Weather Analysis and Forecasting

An Information Statement of the American Meteorological Society
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Introduction

Across the United States, government agencies (including the military), private industry, and private citizens consult weather analyses and forecasts to support decisions ranging from the routine (e.g., whether to hold an event) to important and urgent actions to help protect life and property when threatened by hazardous weather. Weather's impacts are substantial and wide-reaching and occur on multiple temporal and spatial scales. Examples include the following:

- 291 billion-dollar weather and climate disasters (e.g., tornadoes, hurricanes, extreme temperatures, and floods) have occurred in the United States since 1980, including 22 billion-dollar disasters in 2020 alone. Of these billion-dollar weather and climate disasters since 1980, tropical storms and hurricanes have been the costliest, with losses totaling nearly $1 trillion.
- Excessive heat is the leading cause of weather-related fatalities, with recent peer-reviewed estimates of excess mortality ranging from 5,600 to 12,000 per year.
- As of March 2021, approximately 70% of air traffic delays are caused by adverse weather conditions. The FAA also reports an annual average of nearly 167,000 total delay hours, at a cost to airlines between $1,400 and $4,500 for each delay hour.
- High-impact weather events, including billion-dollar disasters such as the 2019 California wildfires, August 2020 Midwest derecho, and 2021 central United States cold-air outbreak, account for 90% of all large (>50,000 affected customers) U.S. power outages.

Motivated by weather's significant impacts, this statement discusses who uses weather and forecast information to make important decisions, describes how weather forecasts are made and communicated to others, illustrates the types and overall quality of forecasts that are used to inform people and become the basis of decision-making in a range of settings, and provides insight into how forecast skill and communication can be further improved to benefit society.

How are weather information and forecasts used?

Steady improvements in forecast technology and quality have enabled meteorologists to provide end users with increasingly precise and skillful forecasts (each relative to established baselines for forecasts at a given lead time) tailored to their needs on which those end users can base subsequent actions that increase economic efficiency and productivity and mitigate impacts from weather hazards. Forecast improvements include better accuracy at finer spatial scales and longer lead times (i.e., for deterministic weather forecasts out to ?10 days and for probabilistic predictions at monthly to seasonal time scales), as well as probabilistic representations of uncertainty. Specific examples include, but are not limited to the following:

- Government officials use hurricane forecasts to inform evacuation decisions, declare states of emergencies, and spur the public to action in advance of the expected hazards.
- Power companies use forecasts of high-impact weather events such as severe thunderstorms, hurricanes, extreme heat and wildfires, and freezing rain and blizzards to deploy equipment and personnel to help restore power after the associated threats have subsided.
- Departments of Public Works or Transportation use forecasts to order supplies such as salt and de-icer, prepare equipment, and coordinate staffing to prepare for and respond to winter storms.
- Water management and treatment agencies use short- to medium-range forecasts to determine if water should be released from a reservoir or treated and released from a water-treatment facility in advance of anticipated rainfall.

How are forecasts made and communicated?

Forecasters are tasked with synthesizing observations, output from numerical weather prediction (NWP) models, scientific theory, and experience-based intuition to arrive at a forecast. Whether in the public or private sector, these forecasts are often made collaboratively among teams of meteorologists that routinely integrate new information as it becomes available. Forecasters are also increasingly responsible for effectively communicating forecasts and anticipated impacts to end users and stakeholders in collaboration with affected sectors.

Analyses of weather data

Weather forecasting begins with an analysis of the current state of the atmosphere, ocean, and land surface. Reliable observations drawn from many platforms, including satellites, radar, weather balloons, surface stations, and aircraft (both crewed and uncrewed) are crucial for generating accurate analyses. Because forecast quality is partially reliant on the quality of the underlying analysis, scientists continue to develop techniques to integrate observations into four-dimensional model representations of the Earth system. In addition to their vital role in weather forecasting, these analyses support scientific investigations designed to help develop improved weather prediction tools and techniques.

Forecast techniques

Meteorologists have traditionally used their intuition and available observations to create forecasts up to a few hours ahead of time. Thorough human diagnosis of some complex scenarios, such as severe-thunderstorm environments, remains necessary to optimize situational understanding and to make and communicate high-quality forecasts. In addition, rapidly updating numerical models, as well as statistical tools and artificial intelligence–based models that blend observations with NWP outputs, are increasingly used to make short-term forecasts, whether those issued by official forecast agencies or those available through popular smartphone applications.

