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STORM FORECASTING FOR EMERGENCY RESPONSE
A United States perspective

Donald R. Wernly and Louis W. Uccellini

INTRODUCTION

The ability to foretell future events has been the goal of humankind since the beginning of recorded history. In the ancient world, Egypt stood alone among its contemporaries as a thriving civilization. The recurring floods of the Nile established a cycle of sowing and harvesting that made Egypt the preeminent civilization in the world at that time. Elsewhere, nature’s vagaries forced the inhabitants to remain nomadic, moving across the landscape in search of fodder for their animals and food for themselves. The inherent predictability of the Nile floods enabled the Egyptians to transcend mere reaction to their environment and to use natural events to the well-being and advancement of their society. (In this instance predictability equates more to persistence, regularity or climatology.)

The cyclic nature of the Nile suffered interruptions with disastrous effects. Nevertheless, the gift of the Nile afforded the Egyptians a degree of independence that other peoples could only dream about. Today, we still strive to live in harmony with nature’s elemental forces. Past experiments in weather modification, such as Project Stormfury’s attempt to tame hurricanes, suggest that the best solution toward mitigating the impacts on lives and property lies in maximizing our predictive abilities. The lesson of the Nile underscores the need to apply the disciplines of meteorology and hydrology in tandem. This “hydrometeorological” approach ensures an holistic predictive capability which must be attained if we fully expect to break our bondage to natural events.

Our observational capabilities continue to expand as new in situ observing platforms and remote sensing technologies measure hydrometeorological variables with ever greater spatial and temporal resolution. New atmospheric and hydrologic numerical models provide predictions with accuracies that could not be envisioned just a few years ago. With this comes the opportunity to provide decision-makers with a seamless suite of information from predictions on decadal to centennial climate change all the way to storm-scale events. Nevertheless, hydrometeorological forecasts will never be perfect, and as predictive capabilities are extended to longer time-scales, the inherent forecast uncertainty will increase as the forecast projections increase.

Similarly, the requirements of individual decision-makers will become increasingly complex. As is being pioneered in the hurricane and flood warning programs, probabilistic forecasts that quantify forecast uncertainty hold the best potential for enhancing informed decision-making (Krzysztofowicz et al. 1992, 1993). In this way, users of hydrometeorological forecasts incorporate forecast uncertainties into their decision methodologies that define potential response actions directly related to the amount of risk they are willing to accept. The result is informed decision-making that enables individuals to select the best response option for their particular circumstances.

For humankind to truly break the bondage to natural hazards, the data and information used to enhance our predictive capabilities must be further employed in mitigation efforts. At the present time, though the loss of life has been dramatically reduced, property losses are still escalating at an exponential
rate. As an example of our increasing vulnerabilities, insured exposures for coastal counties along the Atlantic and Gulf coasts now exceed $3 trillion. More than 36 million people live in the most hurricane-prone counties, and this figure is expected to exceed 73 million by 2010 (IIPLR 1995). In the last several decades, 80 per cent of presidentially declared disasters were caused by floods that resulted in billions of dollars in damage (FEMA 1995). Aside from the movement and construction in vulnerable areas, our infrastructure is also becoming increasingly interdependent. Loss of energy production due to a hurricane in Texas can have profound ramifications for the availability of natural gas in other parts of the nation. The Federal Emergency Management Agency (FEMA) developed the National Mitigation Strategy to point the nation toward the creation of hazard-resistant communities through attention to sound building practices and land-use planning. The environmental databases created to enhance our predictive capabilities are being used by federal through local decision-makers to conduct hazard assessments and vulnerability analyses to support mitigation efforts. Similarly, long lead time forecasts from the seasonal to decadal and beyond support water supply and mitigation planning.

This chapter will explore the future of storm forecasting and its support to the response efforts of local decision-makers through the framework of an end-to-end forecast process and the recently modernized National Weather Service (NWS).

THE “END TO END” FORECAST PROCESS

In the United States, the production and delivery of critical warning and forecast products is vested in the local weather forecast offices (WFOs). The entire NWS structure is focused around the WFOs to ensure they have the information and data necessary to meet customer expectations. This customer-driven approach enables the NWS to respond quickly to customer requirements by working with them in the creation and delivery of new products and services.

In order to develop an appreciation for the full delivery of service, the forecast process needs to be viewed in a larger context. The end-to-end forecast process (Figure 6.1a) provides an outline for the NWS’s entire hydrometeorological forecast system. The various components of the process include: observations, the guidance and products provided by the National Centers for Environmental Prediction (NCEP) Modeling and Service Centers as well as River Forecast Centers (RFCs), the delivery of specific local warning and forecast products from WFOs acting in partnership with other government organizations and the private sector, and the response of the user who receives and makes decisions from the resulting information. This perspective illustrates how all data, information, organizations and users work together to enhance our predictive abilities and to maximize response.

It must be stressed that products developed by each component of the forecast process are an end in themselves (Figure 6.1b). As the main service delivery point for the NWS, WFOs have the ultimate warning and forecast responsibility for their assigned area of responsibility. This includes producing and issuing all of the traditional critical information products as well as working with all NWS partners in the warning process to coordinate preparedness planning efforts and hazard awareness activities. Concerning the other components of the end-to-end forecast process, observations not only feed the process but are operational requirements for the aviation and marine communities, private forecasting firms, water resource interests and the media. Surface observations also support hazard assessments, land-use planning efforts, sustainable development activities and the development of building codes. Similarly, numerical model forecasts, products from NCEP Service Centers, and data and forecasts from RFCs are used directly by government, media, private hydrometeorological firms and other weather-sensitive organizations in support of their activities. Products from each step in the forecast process multiply the nation’s abilities to meet the growing demand for hydrometeorological data and information while providing information of consistent quality and quantity which other organizations can build upon.

The end-to-end forecast process should not be viewed as serial in nature as Figures 6.1a and 6.1b might suggest. Rather, it is a parallel process where forecasters at the WFOs, RFCs and NCEP Service Centers integrate all of the available information to
make the best possible forecast. Finally, the end-to-end forecast process can be inverted to form the requirements process of working with users to meet their needs. Here, user requirements drive the development of forecast and service products. These require, also in a parallel process, appropriate guidance from national service and modeling centers, new or different data sets, and potentially new observations and observing platforms. The end-to-end forecast process, both in its normal and reversed forms, can be used to:

- meet user needs and expectations;
- outline the roles of all members of the hazards community in the forecast process;
- define the structure of national hydrometeorological services; and
- suggest relationships between the public and private weather services.

This further implies that everyone whose decisions are based on hydrometeorological information are part of the end-to-end forecast process. Each person gives something to the process while taking what they need to satisfy their requirements.

Uccellini et al. (1995, 1997) note that over the past fifty years the forecast process has evolved from observations and subjective forecasting to an intricate process based on mathematical and physical principles as well as the application of powerful computer models run on the world’s largest and fastest computers. In the modernized NWS of the 1990s, professional meteorologists and hydrologists (located at the WFOs, RFCs and NCEP Service Centers) employ the latest science to create warnings and forecasts by integrating observations and numerical model output. Each WFO is staffed with a science and operations officer (SOO), a warning coordination meteorologist (WCM), and a data acquisition program manager (DAPM). The SOO ensures that the latest science is folded into the forecast process while the
WCM ensures that all users of hydrometeorological information get what they want and know how to use it (Zevin and Carter 1994). DAPMs manage the entire WFO data acquisition program so that the data needs of the office are met. A majority of WFOs also include a service hydrologist who supports the entire hydrologic program of the WFO including the river and rainfall reporting network as well as hydro-meteorological training activities. Hydrometeorological technicians assist the meteorologists and hydrologists in the real-time acquisition of data and in communicating critical information to users.

