State of the Science FACT SHEET

Uncertainty in Forecasting Weather and Water

Uncertainty is… a fundamental characteristic of weather, seasonal climate, and hydrological prediction, and no forecast is complete without a description of its uncertainty (National Research Council, 2006).

Uncertainty is an inherent part of all predictions. Understanding the uncertainty associated with specific forecasts enables users of those forecasts to strengthen their decision making. Forecast users and industry partners now look to NOAA to regularly characterize and convey forecast confidence and uncertainty. As a result, NOAA is: (1) quantifying forecast uncertainty; (2) providing uncertainty information visually and verbally in decision support services and (3) assessing the benefits and challenges of using uncertainty information to enhance decision making. Building relationships with its partners and understanding their needs and risk preferences enable us to evolve our science and services and provide better ways to communicate risk to decision makers.

Sources of Forecast Uncertainty

All prediction is inherently uncertain and effective communication of this uncertainty about weather, climate, and water benefits users' decisions. As numerical models are widely used in weather forecasting and hydrological prediction, they are impacted by two major sources of uncertainty. The first source of forecast uncertainty is from "initial conditions" due to the imperfect observations and the errors introduced in preparing the gridded input data at the beginning of the forecast. The second is due to "model structure" and is caused by imperfections in how a model approximates the atmospheric, ocean and hydrological evolution during a simulation. While NOAA continues to reduce forecast uncertainty through improved observations, including the most recent suite of NOAA satellites and improved data assimilation and numerical modeling techniques, some forecast uncertainty will remain because even small errors in the estimate of a model's initial state often grow with increasing forecast lead time. In addition, predictions of future states are affected by uncertainties in the modeling of the real world. To address this, NOAA considers numerous model simulations, known as ensembles, and uses statistical techniques to characterize the uncertainty and improve prediction accuracy and reliability.

How NOAA Communicates Forecast Uncertainty

Deterministic, or single value forecasts (*e.g., the temperature will be 75 degrees*), are easier to convey, but do not include information related to forecast uncertainty.

NOAA communicates the uncertainty of its forecasts in several ways.

- Range predictions for a specific element *(e.g., the temperature will be 70 to 78 degrees)* quantify possible uncertainty values in a forecast.
- Using words such as "chance" or "likely" to express the probability of an event, like precipitation, tropical cyclone development, severe weather and/or other extreme events.
- Percentages and categories (e.g.,60-70% below normal) for a weather or climate event indicate a range of uncertainty for that event (Figure 1).

While all of these methods deliver value to decision makers, they can fall short. Capturing the probability of an event does not always provide the specific information most critical to a decision maker. For instance, citrus growers see impacts at specific temperatures. Highway maintenance crews care most about specific temperatures, snowfall amounts and timing. Others, such as emergency managers or residents may best use a combination of probabilities and thresholds to prepare for the specific impacts of tropical storms, such as wind (Figure 2) or storm surge, and other severe weather events. Accordingly, NOAA continues to develop and communicate probabilistic information to provide a spectrum of possibilities that allows users to assess their risk using their respective criteria and thresholds.

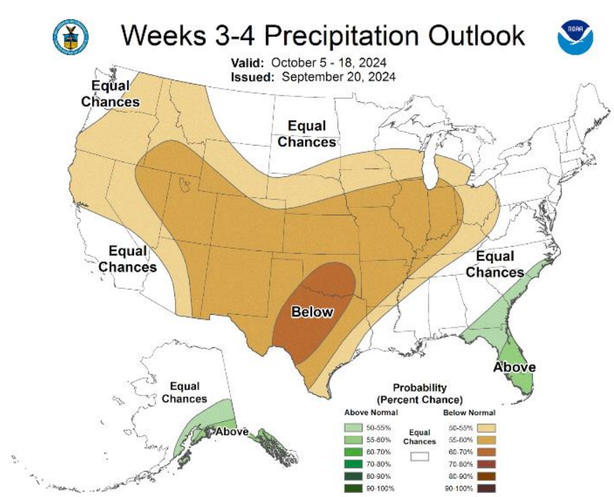

Figure 1. Outlook of weeks 3-4 precipitation probability map shows where precipitation will be above normal, equal chances, or below normal accompanied with percentages.

