

Weather Analysis and Forecasting

An Information Statement of the American Meteorological Society

(Adopted by AMS Council on 8 August 2007) *Bull. Amer. Meteor. Soc.*, **88**

This Information Statement describes the current state of the science of weather forecasting and analysis from short-term severe weather events to monthly and seasonal forecasts.¹

Introduction

Weather significantly affects the health, safety, and economic well-being of everyone. Over 100 million households in the U.S. consult weather forecasts at least once per day. Population growth and development increase exposure to adverse weather and the influence of weather on everyday activities. This statement reviews advances in our ability to understand and forecast weather. It describes and distinguishes the methods for analyzing and forecasting the weather across time and space scales from minutes to seasons and from the neighborhood to planetary scales. The statement also discusses these capabilities in the context of the significant impact of weather and forecasts on society, the use and dissemination of forecasts, and opportunities for future improvement.

The impact of the weather and the relative value of weather forecasts and warnings are difficult to overstate. Some estimates indicate that weather affects about one-third of the U.S. Gross Domestic Product. Examples of estimated specific adverse weather effects and the economic benefits of improved forecasts in the U.S. include the following facts:

- Nearly 90% of the emergencies declared by the Federal Emergency Management Agency are weather-related.

¹ More specific information can be found in the AMS Statements on the Prediction and Mitigation of Flash Floods (*Bull. Amer. Met. Soc.*, **81**), Hurricane Forecasting in the United States (*Bull. Amer. Meteor. Soc.*, **88**), Tornado Forecasting and Warning (*Bull. Amer. Meteor. Soc.*, **86**), Enhancing Weather Information with Probability Forecasts (*Bull. Amer. Meteor. Soc.*, **83**), and Climate Change (*Bull. Amer. Meteor. Soc.*, **88**); and in the *Glossary of Meteorology* (AMS, 2000).

- More than 7000 road fatalities per year can be directly or indirectly attributed to weather.
- Approximately 70% of air traffic delays are caused by weather, at a cost of about \$6 billion per year.
- Heat waves kill an average of about 175 people each year in the U.S.
- The 1993 Mississippi Valley flood cost more than \$20 billion and killed 48 people.
- National wildland fires (often caused by lightning strikes and drought and affected by strong winds) in 2000 resulted in over seven million acres burned and an estimated \$2 billion in damage.
- Seven of the 13 most expensive hurricanes in U.S. history occurred during the 2004 and 2005 hurricane seasons, including Katrina (more than \$80 billion), Wilma (more than \$20 billion), and Charley (more than \$15 billion) [all estimates in 2006 dollars].
- Severe drought in the Great Plains affected crops during the spring and summer of 2006, producing over \$6 billion in damage and costs.
- U.S. utilities save more than \$150 million per year using 24-hour temperature forecasts to meet electricity demands most efficiently.
- Reducing the length of coastline under hurricane warnings involving the need for evacuations saves approximately \$1 million per coastal mile in evacuation and other preparedness costs.

Analyses of Weather Data

Forecasting the weather requires continuously observing the state of the atmosphere and underlying surfaces. A steadily evolving worldwide suite of observing systems is in place to monitor these conditions. Although major research challenges remain, scientists have made considerable progress in developing computerized weather prediction systems² that transform

² Numerical weather prediction systems typically include highly developed computer software that produces weather analyses by combining observations with short-range forecasts of the weather. These systems use computer models of the atmosphere to generate weather forecasts ranging from a few hours to several months from the initial analyses.

these observations into coherent analyses (snapshots of the atmospheric state at a specific time). These analyses serve as the foundation for weather prediction on scales from individual clouds to the entire climate system. Analyses of past, as well as current, weather support many diverse environmental applications, including fundamental scientific investigations of the climate system. Developing useful weather forecast products requires integrating information obtained from observations, analyses, and computer models, and conveying that information along with forecast confidence to the user community.

Zero- to 12-hour Forecasts

The first 12 hours of forecasts cover two general areas: 1) forecasting the initiation, evolution and movement of short-term, often intense weather phenomena such as tornadoes, hail storms, and flash floods; and 2) predictions for larger-scale weather events such as rain or snow, cold, warm, or windy conditions. Small-scale hazardous weather takes place on a time scale of minutes to hours, whereas larger-scale events have longer lifetimes.