How successful is the end-to-end forecast process? Basically, it has enabled the US to go from being overtaken by events to being able to take proactive measures to mitigate the potential loss of life and property. As one example, consider our ability to cope with major winter storms. March 1888 saw the east coast caught unaware by one of the worst blizzards in America’s history. Metropolitan areas from Washington to Boston were paralyzed. Forty to fifty inches of snow were whipped by gale-force winds into 30- to 40-foot drifts from southern New England to southeastern New York. In New York City, most found out about the storm as they left home for work. The human toll along the east coast was staggering.

Men, women, and children died in city streets, in country fields, and on ice-choked ships and boats. Over 400 died, 200 in New York City alone. Thousands more suffered everything from exhaustion to amputation of frostbitten limbs. Some wandered blindly into snow banks and died quietly. Others became hysterical, shouting and cursing the wind, pounding the snow in tearful frustration.

(Hughes 1976)

The unpredictability of east coast winter storms continued well into the twentieth century. A notable recent forecast failure is the February 1979 President’s Day Storm that saw snowfalls in excess of a foot blanket the east coast from the Carolinas to New York City, with a bullseye of greater than 20 inches centered on Washington, DC. Although NWS forecasters issued winter storm watches and warnings in advance, the predicted snowfall for the Washington Metropolitan area was only 4 to 6 inches.

The 1993 Superstorm of March 12–14 proved to be a watershed not only in the forecast community’s ability to predict east coast winter storms of historic magnitudes but in the public’s perception of the forecaster’s capabilities (Uccellini et al. 1995). Bill Nichols in the March 16, 1993, edition of USA Today notes:

The Blizzard of March 12, 1888, which killed more than 400 people... is the benchmark against which all winter storms used to be measured. Not any more... Forecasters proudly pointed out that the severity of this storm (March 1993 Superstorm) was being predicted as much as a week beforehand, giving most residents a chance to batten down the hatches with food, drink, batteries, and maybe a favorite video or two.

When the “Blizzard of ’96” was forecast for the east coast, the public and the private sectors took dramatic action well before the storm. Before the first flakes of snow fell, the Governor of Virginia declared a state of emergency while emergency services offices were opened in Massachusetts, Pennsylvania, Rhode Island, Connecticut, Maryland and New Jersey (DOC 1996). Airlines removed their aircraft from vulnerable east coast airports to optimize flight schedules and to expedite snow removal. The mayor of Boston sped up pre-existing snow clearance to prepare for the new onslaught. North Carolina officials prepositioned road crews and changed chemicals for the ice accumulations forecast there.

Similar parallels can be drawn for tropical cyclones and severe convection. In 1900, the US suffered its worst national disaster when a Category 5 hurricane swept across Galveston Island in Texas, killing over 6,000 persons. Contrast this to 1992 when Hurricane Andrew slammed into south Florida and Louisiana. Although property damage was astronomically high due to construction practices and land-use issues, only twenty-three persons died. Concerning severe convective storms, Figure 6.2 shows the dramatic increase in the probability of detection of severe local storms (warning accuracy) and decrease in false alarm rates since the late 1970s. The crossover point of the two plots occurs around 1988 when deployment of the new next generation Doppler radars (NEXRAD) or weather surveillance radar-1988 Doppler (WSR-88D) began. Figure 6.3 demonstrates warning lead times for severe convection. Both figures suggest that for severe local storms we are now entering the era of
predictive rather than reactive warnings.

The end-to-end forecast process works. But for it to be truly successful, everyone involved in the process must understand the process and their roles in it. The following is a brief look at each aspect of the process.

**OBSERVATIONS AND ANALYSES**

**Observations**

All predictive capabilities start with observations. Observation systems fall generally into two types. *In situ* systems directly measure hydrometeorological variables, such as temperature, pressure and dewpoint. Examples include surface observing systems and radiosondes. In contrast, remote sensing systems, such as satellites, radar and atmospheric profilers, measure parameters which can be used to determine the basic hydrometeorological variables either from mathematical/empirical relationships, the use of conceptual models or the application of sophisticated computer algorithms. Nevertheless, trends toward automation and use of new sensor platforms are blurring the distinction. The new automated surface observing system (ASOS) uses algorithms to determine present weather conditions, such as surface visibility restrictions. Instrumented aircraft contain a mix of sensors for both direct measurement and remote sensing. For example, flight-level winds can be directly measured while stepped frequency microwave radiometers and onboard Doppler radar can be used to infer surface-based wind fields.

Traditionally, routine surface and upper-air observations are taken at internationally defined times around the globe in support of the World Meteorological Organization's (WMO) World Weather Watch (WWW). These "synoptic" observations are
supplemented literally with a renaissance of “asynoptic” or non-scheduled observations from remote sensing systems, local public and private sector mesoscale observing networks, lightning detection systems, meteorological observations from commercial aircraft, buoy and ship observations, and voluntary observations from various cooperating organizations and individuals. Where available, these asynoptic data provide much higher spatial and temporal resolution while filling some of the data voids over the oceans and sparsely populated areas. Evolving sensor capabilities, the need for greater spatial and temporal resolution, the use of targeted observing systems to enhance numerical weather prediction, and even more rigorous resource constraints suggest that a total observing system must be created that integrates all of the necessary subsystems into a unified cost-effective whole. The North American Atmospheric Observing System (NAOS) was established in the National Oceanic and Atmospheric Administration (NOAA) to ensure a comprehensive environmental database.

As the observing system continues to evolve, the need for “ground truth” information will continue to increase. In the United States today, over 120,000 trained storm spotters provide critical ground truth data to both WFOs and national centers concerning the location and intensity of tornadoes, severe thunderstorms, precipitation amounts, river stages and storm surges. Many of these individuals are amateur radio operators who, as part of a local or regional net, can be prepositioned and redirected to provide critical information on the storm’s most dangerous characteristics. This information is correlated with radar and satellite signatures to provide timely warnings, update system algorithms, increase our knowledge of storm-scale structure, identify sensor error characteristics and provide a basis for quantifying forecast uncertainty.

Figure 6.3 Warning lead time for all severe local storm warnings compared to tornado warnings only.
The NWS operates the Cooperative Observer Network made up of over 10,600 volunteer observers who collect daily climatological, meteorological and hydrological data. Five thousand of these are devoted to climate observations although 3,600 of these also support hydrologic requirements. The remaining 5,600 are hydrologic stations observing river stage, precipitation, temperature, snowfall, snow depth, evaporation and other parameters. Information from cooperative observers provides the database in support of climate and climate change issues as well as hydrologic predictions and support to meteorological warnings and forecasts. With the advent of automated observing systems, cooperative observers have become increasingly important in supplementing these systems for operational forecast requirements and in providing ground truth for sensor development and algorithm modifications.

For marine observations, the NWS manages the Voluntary Observing Ship program that has resulted in approximately 1,600 ships providing valuable observations on the high seas and Great Lakes. Port meteorological officers manage the program from thirteen strategic locations along the US coasts. Similarly, the Marine Observation (MAROB) program encourages fishing fleets, party boats and other cooperators to voluntarily take and phone marine observations to WFOs.

Analyses

Forecasters use these observations to diagnose the weather situation and to prepare and issue short-term warnings and forecasts up to twelve hours in advance. However, these data also need to be “assimilated” into numerical models for longer-term predictions. As already noted, these observations can be made up of directly measured traditional hydrometeorological elements, such as temperatures and wind speeds at specified times and locations, or digital parameters, such as satellite radiances. For the numerical model to function, these datasets must be assimilated into a common form in order to depict the atmosphere’s “initial state”.

Unfortunately, when trying to describe the initial state, large data voids and errors still exist. Accordingly, any data assimilation scheme begins with a first-guess field that is usually a forecast for the initial state from a previous numerical model forecast run derived from an earlier analysis. Then the current data are ingested, quality controlled and run through an interpolation scheme that uses the data to modify the first-guess field. The result is an analysis that can be used as the initial conditions for a numerical forecast model. At the NCEP, the global data assimilation system (GDAS) provides the first guess for the various numerical models run at the center (Derber et al. 1994; Parrish and Derber, 1992; Kanamitsu et al. 1991; Derber et al. 1991). It is global in nature and uses both synoptic data and radiances from geostationary and polar orbiting satellites. As more synoptic data become available, data assimilation and analysis schemes are being developed to ensure that this valuable information gets into the forecast process. One example is the NCEP’s rapid update cycle (RUC) (Benjamin et al. 1994). The intention of the RUC is to literally create a new analysis every hour.

