processing requirements add another dimension to the problem.

**Performance Measures and Targets:**
- 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.

**Solution Strategy:** The major need is to educate users on the size of the problem early enough so the planning process will result in infrastructure commensurate with future needs. The biggest problem will be that many software systems will require a thorough redesign because at least one dimension (the ensemble member) and possibly another (the reforecast base date) is (are) added to an existing process. Any solution will require fast network access. However current trends towards providing commercial digital media (e.g., high def TV shows) suggests that typical high end home internet capability will keep up with evolving demands of ensemble forecast data.

**Responsibility:** Data providers and AMS must engage potential clients in other organizations (including government, university and industry organizations) in a variety of venues.

**Short-term (0-2 years):**
- XX (Lead: )
- Publication and dissemination of the ACUF report to educate users on the requirements for ensemble data. (Lead: NCOs)

**Medium-term (2-6 years):**
- Add sessions on this topic to appropriate AMS conferences. (Lead: NCOs)

**Long-term steps (6+ years):**
- Encourage development of user community to exchange ideas, methods, and applications. (Lead: All)