Beyond a few hours ahead of time, NWP has long been the dominant forecasting tool. Modern NWP models start from an initial analysis of meteorological conditions produced through data assimilation and then apply the physical and dynamical equations that govern atmospheric evolution to predict the weather. Such models are continuously developed and collaboratively maintained by multiple entities. Despite their increasing skill and ability to depict progressively smaller-scale phenomena, NWP models are imperfect. Model shortcomings exist due to limited observations, imperfect data assimilation methods, and the approximations required to represent small-scale physical processes such as energy exchanges between the surface and atmosphere as well as phase changes of water. Approaches such as statistical bias correction, model blending, ensemble forecasts, and artificial intelligence/machine learning are increasingly used to mitigate NWP models' shortcomings while improving forecast skill.

Role of humans

Forecasters apply their expertise to create forecasts by interpreting and adding meaning to the abundant and complex data and information drawn from observations and NWP. Humans add value to the forecast process by utilizing this expertise and maintaining situational awareness, which can build trust and deepen valuable relationships with end users while creating a solid foundation for the enhanced communication of predicted weather impacts.

The effective translation of a forecast relies on three key dimensions: 1) scientific understanding and information interpretation; 2) data access and the skilled use of forecast tools; and 3) an understanding of the needs of the diverse community of end users reliant upon weather information, developed through ongoing collaboration between forecasters and end users. Forecasters must frequently interact with and gain understanding of stakeholders, end users, and partners. This enables weather information to be tailored to user needs and enables users to be more engaged in the dissemination process. In addition, forecasters must devote time to completing training, reviewing best practices, and engaging local communities to learn how to best communicate actionable forecast information underpinning life- and property-saving decisions.

Humans are not necessarily involved with all forecasts that are disseminated to end users. For example, many popular smartphone applications provide users with accessible, often graphically appealing forecasts drawn from computer-based weather prediction systems. Furthermore, private- and public-sector forecast entities increasingly rely on computer-based weather prediction systems to develop a baseline forecast that humans are primarily responsible for disseminating and communicating rather than making themselves. Humans' roles in the forecast process are likely to continue to evolve toward communication as predictive abilities continue to improve.

Forecast dissemination and communication

As technology improves, methods for disseminating weather information and forecasts continue to evolve. For example, location-specific information including hourly forecasts, storm-based severe weather warnings, and radar data now can be directly delivered to smartphones and other smart devices. Forecasters must also consistently collaborate with end users and stakeholders to better optimize forecast dissemination methods and tools.

Forecast products have historically provided users with the best estimate of what may potentially happen, such as high temperature and snowfall amounts. However, because users often consider the *range of possible scenarios* beyond just the most likely outcome when evaluating risk, they also require forecast confidence and uncertainty information to make optimal decisions to protect life and property. Since each user's requirements are unique to their specific operations, optimal decision-making requires effective and continual communication between forecasters and users. Recent advances in forecast skill and technology allow for increasingly reliable, although still imperfect, uncertainty information to be provided to end users. Further, collaborative research between physical and social scientists has recently led to improvements in communicating forecast uncertainty, although further research is warranted to identify how to optimally design and communicate weather information.

How reliable are today's forecasts?

Background

Meteorologists use specific metrics to quantify forecast quality and reliability. Forecast *skill* is a measure of accuracy compared to a baseline prediction (e.g., persistence, climatology, or other human standard). The *predictability* of potential meteorological events is dictated by an event's size and timing, with predictability being higher for larger-scale features (those spanning hundreds of miles/kilometers or more) at shorter lead times (less than a few days) and so is based on the weather phenomenon itself. A skillful forecast acquires *value* when it can inform specific user actions because people can understand it and use it to make decisions.

Very-short-range forecasts

Very-short-range forecasts, colloquially referred to as "nowcasts," are produced for smaller-scale phenomena such as thunderstorms at lead times of minutes to hours. Examples include tornado, severe-thunderstorm, and flash-flood warnings containing actionable information to help protect life and property (e.g., telling people to shelter in place, or used by air traffic controllers to reroute aircraft). Very-short-range forecasts have become increasingly skillful, reliable, and actionable in recent years as novel tools such as artificial intelligence-based models (particularly in the private sector), NOAA's ProbSevere statistical models, and NOAA's operational High-Resolution Rapid Refresh (HRRR) NWP model have been developed.