NUMERICAL PREDICTION

Numerical models

Once observations are assimilated in an analysis that defines the initial state of the atmosphere, numerical models using hydrodynamic equations are integrated over time to produce forecasts of the desired hydro-meteorological variables. These numerical model forecasts serve as guidance to forecasters for the development of the official forecast. At the NCEP’s Central Operations in suburban Washington, numerous runs are performed on a series of models created for specific purposes.

The dynamical models run at NCEP Central Operations vary from global models, such as the medium range forecast (MRF) model that runs once per day with a horizontal spectral resolution equivalent to 105 kilometers (km) out to 7 days and 210 km out to 16 days (Kalnay et al. 1996), to the RUC that is projected by the year 2000 to run hourly over a North American domain with a horizontal resolution of 20 km, a vertical resolution of 60 layers, and a forecast out to 12 hours. Numerical forecasting capabilities for larger-scale or synoptic weather events have improved so much that our present...
forecasts for Day 5 are equivalent in accuracy to our Day 3 forecasts only fifteen years ago (Uccellini et al. 1997). Efforts to enhance the prediction of small-scale or mesoscale systems on the order of 400 km to 4 km, such as squall lines and meso-cyclones that produce tornadoes, has resulted in an increase in regional and local model development. At the NCEP, the mesoscale eta model is run four times a day to provide a 48-hour forecast for North America with a horizontal and vertical resolution of 29 km and fifty layers. By the turn of the century, horizontal resolution will increase to 5 km.

At the NOAA’s Forecast Systems Laboratory (FSL) in Boulder, Colorado, a four-dimensional data assimilation system is under development in the Local Analysis and Prediction System (LAPS) branch that produces hourly three-dimensional mesoscale analyses of temperature, wind and moisture variables which the Colorado State University Regional Atmospheric Modeling System uses to prepare 0- to 12-hour mesoscale forecasts over a domain the size of Colorado. The CSU-RAMS model uses non-hydrostatic physics and microphysics as well as surface and vegetation parameters to provide forecasts with a 10 km resolution (Snook et al. 1995; Snook and Pielke 1995; Cram et al., 1993).

Questions have been raised as to the best way to pursue numerical modeling in the future. With more local and regional models being developed, a tension is arising as to whether there should be more centralized modeling efforts or more distributed modeling for regional and local applications. Local and regional models developed in cooperation between universities and local NWS field offices push the envelope toward incorporating science and high resolution datasets into local forecast operations for short-term predictions. The NCEP, on the other hand, has the critical mass of resources necessary to develop and run sophisticated global through mesoscale models on an operational basis for the entire United States. The most likely trend is to see the NCEP implementing lessons learned from local and regional models into their operational mesoscale models as well as providing support to some local models that can be implemented at local field offices nationwide. Similarly, local and regional modelers would look to the NCEP to provide the global and regional analyses which can support the local and regional models first-guess fields.

Statistical models

Even with better physics, finer resolution and better initial conditions, numerical forecasts will still contain errors. One solution is for forecasters to use their knowledge of the model’s performance and error characteristics to make modifications to the model’s output. Another approach is to apply statistical modeling concepts to the dynamical models to provide forecast variables that account for model errors. Carter et al. (1989) provide an excellent treatise on the concept of model output statistics (MOS).

The MOS approach requires an archive of dynamical forecast model forecasts. Some statistical method, usually multiple linear regression, is then used to determine relationships among various observed weather elements (predictands) and numerical model output variables (predictors) at projections near (before, at, or after) the specific valid time of the predictand. To make operational forecasts, MOS equations usually are applied to the same dynamical model that provided the developmental sample. The equations account for some of the bias and systematic errors found in the dynamical model. The MOS technique also recognizes the predictability of the model variables by selecting those variables that provide useful forecast information.

The application of MOS techniques toward the development of basic forecast parameters (such as snow, sleet, cloud cover, etc.) as guidance to forecasters has been in use within the NWS for over two decades and is expected to continue. However, it must be realized that MOS operates best the longer the archive of dynamical model forecasts. Numerical models are not static entities. Once changes are made, MOS forecasts will suffer until a sufficient archive of new forecasts from the model are built.

Another approach that is also being applied is to acknowledge that forecasts are not deterministic. Since multiple outcomes occur through the growth of differences in numerical models as a result of slight variations in initial conditions, numerical model forecasts should be viewed in a probabilistic sense. This is considered especially true for medium-range forecasts (Mullen and Baumhefner 1993) even though short-
range forecasts can benefit from this approach as well. At NCEP (Tracton and Kalnay 1993; Toth et al. 1997), the concept of ensemble forecasting is being practiced where the medium-range forecast model is run fourteen different times from varying initial conditions. The resulting range of possible solutions depicts the uncertainties inherent in the forecast due to uncertain initial conditions. How the solutions group themselves can then assist the forecaster in determining the best course of action for the official forecast.

THE HUMAN TOUCH

As noted earlier, the forecast process is not a linear activity. Accordingly, everything that has been discussed so far should be viewed as occurring in parallel; that is, observation receipt, numerical model runs, and forecaster iteration with the observations and numerical model output. As discussed by Sullivan et al. (1993), the use of real-time in situ and remote sensed observations is more meaningful in the short term than dynamical model output, especially in the first twelve hours, for such events as heavy convective rainfall. Figure 6.4 illustrates the time series of current data usefulness versus numerical model predictions. Obviously, the growth of regional and local modeling will push the intersection point to the left.

However, the graph does illustrate the inherent parallelism in the forecast process and the need for human intervention. Of critical importance is the fact that the human forecaster is absolutely vital to the forecast process. Ultimate responsibility resides with the last forecaster to iterate with the observational and numerical model information before it is released to the public. How much time is spent on the forecast process will depend on what the forecaster determines is the problem of the day, whether it be short-fused warnings or assessing the development of a winter storm three days or more in the future. The following discussion outlines the human aspect of the forecast process.

Forecast formulation

Any predictive activity, whether hydrometeorological, medical or economic, requires both a diagnostic and a prognostic component. Before one can make a prediction for the future, one must be able to diagnose or explain why current events are occurring as they are. In hydrometeorological terms, forecasters must analyze the current observations and apply diagnostic computations and physical reasoning to define the present situation. Once the reasons for the present weather conditions are outlined, the forecaster can then define the hydrometeorological reasoning for the future state. Ideally, this should be done before consulting any numerical model guidance. Then, with the forecaster’s perceptions enhanced by their physical understanding of the present conditions, they can review the various numerical model solutions and select those aspects of each which are the best extension of the current state. Then, as additional observational and model data arrive, they can factor them into what will become the official public forecast.

Snellman (1982), in his discussion contained in the 1992 version of the Cooperative Program for Operational Meteorology, Education, and Training (COMET) distance learning module titled The Forecast Process, defines the concept of the “forecast funnel” which can aid forecasters in formulating their forecast. Basically, the forecast funnel concept states that the diagnostic and prognostic process can be enhanced by addressing all atmospheric scales from the hemispheric circulation down through the
mesoscale. Although the time spent on each scale increases as one goes down the scale from hemispheric, to synoptic, and finally to the mesoscale, each is important to the total understanding of the atmospheric processes and scale interactions that affect the forecast.

While working their way through the forecast funnel, forecasters develop a forecast taking into account:

- physical bases behind the current conditions;
- relationships between model initial conditions and observations;
- known biases in each numerical model;
- pattern recognition and conceptual models;
- subjective guidance from identified centers of expertise.