Forecasts for short time scales have shown increasing levels of skill, which has resulted in greater use of these products. The *skill* of a forecast refers to how accurate the forecast is compared to some simple reference forecast such as climatology; that is, a forecast is said to have skill if it is more accurate than a forecast based on the simple method. Skill is measured by a statistical evaluation of the accuracy of forecasts or the effectiveness of detection techniques. As the scale of the weather phenomenon decreases or the time range of the forecast increases, the predictability of the phenomenon generally decreases and the uncertainty of the forecast increases, resulting in a decrease of skill with time. In addition to the inherent decrease of predictability with time, accurate forecasts of small-scale systems are often hampered by limitations in computational power, inadequate observations, and limited understanding of the physical processes involved. General areas where these important small-scale systems are likely to form can often be predicted a few days in advance, based upon large-scale weather model output, but predicting their precise location, timing, and severity depends upon the continual monitoring and analysis of the observations. An example is a springtime severe thunderstorm and tornado system in the Midwest. Forecasters may know where the surface low pressure system will be several days in advance, but the location of associated individual thunderstorms will not usually be known until hours or minutes prior to their occurrence.

Despite the difficulties in predicting small-scale weather phenomena, the lead time notification for specific weather-related hazards has increased. For example, from 1987 to 2004, the nominal lead time for tornado warnings increased from less than five minutes to 13 minutes. Over the same period, the ratio of tornado warnings to confirmed tornado events (known as "probability of detection") increased from approximately 40% to nearly 80%. Similarly, the probability of detection for flash flooding has also increased from 46% in 1994 to 89% in 2006. Continuous improvement in high-impact event prediction must take into account the risk of increased false alarms. Enhanced detection by radar and satellite technology, along with advances in scientific understanding by forecasters all contribute to these improvements.

Short-range Forecasts (12 hours to a few days)

Over the past several decades, improvements in observing systems, computer model physical processes, and assimilation of data into numerical weather prediction systems have produced steady improvement in the ability to predict the evolution of larger-scale weather systems as well as day-to-day variations in temperature, precipitation, cloudiness, and air quality. Examples of these improvements in the short range include:

- The 2006 average 48-hour forecast hurricane track error in the Atlantic basin was 111 miles, as compared with 336 miles in 1985.
- 48-hour precipitation forecasts are now as accurate as 24-hour forecasts were a decade ago.
- Winter storm watch lead time for the season ending in 2006 was 17 hours, an increase of 70% since 1999.

Significant room for improvement remains in forecasting high-impact weather such as hurricane intensity and winter storms. For example, forecasting rapid intensification (or weakening) of hurricanes and differentiating between snow, sleet, freezing rain, and rain with narrow transition zones in winter storms remains a forecast challenge. Advances in computer models and improved understanding and representation of cloud processes in the models will increase the ability to predict these small-scale features. Together with advances in observations and methods of incorporating data, these steps will lead to enhanced forecasts of precipitation intensity and location.

Short-range Forecasts of Hazardous Weather Products (up to a few days)

Prediction of hazardous conditions is a multitiered process that reflects growing uncertainty as forecast lead time increases. To help convey this uncertainty, the National Oceanic and Atmospheric Administration's National Weather Service issues a number of products to inform the public of such hazards. The steps in the process are shown in the table below, with lead time, degree of event certainty, and expected outcome or action.

Product	Lead time	Certainty of event	Purpose/outcome
Outlook	Hours to a few days	<i>Possible</i> occurrence of hazardous weather	Adequate notice to those who need hours to longer lead times
Watch	Less than 1 day for severe weather (e.g., thunderstorms, flash floods, tornadoes) 1–2 days for large scale events (e.g. winter storms, hurricanes)	Risk of hazardous weather has increased but not necessarily occurred	Notify public to carefully monitor local weather conditions; prepare to protect life/property
Advisory	Hours for large-scale events	A hazardous weather event is occurring, is imminent, or has a very high probability of occurrence	Conditions <i>may</i> require immediate action to protect life and property; impacts are generally not as severe as with a warning
Warning	Hours for large-scale	A hazardous weather event is	Conditions <i>require</i> action

	events Minutes for severe weather	occurring, is imminent, or has a very high probability of occurrence	to protect life and property;
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Medium-range Forecasts (a few days to two weeks)