Short-range forecasts

Short-range forecasts, such as those of benign weather conditions for specific locations and those issued over broader regions for high-impact weather events (including snow and ice, severe thunderstorms, excessive heat, and hurricanes), encompass lead times of a few hours up to two days. Short-range forecasts have increased in both skill and value in recent years: specifically, these forecasts are increasingly used to inform future actions by users ranging from citizens (e.g., whether to hold a scheduled event) to government officials (e.g., whether to issue an evacuation notice for flooding or a hurricane).

Medium-range forecasts

Medium-range forecasts, typically defined as those at lead times of 2–10 days, continue to improve with discernible subcontinental-scale skill extending to lead times of 8 days. The chaotic nature of the atmosphere results in predictability progressively decreasing with lead time, but improvements in ensemble NWP, machine learning techniques, data assimilation, and our understanding of the relationships between weather conditions and more slowly evolving climate conditions have led to increased forecast skill for large-scale weather features. This skill is often leveraged to facilitate useful probabilistic forecasts of potential high-impact weather, such as the NOAA Weather Prediction Center's Days 3–7 Hazards Outlook.

Subseasonal forecasts

Subseasonal forecasts are typically issued for meteorological phenomena that cover areas up to the size of a continent and involve lead times from 1 to 2 weeks to less than a season. Subseasonal forecasts are generally prepared using numerical weather prediction outputs, knowledge of shorter-term climate variability such as the Madden–Julian oscillation and Arctic Oscillation, and, at longer lead times, long-term trends and knowledge of longer-term climate variability such as that associated with El Niño–Southern Oscillation. Presently, deterministic forecasts of specific weather conditions typically have low accuracy at these lead times. However, probabilistic forecasts issued to highlight significant trends (e.g., warmer than normal, wetter than normal, higher likelihood of extreme events) can be skillful when compared to a baseline forecast. Subseasonal forecasts have generally become more skillful in recent years, leading to the development of new forecast products such as the ECMWF's Extreme Forecast Index and NOAA Climate Prediction Center's Week 2 Probabilistic Hazards and Weeks 3–4 Probabilistic Temperature and Precipitation Outlooks.

Seasonal forecasts

Seasonal forecasts are typically issued for meteorological phenomena that cover areas ranging from the size of a continent to the entire planet for multiple months. Seasonal forecasts are generally prepared using knowledge of longer-term climate variability such as that associated with El Niño–Southern Oscillation, numerical climate-model outputs, and long-term trends. Skill in monthly and seasonal forecasts is variable but generally increasing. Increases in forecast skill at these lead times can largely be attributed to an improved understanding of and ability to forecast major modes of large-scale climate variability such as El Niño–Southern Oscillation, the Arctic Oscillation, and the Madden–Julian oscillation.

Opportunities for future improvement

Realizing opportunities to improve forecast skill begins with continued fundamental and applied research to better understand the physics and dynamics of high-impact weather systems. This research is likely to result in NWP improvements, including collecting and assimilating more-numerous, higher-quality observations of the atmosphere, ocean, and land surface, improved physical parameterizations and numerical methods, increased spatial and temporal resolution facilitated by advances in computing power, and the increased reliability of ensemble prediction systems. This research is also likely to result in advances beyond NWP, including the continued development and application of machine learning, artificial intelligence, data mining, and data visualization techniques to aid forecasters in preparing accurate forecasts. These activities will require constructive collaborations between researchers and forecasters.

The value of weather forecasts will increase with continued collaborations between forecasters and users that help effectively incorporate information into decision-making processes. Using social science to fully connect forecasts with end users' needs is necessary to achieve this goal. Opportunities to do so include the following:

- Developing infrastructure to deliver weather warnings across multiple media to reach vulnerable populations.
- Taking insights from studies of how different public groups perceive risk and uncertainty and incorporating those insights into forecast operations and dissemination.
- Continuing to investigate how various user groups decide whether to take protective actions when confronted with a potential weather-related hazard.

Conclusion

Weather forecasts are increasingly skillful and useful, and their benefits extend widely across the economy. The forecasting community works closely with users to ensure that forecast information meets their specific needs. This includes collaborations between physical and social scientists to ensure that accurate and reliable forecast information is communicated in ways that enable users to incorporate it in their decision-making processes. Simultaneously, the forecasting community is improving existing forecast tools, developing new forecast techniques, and leveraging new and expanding observation networks to help improve forecast skill. These efforts have increased, and continue to increase, the value of forecast information to everyone.

[This statement is considered in force until December 2026 unless superseded by a new statement issued by the AMS Council before this date.]