Fitting a structure to the process

The last element dealing with identified centers of expertise is critical if a consistent level of service is to be provided across a country with a diverse climatology. In the United States, although various types of severe weather and flooding can occur virtually anywhere, there are preferred locations where forecasters, frequently confronted with a specific hazard, can develop a high level of forecast expertise for that event. However, a consistent level of forecast expertise for any one hazard should not be expected to prevail at each weather office in the US. Nevertheless, each citizen, no matter what their location, should expect an equal level of warning service for a particular event. This suggests the creation of centers of expertise where personnel devoted to a specific hazard can provide critical guidance information nationwide that will support a consistent warning and forecast program (Zeivin and Carter 1994).

When establishing a national weather service charged with safeguarding a nation’s citizens from the vagaries of natural hazards, a decision must be made as to the proper mix between centralized and distributed services. The initial NWS modernization paradigm was to assign warning and forecast responsibility to an office that had the most information concerning the area in question. In most instances, this is the WFO which has available the nationally provided numerical model guidance and observation sets as well as the rich data fields from the WSR-88D, local mesonets and spotter networks of which only a subset is available to a national center. Each WFO’s area of responsibility is defined commensurate with the areal coverage of the highest resolution data which equates roughly to the effective coverage area of the office’s Doppler radar(s). When the forecast area lies outside of this area, the national datasets would be the primary information sources which would support a national or centralized warning and forecast service.

The NWS modernization capitalizes on the concepts of the best source of information and centers of expertise to establish a warning and forecast service made up of the NCEP Service Centers, RFCs and WFOs.

The NCEP is made up of eight centers. Five are located in suburban Washington, including Central Operations, where the numerical models are run; the Environmental Modeling Center (EMC), where the numerical models are developed; the Hydro-meteorological Prediction Center (HPC), which is the center of expertise for model interpretation and quantitative precipitation forecasts; the Marine Prediction Center (MPC), which provides warnings and forecasts for the high seas and offshore forecast areas; and the Climate Prediction Center (CPC), which is the center of expertise for long lead time and climatological forecasts. The Tropical Prediction Center (TPC) in Miami, Florida, is the center of expertise for hurricane forecasting. The National Hurricane Center (NHC) as part of the TPC and the Central Pacific Hurricane Center in Honolulu issue watches and warnings for hurricanes and tropical storms for the Atlantic Basin and the Pacific Basin to 180°W. The Storm Prediction Center (SPC) in Norman, Oklahoma, is the center of expertise for the mesoscale aspects of all weather hazards, including severe local storms, winter storms and fire weather. They presently issue watches for severe thunderstorms and tornadoes although this function is expected to translate to WFOs once the data-integrating capability of the advanced weather information processing system (AWIPS) is deployed. Finally, the Aviation Weather Center (AWC) in Kansas City, Missouri, is the center of excellence for aviation-related forecasts,
including the issuance of SIGMETS and AIRMETS which are aviation warnings for severe convection, turbulence, icing, and low ceilings and visibilities. Although not part of the NCEP, the Alaska Aviation Weather Unit in Anchorage provides a similar function for Alaska. Also, at each Federal Aviation Administration (FAA) Air Route Traffic Control Center (ARTCC), NWS meteorologists provide the meteorological expertise necessary to enable the FAA to manage the national airspace effectively.

The NWS operates thirteen RFCs which are centers of expertise for river and flood forecasting, providing site-specific forecasts for more than 4,000 flood-prone areas along America's rivers. Each RFC area of responsibility covers one or more major river systems where stage, flow, volume and velocity forecasts are made for up to four days, and extended-range forecasts for more than a week. These forecasts are provided to WFOs for assimilation into flood warnings and forecasts for hydrologic interests. RFCs also provide flash flood guidance to WFOs in support of the flash flood warning program (Zevin 1994).

The front line in the end-to-end forecast process is made up of the 119 WFOs that provide the warning and forecast service to their area of responsibility. Aside from the considerations outlined earlier, a WFO's area of responsibility is further defined by customer needs and expectations including identification of local citizens with metropolitan areas, local and regional emergency management areas, and media areas of dominant influence. The WFOs provide the link to the local communities in the development and nurturing of warning partnerships which could not be supported by a centralized forecast structure. In areas with a sparse population, such as Alaska, WFOs have responsibilities that cover larger areas. The trade-off is a cost-effective structure that can provide the best service to a majority of the population.

All of this is managed from National Weather Service headquarters that establishes national policy for hydrometeorological services and six regional offices that work with their field offices to implement policy and to evaluate service provision. During significant events, such as hurricanes, regional offices closely monitor office operations and manage resources to ensure a continuous delivery of critical information.

Putting it together

Figure 6.5 (NOAA/NWS 1996) attempts to capture the essence of hydrometeorological forecast operations at a WFO by illustrating how all of the information is integrated to create flood warnings and hydrologic forecast products (Fread et al. 1995; Larson et al. 1995). In actuality, it serves as a generic model for the provision of all WFO products and services.

In the center of the figure is a WFO forecaster at work at the AWIPS workstation that integrates all of the relevant datasets in support of forecast creation and dissemination. Flowing into AWIPS from the top of the figure are the various data sources, including the WSR-88D; surface observing systems, including ASOS; geostationary and polar orbiting satellites; and river observations. From the bottom left, gridded analyses and forecast fields flow into the system from the various NCEP centers. These data fields include those directly derived from the objective numerical models and statistical models, such as MOS. Included also are gridded forecast fields derived both from the numerical and statistical models and the expertise from NCEP forecasters. From the left, graphical and gridded hydrologic forecasts arrive from the RFCs.

This totality of information resides in a four-dimensional database that forecasters can manipulate and modify by taking into account all of what has been discussed so far as well as their expertise on local forcing on hydrometeorological parameters. Rather than thinking about specific products for specific customer groups, forecasters make changes to the gridded database to capture the present and future state of the hydrometeorological conditions that best fit their paradigm. Then, the integrated forecast preparation system (IFPS) of AWIPS generates and prepares for dissemination suitable forecast products according to defined user requirements. Flowing out of the system on the right are the various warning and forecast products, including gridded forecast data which go not only to external customers but also internally to other WFOs, RFCs and NCEP centers.

Figure 6.6 illustrates how value is added at each step as the various gridded forecast fields flow through the NCEPs, RFCs and WFOs. Forecasters at NCEP centers, RFCs and WFOs each receive the
model output grids as well as grids which have the additional benefit of statistical MOS forecasts. Forecasters at the WFOs and RFCs also receive gridded forecasts that include the additional expertise provided by NCEP Service Center forecasters. Similarly, NCEP Service Center forecasters receive gridded forecasts that contain the added expertise from the hydrometeorological forecasters in the RFCs and WFOs.

AWIPS and IFPS are establishing a whole new concept on how forecasters approach their job. The forecasters’ focus will now be totally on the present and future state of the hydrometeorological situation. In the past, forecasters were dedicated to preparing forecasts for specific communities of customers with local offices staffed with public, marine, aviation and fire weather forecasters. Now, with a greater focus on the hydrometeorological conditions, division of labor will focus on the temporal aspects of the forecasts. WFOs are just beginning to restructure their internal forecast operations along the concept of short-term and long-term forecast responsibilities. When severe weather is imminent, most if not all WFO resources will focus on the short-term warning function. Forecasts for the longer periods will be created by the IFPS using the gridded fields arriving from the NCEP Service Centers that incorporate modifications by NCEP Service Center forecasters.

**FORECAST COORDINATION**

The bottom line in the forecast process is that users get the information they need and make optimal decisions from it. According to Miletci and Sorenson (1990), response is enhanced if consistent information is received from multiple sources. In order to achieve this consistency, all partners in the warning and forecast process must be brought into a common understanding of the hydrometeorological situation so they can speak with one voice to the public. This
requires the coordination or exchange of information which should include a verbal two-way discussion between participants. Normally, coordination should occur first between affected NWS offices and then be expanded to include the NWS partners in the warning process.