The ability to resolve the location and timing of weather events decreases as forecast length increases. At present, medium-range forecasts rely primarily on global numerical weather prediction systems. On average, these systems produce skillful forecasts more than a week in advance, although their performance varies by season and region. Forecasters use ensemble methods to increase the skill of medium-range predictions by a day or more and to gain insight into the potential skill of a forecast before it is verified. Ensemble forecasts are multiple predictions from a set of numerical weather prediction systems with slightly different initial conditions and/or slightly different versions of atmospheric models. Differences between the individual predictions in the ensemble indicate likely forecast skill and confidence. The use of ensemble forecasts is increasing at a fast rate and is revolutionizing the entire process from short-range weather to climate.

Over the past three decades the skillful range of medium-range forecasts has been extended by roughly one day per decade. Major winter storms are now often forecast a week or more in advance, allowing road maintenance personnel and emergency managers time to prepare.

Examples of other advances in medium-range forecast skill include:

- Three-day forecasts of 1 inch or more of precipitation are as accurate as two-day forecasts were in 1998.
- The skill of five-day forecasts has more than doubled since the late 1970s.
- For major cyclonic storm location and intensity, five-day predictions are as skillful as three-day forecasts were in the early 1990s.
- Surface temperature forecasts for the U.S. now show considerable skill on days three through five, with the skill decreasing to more marginal levels by day six.

Extended-range Forecasts (week 2 and beyond)

The current skill in forecasting daily weather conditions beyond eight days is relatively low. However, products designed to highlight significant trends (e.g., warmer than normal, wetter than normal), such as 6–10 day and 8–14 day temperature and precipitation probability outlooks, often have useful skill. The skill of operational forecasts of U.S. temperature and precipitation for an average of 6–10 days has more than doubled since the 1970s. Precipitation forecasts are less skillful than those for temperature. Forecasts for 8–14 days (week 2) have been issued since 2001.

Ensemble techniques have greatly enhanced the skill of forecasts a week out and beyond. During the Northern Hemisphere winter, ensembles, on average, produce useful two-week forecasts and indicate specific times for which the forecasts will be more or less reliable than usual. Running a large number of forecasts over a well-observed historical period (hind-casts or re-forecasts) can provide adjustments to extended-range and monthly and seasonal forecasts, greatly increasing their usefulness and providing better estimates of forecast skill. As the numerical weather prediction systems and ensemble techniques improve, the ability to predict extreme weather events, including those beyond week one, is expected to increase and will provide forecasters enhanced opportunities to predict those events. Efforts are underway to fill in the gap in predictive skill between the two-week and one-month forecasts, using a combination of statistical techniques and numerical weather prediction systems.

Monthly and Seasonal Forecasts

Monthly and seasonal forecasts will likely never include day-by-day detail but will predict temporal averages and variability over substantially longer periods. Skill in monthly and seasonal forecasts is extremely variable from period to period. The skill of monthly and three-monthly forecasts of average temperature and precipitation approximately doubled between 1995 and 2006. This remarkable development reflects a fuller understanding of the interrelationship between the ocean and atmosphere (especially the El Niño/Southern Oscillation) in producing weather and climate. Other reasons for the improvement include better observations of the ocean; improved use of the observations; better numerical weather prediction systems that couple improved models of the land, ocean, and atmosphere; and improved ensemble and re-forecast

methods. Forecast techniques use the skill histories of numerical weather prediction systems and other tools to objectively combine them into better forecasts. Weather forecast providers are now helping customers to use the information in probabilistic monthly forecasts and to apply the information locally. These efforts require climate forecasters to understand the needs of users, which has led to closer relationships and better communication between forecast producers and users. Yet the skill of seasonal forecasts still remains limited in many cases.

Role of Forecasters

Even with the improvement in the models and objective guidance tools, highly skilled forecasters remain an integral part of the current state of forecasting. Forecasters today are better educated and continually trained on how best to use the latest data, model outputs, and forecast tools. Forecasters are thus able to improve on raw data and guidance for both forecasts and warnings, especially for short time scales (up to a day or two).