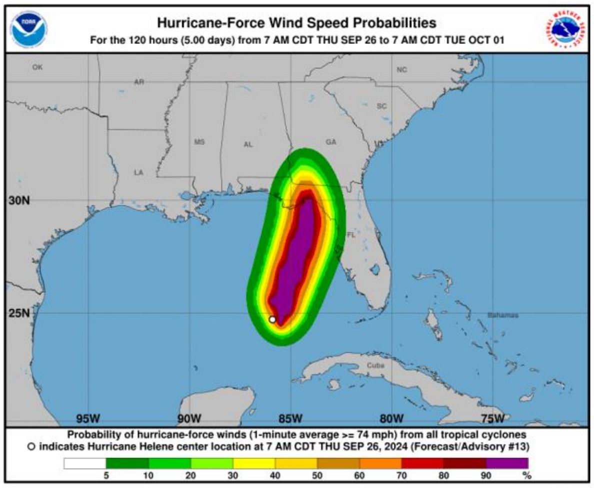

Figure 2. Range of probability of hurricane force surface winds during Hurricane Helene indicating the range of uncertainty

Decision Making with Forecast Uncertainty

Forecasts possess no intrinsic value. They acquire value through their ability to influence the decisions made by users of the forecasts (Murphy, 1993).

In response to the needs of decision makers, NOAA continues to research and develop innovative ways to quantify the uncertainty of model forecasts and effectively communicate it to the users and partners. A probabilistic Impact-based Decision Support Services (IDSS) initiative is being carried out to enhance NWS's support to decision makers by providing users and stakeholders with a comprehensive range of possible outcomes to support crucial decisions regarding high impact weather, water and climate-related events. Forecasts are now increasingly based on ensembles of forecasts that provide a range of possible future atmospheric states and quantify the forecast uncertainty. NOAA's constituents require and use probabilistic forecast information to make more data-informed, risk-based decisions. Here are a few examples of decision making with forecast uncertainty:

- Providing areas of potential thunderstorms allows the FAA to reroute aircraft when thunderstorm coverage and permeability exceeds pre-defined thresholds, increasing efficiency and safety of the National Airspace System.
- Integrating probabilistic forecasts into IDSS helps school superintendents decide to delay or close school due to inclement winter weather.
- Providing probabilistic information allows FEMA to respond well in advance of possible high-impact events, increasing efficiency in deploying response and recovery resources to locations.
- Probabilistic wind direction forecasts and direct-onsite Incident Meteorologists (IMETs) enable fire management agencies to improve fire suppression efforts by deploying resources to guard against dangerous wind shifts.
- NOAA-generated uncertainty forecasts provide opportunities to assist weather-dependent industries, such as utilities, to reduce operating costs.
- Ensemble streamflow forecasts allow users to make informed, risk-based decisions related to flood potential, drought services, and reservoir management.
- Providing water level forecast guidance uncertainty supports ship captains in managing underkeel and overhead clearance to avoid ship grounding, bridge collisions, and support safe navigation.

Key Research Goals for Forecast Uncertainty

NOAA is advancing its research efforts to provide a more comprehensive suite of products and decision support services to continue meeting user needs. NOAA's research will:

- Use social and behavioral science to understand what motivates people to prepare and take action, and help us improve the way risk and its associated uncertainty is communicated.
- Build an end-to-end forecasting and messaging framework designed to manage and clearly convey hazardous weather information and forecast uncertainty through an approach known as Forecasting a Continuum of Environmental Threats (FACETs, http://www.nssl.noaa.gov/projects/facets)
- Improve ensemble prediction techniques by: (a) improving its data assimilation system and forecast model; (b) more accurately quantifying uncertainty in the initial estimate of the model system, (c) employing improved, more physically based methods for quantifying the growth of forecast uncertainty due to model imperfections and (d) utilizing statistical post processing methods to improve the skillfulness and reliability of the ensemble model output.
- Provide high-quality real-time and retrospective ensemble forecast and analysis data and post processed probabilistic guidance to the weather, water and climate enterprise partners, enabling them to develop their own decision-support tools.
- Develop probability-based decision-support tools to facilitate the delivery of data, products, and services for key customers.
- Improve ensemble model visualization

capabilities to convey uncertainty information to forecasters and users.

- Radiative transfer modeling (RTM) serves as the bridge between satellite observations and atmospheric variables through forward operators. AI/ML enhances the accuracy of these forward operators by modeling complex nonlinear interactions and radiative processes that are computationally prohibitive for traditional RTM. By correcting biases and improving the physical realism of RTM, AI/ML strengthens data assimilation, resulting in more accurate initial conditions and reduced uncertainty in weather forecasts.
- Use the latest development of Artificial Intelligence (AI) and Machine Learning (ML) techniques to quantify forecast uncertainty
- Develop AI/ML based global and regional ensemble forecast models
- Use AL/ML technique to represent forecast uncertainty in ensemble post processing applications.

Recommended Reading

- Hirschberg, P.A. and Coauthors, 2011: A Weather and Climate Enterprise Strategic Implementation Plan for Generating and Communicating Forecast Uncertainty Information, *Bull. Amer. Meteor. Soc*., **92**, 1651-1666.,
- Murphy, Allan H. 1993: What is a Good Forecast? An Essay on the Nature of Goodness in Weather Forecasting. *Wea. Forecast*., **8**, 281-293
- National Research Council (NRC), 2006: Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts. National Academies Press, 124 pp