**Internal coordination**

Concerning internal coordination, it is expected that a mix of both routine and event-driven coordination will be required. In the past, coordination was tied to the availability of numerical model guidance and pressures of forecast deadlines. Now with numerical models being run with increasing frequency, scheduled coordination will occur early in the forecast shift to share initial ideas and establish opportunities to promote consistency. Event-driven coordination will be triggered when significant changes to the existing forecast data base are anticipated. The goal for internal forecast coordination is for all parties to arrive at a consensus forecast that proves better than any individual effort while avoiding the pitfalls associated with a compromise forecast. Any forecaster should be able to act as a facilitator by initiating a coordination call. For routine coordination, this could be delegated at the local office level to the WFO designated to conduct external coordination with state officials. For event-driven coordination, it could rest with the individual who established the coordination effort: whether at a WFO, RFC or NCEP center.

System requirements to support internal forecast coordination require that AWIPS is able to link multiple offices in a coordination activity where the coordination facilitator could take all of the involved offices through a hydrometeorological discussion.
Information on the facilitator's workstation would be simultaneously available on all of the linked AWIPS systems as well. This would allow everyone involved in the coordination activity to view the same gridded data instantaneously. For a two-way discussion, any office in the coordination activity would be able to interject their concerns by temporarily taking control of the system to present information in support of their case. This type of AWIPS functionality is expected as the system matures.

External coordination

Once a consensus forecast has been achieved, it is time to reach externally to the broader hazards community. The hazards community has been defined as all organizations involved in the warning process. As defined by social scientists, Miletie and Sorenson (1990), the warning process involves three equally important functions:

- detection and warning;
- communication;
- response.

If any of these functions fails, the entire warning system is deemed to have failed. Viewing the warning process in this way, the hazards community includes government agencies from national to local level, emergency management officials, local government officials, the media, local decision-makers, private sector meteorologists and various volunteer organizations. The hazard community is a warning partnership that must be nurtured to ensure effectiveness. Furthermore, each organization must understand its role in the warning process to ensure the communication of a consistent message to the public.

External coordination must occur at several levels. Nationally, it must involve all federal agencies with responsibilities defined in the Federal Emergency Management Agency's (FEMA) Federal Response Plan. Next, state and local emergency management organizations must be brought into the process. Finally, coordination should occur with the broadcast media.

The NWS and FEMA are developing capabilities to coordinate with federal agencies at the national level and are exploring state and local coordination methodologies that are both efficient and cost effective. The initial impetus is in the hurricane program where the NWS and FEMA established a videoconferencing capability linking NHC, HPC and NWS headquarters with FEMA's Emergency Information Coordination Center (FICC) that includes representatives from all involved federal agencies. For coordination with state and local emergency managers, FEMA and the NWS created a hurricane liaison team at NHC made up of FEMA regional personnel and non-affected local emergency managers. The functions of this team are to establish the national videoconferences as well as subsequent teleconferences between NHC, state officials, and local NWS WFOs. Once this coordination is completed, the local WFOs conduct conference calls for local emergency managers in their county warning and forecast area. This effort proved extremely successful during the 1996 hurricane season. At the national level, FEMA was able to pre-deploy first-response teams and locate safe areas for disaster supplies to maximize help to the affected areas. Similarly, emergency managers at the state and local levels operated off the same information which enhanced critical decision-making from state through local levels.

FEMA and the NWS will expand the use of videoconferencing at the national level to include coordination for all natural hazards. They must also establish an effective and cost-efficient all-hazards coordination capability between the involved federal agencies, WFOs, and state and local emergency managers. This system must include not only two-way voice communication but also the exchange of graphics and digital data.

In some locations, WFOs have established coordination lines in concert with the broadcast media to ensure the consistent communication of critical information to the public. NHC also has conducted coordination calls with the major media outlets to coordinate the release of hurricane warnings. In the future, all WFOs as well as NCEP entities must be provided with capabilities to conduct teleconferences with the broadcast media. Inclusion of appropriate emergency managers in these conference calls would enhance the warning partnership by ensuring that consistent warning as well as response information was disseminated to the public.
FORECAST PRODUCTS: CREATING USEFUL INFORMATION

Seamless continuum of information

The renaissance of information residing in the forecasters' four-dimensional database must be translated into the types of products that will enhance informed decision-making at all levels from national agencies to the general public. The gridded database lends itself to a "seamless continuum of information". This concept, envisioned by the past NWS Deputy Assistant Administrator for Operations Susan Zevin, encompasses a delivery of services that extends through all time and space scales from decadal and centennial climate change to the storm scale. Longer lead time predictions, though exhibiting greater uncertainty, contain valuable information. Providing forecasts along with a quantification of the forecast uncertainty affords the greatest opportunity for maximizing response (Zevin 1994).

Presently, the continuum of information includes long-term and short-term forecasts, outlooks, watches and warnings/advisories. The terms outlook, watch and warning/advisory place an official status on the degree of uncertainty while providing a heightened level of concern for forecast events that pose a major threat to life and property. Outlooks indicate that a hazardous hydrometeorological event may develop. Watches indicate that the probability has increased to a certain predetermined level but that the chances of occurrence are still uncertain. Warnings underscore that the event is either occurring or has an extremely high probability of occurrence. Advisories treat the potential the same as a warning although the event is considered as more of an inconvenience that would only become life threatening if some minor response action was not taken. Short-term forecasts focus on the evolving and changing weather expected within the next few hours (Wernly 1994).

Probabilistic forecasts: quantifying forecast uncertainty

The outlook, watch, warning paradigm has served well for many years and still has utility as long as it is applied consistently across all hazards and is combined with continued public education efforts. However, new technologies as well as increasing complexity in user decision-making methodologies suggests that more explicit ways of defining the probability of occurrence of an event are required to maximize response actions. For example, in short-fused events, the WSR-88D, in combination with other sensors and extensive training, has enabled NWS forecasters to significantly increase lead times for severe convective storms and flash flooding. With lead times for severe thunderstorms and tornadoes averaging in the tens of minutes, we are now in the realm of predictive warnings. As warning lead times continue to increase, proper response actions will require additional information. Similarly, for longer fused events, the need for amplifying information beyond watch and warning terminology will be necessary as users' varying response requirements may not have a direct correlation to watches and warnings. The creation of probabilistic forecasts is a logical extension of the forecast process where forecasters use probabilistic guidance information to create their forecast and then communicate the forecast and its attendant uncertainty to the ultimate decision-makers. These people then combine this information with their unique situations to assess the risk they are willing to accept and, in combination with the associated costs, determine their most effective response actions.

Presently, these concepts are being used effectively in the hurricane warning program. Pilot projects are under way to expand this to the flood warning program through the creation of probabilistic quantitative precipitation forecasts (PQPF) and the probabilistic river stage forecasting system (PRSF) (Zevin 1994). Application of this must be expanded to all natural hazard warning systems.

Quantification of forecast uncertainty in the hurricane warning program

The current state of the science in hurricane track forecasts is such that the 24-hour average forecast position error is equivalent to approximately 100 nautical miles. This may be visualized by plotting the 24-hour forecast position on a map and then drawing a circle around the forecast position with a radius
equal to 100 nautical miles. Then, the center, or eye, of the hurricane would be expected to lie anywhere within that circle. For greater forecast projections, the forecast uncertainty increases. Because of this, NHC normally does not issue hurricane watches along a coastal segment more than 36 hours before landfall. Landfall is defined as when the eye crosses the coast. Similarly, hurricane warnings are normally not posted more than 24 hours before landfall.

Unfortunately, hurricane evacuation studies, conducted with FEMA, the US Army Corps of Engineers and NOAA, have determined that many coastal areas will require more than 40 hours to evacuate, while other places, such as New Orleans, need 72 hours to evacuate for a Category 5 hurricane (Wernly 1994). For these locations, emergency managers will need to order evacuations well before either a watch or warning is issued.