Users of Weather Information and Forecasts

Government agencies, businesses, agriculture, academia, and the general public have discovered innovative ways to use forecast products to increase economic efficiency and productivity, advance scientific research, and reduce exposure to weather risks. Across the entire spectrum of users, there are growing requirements for accurate forecasts with greater temporal specificity and more precisely defined locations. The demand for accurate, specialized forecasts from various economic sectors has led to the continued growth of the U.S. weather industry. Private forecast services are a growing sector of the economy.

Within the past 10–15 years, improvements in forecast quality have set the pace for advanced and customized applications to suit the needs of various user groups. The need for different levels of detail is dictated by how the information is to be applied and must be economically justified. For example, during a winter storm, different users need specific information relevant to their business operations. People are most interested in precipitation which may impact their plans, activities, and safety. Specialized users, such as utility companies, road crews, and airlines need much more specific forecasts about the snow, sleet, freezing rain, and rain — where it will fall, how much, and when — to determine the need for changes in their operations. These users require a level of specificity not available from general-purpose forecasts. Adjustments in

forecasts for those specifics require concentrated, continuous monitoring of many parameters by highly skilled forecasters.

Communication of Weather Forecasts

Methods for the delivery of weather information continue to evolve in line with advances in technology and human factors research. Due in part to the growing availability of public and commercial weather products through technologies such as automated distribution on the Internet, wireless communication devices, electronic message signs, and other media, private citizens, businesses, and institutions are gradually becoming more sophisticated users.

With advances in technology and communications, the National Weather Service (NWS) has made watch and warning products more specific in forecast intensity, time, and location. Plans and methodologies have been put in place by the NWS to replace county-based warnings with specific storm-based warnings, which will dramatically reduce the occurrence of unnecessary warnings or false alarms to the public. Providers of weather information and forecasts can automate and tailor the products delivered to their clients or create additional products for specific customer needs. The advances in digital technology have also improved the automated dissemination of critical weather warnings to the public and have allowed for the distribution of graphical images of specific roads, towns, and neighborhoods directly on television and on personal communications devices.

Most forecast products and services, especially warnings, are based on discrete, "deterministic" values or thresholds. These services provide users with the best estimate of what will happen. However, for optimal decision-making, users need to consider the range of possible events beyond the most likely outcome in determining the appropriate action. They also need information about the likelihood and probable strength of potential high-impact events as early as is practical, given that the increase in uncertainty with time is a complicating factor. This expression of forecast uncertainty is an area warranting improvement and will require increased communication between users and producers of weather forecasts.

Opportunities for Future Improvement

Opportunities exist for increasing the skill and use of forecasts at all time ranges. The theoretical limit for predictability of the daily evolution of weather systems is about two weeks, suggesting

there is considerable opportunity to improve forecasts, especially in the six- to 14-day range. However, realizing these opportunities will require further research; close international cooperation and coordination; better observations of the atmosphere, ocean, and land and improved incorporation of these observations into numerical models; improved resolution of numerical models; increasingly powerful supercomputers; and collaborative forecast development activities between operational forecasters and researchers. Improved ensembles of numerical model forecasts will allow forecasters to quantify and convey the degree of uncertainty objectively for all temporal ranges.

In summary, weather forecasts are increasingly accurate and useful, and their benefits extend widely across the economy. While much has been accomplished in improving weather forecasts, there remains much room for improvement. Some of the many remaining challenges in weather analysis and forecasting are:

- Improving hurricane intensity and track forecasts;
- Improving forecasts of winter storm details, especially rain-snow-freezing rain transitions;
- Maintaining and improving observations and their optimal use in numerical weather prediction systems which requires extensive, continuing efforts;
- Improving summertime convective precipitation forecasts;
- Improving skill in seasonal forecasts; and
- Enhancing objective techniques to determine forecast uncertainty and effectively communicating uncertainty to the user community.

The American Meteorological Society looks forward to championing these challenges in the decade ahead.

[This statement is considered in force until August 2012 unless superseded by a new statement issued by the AMS Council before this date.]

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