In order to assist emergency managers in their decision-making process, hurricane strike probabilities were developed for specific points along the coasts to quantify the uncertainty in the hurricane track forecasts. Hurricane strike probability is the probability that the storm center will pass within 50 miles to the right or 75 miles to the left of the defined location when looking at the coast in the direction of the storm's motion. The probabilities can be used in two ways. First, they quantify the risk of landfall for the defined point. Second, the variation in probabilities along the coast pinpoints the areas at greatest risk. If a segment of the coast has probabilities all within a similar magnitude, then the threat to that area is the same. Figure 6.7 illustrates the relationship between the forecast track and the strike probabilities for a landfalling storm and a storm paralleling the coast.

With the introduction of hurricane strike probabilities, emergency managers take into account the current forecast track, the uncertainty in the forecast track, the intensity and size of the storm as defined by the forecast wind fields, and defined evacuation clearance times to make evacuation decisions related to their unique concerns. Many PC application programs have been developed by the

![Figure 6.7 Hurricane strike probabilities for a direct hit versus a paralleling storm](image)
private sector to help decision-makers integrate this information with their own datasets using geographic information systems (GIS). These tools enable emergency managers to assess what facilities and populations reside in the threatened areas while providing a decision methodology that can help define what actions to take given the amount of risk they are prepared to accept.

Presently, we have not demonstrated consistent skill in hurricane intensity change forecasts while the storms are over water although a wind decay model shows promise for depicting wind fields and intensity following landfall. Unfortunately, the inland wind decay model does not contain information on forecast track uncertainties which can lead to erroneous decisions if the forecast track is treated as certain. Once the uncertainties in intensity forecasts as well as the inland track predictions are quantified and incorporated in decision aids, emergency managers and other local decision-makers will be able to tailor response actions to their unique concerns.

**Quantification of forecast uncertainty in the flood warning program**

Similar concepts are being developed into an integrated probabilistic hydrometeorological forecast system that has been pioneered by NWS Eastern Region Headquarters through the involvement of WFO Pittsburgh and Roman Krzysztofowicz of the University of Virginia (Zevin 1994). In the past, hydrologic models run at NWS RFCs used observed precipitation amounts to produce river stage forecasts for mainstem rivers. If precipitation was continuing during the forecast process, then forecast stages would be underestimated while future stage forecasts would stair-step as additional observations made their way into the models. An obvious solution was to include forecasts of future precipitation or quantitative precipitation forecasts (QPFs) into the models. This was begun in the Eastern Region in the 1980s.

One of the difficulties in including QPFs in hydrologic models is that the creation of reliable QPFs is extremely difficult. Krzysztofowicz and Drake (1992) note that deterministic QPFs, or single estimate QPFs, show a large bias toward overforecasting as the single estimate does not allow the forecaster to convey the degree of forecast uncertainty. By developing a scheme to quantify the QPF uncertainty, they showed that such a scheme benefits the forecaster in making unbiased judgments while providing valuable information for decision-makers. The use of QPFs as input to probabilistic river stage forecasts should have the following benefits:

When used optimally, probabilistic forecasts are always at least as valuable (economically) as deterministic forecasts. Moreover, the larger the prior uncertainty about the predictand, the greater the potential gains from probabilistic forecasts relative to deterministic forecasts. Inasmuch as precipitation amount is one of the most difficult meteorologic predictands, gains from quantification of forecast uncertainty could be substantial.

(Krzysztofowicz et al. 1993)

A PQPF is made up of two parts, namely a probabilistic forecast of the basin average precipitation over a fixed period plus a deterministic forecast which shows the fraction of the total amount that is expected to occur during each subperiod of the forecast. Figure 6.8 (Krzysztofowicz 1993) shows the basin average precipitation amount estimated in terms of three exceedance fractiles and the probability that basin average precipitation will exceed a given fractile. A continuous exceedance function is then created to obtain an exceedance probability for every possible precipitation amount. Figure 6.9 (Krzysztofowicz 1993) illustrates the deterministic part of the PQPF which depicts what fraction of the amount of precipitation is expected to fall in each subperiod. Finally, Figure 6.10 (Krzysztofowicz 1993) shows an example

![Figure 6.8 Exceedance function of the 24-hour basin average precipitation (BAP) amount](image-url)
Central River Forecast Center in Chanhassen, Minnesota, and the WFO in Des Moines, Iowa. The AHPS incorporates WFO Des Moines' QPFs along with CPC's seasonal predictions to provide probabilistic river stage forecasts up to three months. Figure 6.11 illustrates a probabilistic flood inundation map derived from probabilistic river stage forecasts. Here GIS technology graphically depicts the potential inundation areas along the Des Moines river system in Des Moines, Iowa, for the period March 12 through May 4, 1997. The long lead predictive capability of AHPS will greatly enhance the ability of water resource personnel and emergency managers to mitigate the potential impact of major floods (Braatz et al. 1997). AHPS is expected to be implemented across the major river basins in the country following the turn of the century.

By quantifying the uncertainties in hydro meteorological forecasts, decision-makers can either include this information in their models or use the probabilistic precipitation and river stage forecasts in concert with their particular operational constraints to arrive at the best possible response action related to the risk they are willing to accept. Similarly, the availability of this information poses the opportunity for private sector companies to create decision methodologies which can assist customers in making decisions most responsive to their needs.

**Graphical and event-driven products**

Graphical products hold the greatest potential for effectively communicating probabilistic forecast information. NWS customer workshops indicate a desire for individual products that consist of both graphic and alphanumeric information. The synergy between both formats appears to offer a greater level of comprehension than either could alone.

Just as observational data and forecast guidance will increasingly flow into the forecaster’s database, so too will critical data and information be made available to the customer. This will result in a gradual moving away from a rigorous dependence on scheduled products to the creation of more event-driven products and services, especially at the shorter time-scales. This will be a major culture change for both forecasters and customers. For this to succeed,
Probability of Flooding During March 12 to May 4, 1997

Date forecast issued: March 5, 1997

- less than 25 percent
- 25 to 50 percent
- 50 to 75 percent
- greater than 75 percent
- natural rivers and ponds
- underground storage tanks
- hospitals
- industrial facilities

National Operational Hydrologic Remote Sensing Center

Figure 6.11 A probabilistic flood inundation map derived from probabilistic river stage forecasts
forecasters and customers must understand each other’s operational constraints. This is already being demonstrated in Oklahoma where event-driven forecasts have replaced scheduled issuances. It has succeeded because NWS forecasters at WFO Norman balance forecast updates with known media deadlines.

Finally, the four-dimensional database implies that products can be provided for any location and for any time period. Accordingly, products outlining the most likely present conditions as well as future projections can be created for point locations, specific areas such as valleys or roadways, and various geopolitical boundaries from towns to states. For the NWS, the development of such graphical and alphanumeric products conforms to customer requirements related to the agency’s safety of life and property mandate. For this and other applications, the database can be made available to customers who would use private sector developed software to create an infinite variety of products and services.

**SERVICE DELIVERY**

**Communication and dissemination**

A crucial aspect of the end-to-end forecast process is transmission of critical information to those who need it. With its safety of life and property mission, the NWS has established dissemination mechanisms to deliver warning and critical information products to the public and other members of the hazards community while making available its full suite of forecast and guidance material to all interested parties. At the same time, the evolving communications revolution is opening up new opportunities for dissemination as well as two-way sharing of information.

The NWS delivers critical warning and forecast information through its NOAA Weather Radio (NWR) network which is being upgraded to digital voice technology through the console replacement system. This will take AWIPS products from the IFPS and generate voice messages that will be broadcast over transmitters that presently reach over 75 per cent of the population. NWR has the unique feature of broadcasting an alert tone before warnings which can be used to literally turn on user receivers for receipt of the warning message. The NWR system is also being upgraded with specific area message encoding (SAME) capability to ensure that only receivers in the designated warned area will be turned on. The SAME technology also serves as the entry point into the emergency alert system (EAS) which takes NWS warnings and disseminates them over commercial radio and television stations as well as cable systems. The NWS has a goal of reaching 95 per cent of the population through NWR by the year 2000. This will be achieved through partnering with state, local and private sector entities.

Another NWS delivery method is the NOAA Weather Wire Service (NWWS) that provides hard-copy information of all NWS warnings and forecasts through satellite-based technologies. By the turn of the century, this is proposed to be upgraded as part of the NOAA Weather Information Service (NWIS) to communicate both graphical and alphanumeric products that can be accessed through a graphical user interface for ease in assimilation. This capability would provide the opportunity for the creation of new graphical products to optimize the presentation of probabilistic warning and forecast information. A precursor of this capability is the Emergency Managers Weather Information Network (EMWIN). EMWIN broadcasts NWS warnings and forecasts over the Geostationary Operational Environmental Satellite system that can be accessed through a one-time purchase of a satellite receiver, software, and a PC operating in the Windows environment.

Access to the entire suite of NWS products, data and gridded numerical model information will continue through the NWS Family of Services data-stream. This is available to anyone with charges based on a cost recovery fee structure. Its prime mission is to provide NWS information to weather information providers who then tailor the information to the unique requirements of individual clients. Another information source is NOAAPORT which is a satellite-based system that disseminates satellite imagery, NWS observational data and gridded guidance to NWS offices. Although it can be accessed by anyone, the high bandwidth requires considerable up front user costs for both systems and software. Thus, it is likely to be used as a direct source of information by value-added service providers.
The Internet is an obvious method of making NWS information available. It is not viewed as a delivery system as customers must access the system to get information. The NWS also does not consider it an operational system as timeliness is not guaranteed while information can be easily altered.

For reaching the greatest number of people, the NWS depends upon the broadcast media. Suitable coding and product formats are defined to ensure national consistency and to facilitate rapid dissemination. The Universal Geographic Code (UGC), which is assigned to each product, ensures the delivery of specific warning messages to predefined locations at predefined time periods. Through its partnership with the broadcast media, the NWS is working to ensure that it is considered the single official source for warning information and that it is given attribution when its products are used.

For true two-way communication of critical information, the NWS is developing the local data access and dissemination (LDAD) functionality in AWIPS. LDAD will provide the interface between a WFO and its external user community to facilitate the exchange of data and forecast products. A major contribution will be its ability to exchange gridded databases between the WFO's AWIPS system and participating partners in the WFO's hazards community.

Data sharing and forecast visualization strategies

The flow of data and information into forecast offices whether in the public or the private sector is immense. This was recognized in the preparations for the weather support to the 1996 Olympic Games in Atlanta where the NWS worked with IBM (Treinish and Rothfuss 1997) to create three-dimensional representations of the regional atmospheric modeling system (RAMS) to facilitate forecaster assimilation of information. Although assisting the forecast process in the forecast office, similar types of visualization techniques must be created for the end user to achieve the full benefits of the end-to-end forecast process. Most end users of critical hydrometeorological information will be neither meteorologists nor hydrologists. Whatever is created must be able to integrate hydrometeorological data and information from the NWS AWIPS four-dimensional database with data and information in the customer's database.

In support of this effort, two pilot projects – the Emergency Management Weather Dissemination Project and OK-FIRST – are under way. Both involve direct involvement with the user to define what critical information is required and how best to communicate it. Results from these projects will be used to:

- define the kinds of products necessary for whole communities of users;
- suggest methodologies for the creation of new products and services;
- define how partnerships can be developed and nurtured among all members of the hazards community for the sharing of critical information;
- provide opportunities for the private sector to create products and services that apply the shared data and information to the unique concerns of specific entities.

The Emergency Management Weather Dissemination Project

In the early 1990s, the NWS and NOAA's FSL in Boulder, Colorado, established the NOAA Emergency Management Weather Dissemination Project to determine the use of advanced hydrometeorological information by local government organizations. Emphasis was placed on the four hazards most threatening to Colorado, namely flash flooding, fire danger, severe convective weather and winter storms (Subramaniam and Jesuroga 1995). High resolution weather datasets include WSR-88D data, lightning strike data, high resolution hydrometeorological gridded data from LAPS, and river stage information (Subramaniam 1996). The first system was fielded at the Boulder Emergency Operations Center (EOC) in 1992. Presently, it has been expanded to the Urban Drainage and Flood Control District (UDFCD) in the Denver metropolitan area as well as the Denver WFO and the Colorado Department of Transportation.

The system was designed to use off-the-shelf hardware within the operating budgets of local emergency managers. It consists of PCs running Windows
NT and a community server which is a PC running the Windows NT advanced server operating system. The community server is intended to be run by the local hazards community and serves as the shared database and messaging center for all partners in the warning process. The shared database contains the user-defined hydrometeorological information from the WFO as well as from other partners such as the UDFCD, action rules from emergency operating plans, and GIS data. FSL-developed software in the display PCs takes the information from the database and creates user-defined graphic and alphanumeric products that support user-defined decision methodologies.

Since the system is operating off high-resolution gridded data, current as well as forecast information can be provided for any desired area. The display workstation has three modes, namely picture, probe and text. In the picture mode, a user can view an image that overlays information, such as precipitation type, accumulation, visibility and interstate highways. The LAPS precipitation graphic (Figure 6.12) is created from radar reflectivity and 3-D temperature (Kelsch and Stamus 1993). Representation of the various fields is done in colors and symbols that have been specified by the user. The emergency manager can then switch to probe mode to further query the system on the area of interest. If a hospital were located in a threat area, the system could be tasked to provide information on the expected weather at the

![Figure 6.12 LAPS precipitation graphic, created from radar reflectivity and 3-D temperature](image-url)
hospital location area as well as the type of hospital, number of beds, emergency contact point and number of persons in the surrounding area that should be evacuated (Subramaniam 1996). Finally, the text mode can be used to view all of the pertinent alphanumeric warnings and forecasts.

**OK-FIRST**

Created as a two-year demonstration project, OK-FIRST (Oklahoma's first-response information resource system) proposes to implement an interactive information support system for Oklahoma public safety agencies. The project's goal is to create a transportable, agency-driven information system that ensures local decision-makers have the information they need.

OK-FIRST will link approximately fifty civil defense offices, fire departments and law enforcement agencies through computer linkages to the Oklahoma law enforcement telecommunications system (OLETS) and the state’s Internet access (OneNet). Over these links, OK-FIRST will make available products in cooperation with FSL through their WFO advanced workstation at WFO Norman as well as graphical products from the Oklahoma Mesonet (operated by the Oklahoma Climatological Survey). Information from the Oklahoma Mesonet includes: unaltered WSR-88D products and mosaics, value-added products from the WSR-88D and Mesonet, and NWS critical information products. Also, OK-FIRST will distribute automated products, such as alerts, based upon severe wind speeds or excessive rainfall measured by the Mesonet as well as from the processing of WSR-88D products. This undertaking will expand the concepts started in Colorado and assess how organizations in another state develop shared information capabilities that are responsive to their specific concerns (personal communication with Dr Kenneth C. Crawford, Director, Oklahoma Climatological Survey).

**PUBLIC AND PRIVATE SECTOR PARTNERSHIPS**

Aside from the creation of products that assist decision-makers, the above two projects will explore the organizational dynamics surrounding the creation of a warning partnership centered on a shared database. Ultimately, these partnerships should be replicated across the country and involve the entire hazards community as well as appropriate private sector entities for the public’s benefit.

The FSL project is an offshoot of the highly successful flood warning partnership in the Denver/Boulder metropolitan area, involving the NWS, the UDPCF, other government agencies, the media and the private sector. The NWS uses observations from its own networks, voluntary spotter reports and remote sensing systems in concert with data from other agencies and the UDPCF to create official NWS warnings and forecasts for specific flood-prone areas. These are disseminated directly by the NWS to the public and to the UDPCF as well as being broadcast by the media. The UDPCF takes NWS information and merges it with their own data and forecast guidance from private sector meteorologists supporting the UDPCF to provide highly detailed critical information products unique to the response needs of local governments within the UDPCF. This enables all participating local governments within the six-county metropolitan area to take timely actions, such as the ordering of evacuations, for precisely defined vulnerable areas (UDPCF 1992; Stewart 1995).

The above example demonstrates the workings of a successful warning partnership between public and private weather services. The NWS is charged with providing warnings and forecasts for the protection of life and property. The NWS creates and delivers critical information with utility to whole communities of users, such as the aviation and marine industries, as well as the general public. When it comes to individual entities, the private sector is available to create products and services that more specifically meet individual or corporate needs. This distinction is blurred somewhat in regard to the emergency management community. Considering the government-to-government relationship with regard to the safety of life and property, the NWS is prepared to create unique products for subsets of emergency managers. Nevertheless, the NWS WFOs will not be able to deal with each individual government entity in their warning and forecast area.

In order to facilitate partnerships, WCMS in each WFO act as service representatives to assess user
requirements, explore capabilities to meet those requirements, train customers on how best to use NWS products and services and define how each user can contribute to the end-to-end forecast process.

RESPONSE

The ultimate goal of the end-to-end forecast process is getting people to respond to the message. Milet and Sorenson (1990) note that warnings are not a stimulus response action. Persons receiving a warning will seek additional information to confirm their risk. Similarly, persons will not follow recommendations in warning messages unless they make common sense. Milet and Sorenson (1990) and Wernly (1994) note that in order to elicit the proper response, warning messages should:

- be specific, internally consistent and accurate;
- be clear as to location, actions to take and time before impact;
- explain uncertainty, address why the event should be treated as certain, stem from multiple sources and be issued or updated frequently.

The concept of the seamless continuum of information, the use of graphical products to highlight uncertainty and to enhance risk perception, and the delivery of warning messages from multiple entities in the hazard community partnership all support these goals. Additionally, preparedness can be enhanced when persons or organizations can identify which hazards could affect them, can demonstrate appropriate life-saving actions, and have developed and routinely exercise a personal, family, or corporate action plan.

The deaths of twenty individuals in the Goshen United Methodist Church of northern Alabama during the March 27, 1994, tornado outbreak is a tragic reminder that the warning or forecast process does not end with the issuance of timely watches and warnings. On that Palm Sunday morning, the National Severe Storms Forecast Center (now the SPC) issued a tornado watch more than two hours before the tornado struck, while WFO Birmingham issued a tornado warning twelve minutes in advance. This is on the cutting edge of the present science and technology. The congregation did not receive the warning as that area of northern Alabama was not in effective coverage of the nearest NWR transmitter, and no one was monitoring the broadcast media during the service. Those who died were killed as the roof collapsed on the sanctuary. However, an interior hallway in the church remained intact and could have provided safety for up to 150 persons (DOC 1994).

As a result of this tragedy, the NWS, through its local WFOs in Alabama as well as nationally, is forging partnerships to expand NWR coverage. Equally important is the need for the development of action plans to enhance response. One of the major roles of the WCMs in WFOs is to work with local organizations and the public to support hazard awareness activities and preparedness planning efforts. Since 1990, the NOAA, FEMA and the American Red Cross have been cooperating in the development of hazard awareness and preparedness information. These materials are used by WCMs to assist families and organizations in the development of preparedness plans so that they can respond in a predetermined manner when they receive a warning or are confronted with a hazard.

Since that fateful spring day, good things have been happening in Alabama. Active public/private sector partnerships have expanded NWR coverage to over 90 per cent of the state’s population with the installation of five new transmitters. The Goshen United Methodist Church can now receive warnings from NWR as well as a new outdoor siren system. Finally, the church has a preparedness plan on what to do if a warning is received or severe weather is observed. When severe weather next comes to northern Alabama, the citizens will be ready.

CONCLUSION

Revolutionary changes have come to the forecast process. Fifty years ago, forecasting was viewed as a subjective art. Today, weather forecasting and storm warning is an applied science based on mathematical and physical principles. The transformation of the forecast process has provided a basis for the modernization of the NWS as reflected through:

1. the incorporation of new observing systems, such as Doppler radars, digital geostationary and polar
orbiting satellites, and automated surface observing systems;
2 the introduction of finer resolution numerical models employing better physical parameterizations and numerical methods while being run on the world's most powerful computers;
3 the creation of both a distributed and centralized service infrastructure to best meet user expectations; and
4 the establishment of service delivery mechanisms, user education initiatives and partnerships to ensure the best use of property and life-saving information.

The transformation of the forecast process into a truly end-to-end concept has made tremendous improvements in our ability to predict the weather at all time and space scales. We now have the ability to identify seasonal and inter-annual climate variability, predict winter storms four to five days in advance, track hurricanes and quantify their most likely strike location 36 hours before landfall, highlight the potential for severe convection 48 hours in advance and issue predictive warnings for tornadoes and severe thunderstorms within tens of minutes. We have within our grasp the capability no longer to be surprised by natural hazards. The predictions of the Superstorm of 1993 and Hurricane Andrew provide a dramatic contrast to the Blizzard of 1888 and the Galveston Hurricane. Recent successes in our predictive abilities have fostered a credibility that did not exist fifty years ago. As a result, the public and local decision-makers are taking predictions seriously and through vigorous educational outreach programs are responding in an evermore informed manner.

Nevertheless, still there is much work to do. Warnings and forecasts still suffer from error and uncertainty. Although many decision-makers are becoming increasingly capable of incorporating hydrometeorological predictions into complex decision methodologies, not all parts of the country are equally equipped to either receive the information or apply it effectively. The recent spate of natural disasters, including Hurricanes Hugo, Andrew, Iniki, Alberto and Fran; the east coast winter storms of 1993, 1995 and 1996; the Mississippi Basin flood of 1993; the northeast and northwest floods of 1996; the Ohio River, Red River of the North and California floods of 1997; and the tornado outbreaks in Alabama in 1994, and in Arkansas and Texas in 1997, highlight our continued vulnerability to extreme hydrometeorological events. Now, as the capabilities to mitigate the effects of natural hazards are within our grasp, it is time to take steps to "weatherproof" our nation and ourselves.

Acknowledging that all forecasts are uncertain, effecting the transition to probabilistic forecasts will enable decision-makers to combine critical hydrometeorological information along with their decision methodologies and unique response requirements to determine the most effective actions commensurate with the degree of risk they are willing to accept. Not only will better decisions be made, but the use of probabilistic forecasts will increase the lead times that emergency managers demand while providing valuable preparedness and planning capabilities in the seasonal and longer time-scales (Zevin 1994). Improved visualization strategies will enable both forecasters and decision-makers to better assimilate the renaissance of information available to them.

Developing partnerships with all members of the hazards community, including the private sector, at each step in the end-to-end forecast process will afford the US the capability to do together what no one can do alone. This ranges from the establishment of local and regional observing networks all the way to dissemination capabilities and user education activities to enhance response. The pioneering efforts in Colorado and Oklahoma illustrate what can be accomplished through the development of warning partnerships built around a shared environmental database. The shared database, residing in a community server that supports all organizations in a WFO's forecast area literally embodies the end-to-end forecast process. For, in that database, each member contributes their information and takes what they need to accomplish their mission - from observations, to forecasts, to response and back to observations. The cycle is complete.

Our abilities to forecast the weather have come a long way from the surprise blizzard of 1888 that crippled New York City and the northeastern United States. We are heading toward an age where highly detailed hydrometeorological information will be the
basis for unique weather-sensitive decisions for everyone in America. As people become more tuned to their environment, longer-term planning and mitigation efforts should increase. This should include demands for shelters and hazard-resistant structures as well as sound land-use planning. Wherever we live, the equivalent of the Nile will rise and fall. But we are developing the capabilities to capture the variability of weather extremes in terms that can be understood, seen in advance and acted upon. The future of storm forecasting affords the opportunity for humankind to live in harmony with nature and to expect a system that keeps natural hazards from becoming disasters.

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