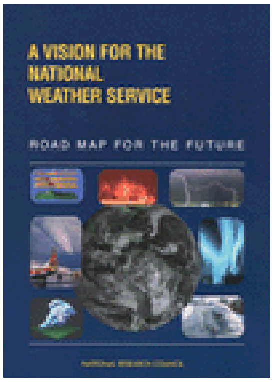

A Vision for the National Weather Service: Road Map for the Future

Panel on the Road Map for the Future, National Weather Service, and National Weather Service Modernization Committee, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

A VISION FOR THE NATIONAL WEATHER SERVICE

ROAD MAP FOR THE FUTURE

Panel on the Road Map for the Future
National Weather Service

National Weather Service Modernization Committee
Commission on Engineering and Technical Systems
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PANEL ON THE ROAD MAP FOR THE FUTURE NATIONAL WEATHER SERVICE

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Preface

In 1990, the National Oceanic and Atmospheric Administration (NOAA) asked the National Research Council to provide oversight and review for the modernization and restructuring of the National Weather Service (NWS). In response, the National Research Council established the National Weather Service Modernization Committee (NWSMC). This report is the last major review, under the auspices of the committee, of what has been achieved, with an additional focus on what lies ahead for the NWS, now that the modernization and restructuring is nearing completion.

In the most recent formal statement from NOAA of subjects the NWSMC should explore, the need for a long-term look at the future was expressed in these words:

> The committee's review will help ensure a continuous modernization to capitalize on the substantial investment already made in new technology, and opportunities available from emerging scientific and technological research and development efforts that will complement and enhance the modernization. Specifically the committee shall investigate the need and opportunities for continuing the modernization of the NWS beyond current plans.

This request from NOAA provided the basis for the Statement of Task for the study panel from the Governing Board of the National Research Council (see box). These instructions have guided the panel's efforts.

During the past nine years, the committee and its panels have provided advice and guidance to the NWS and NOAA on the development and implementation of each major technical system included in the modernization, as well as a host of issues related to the restructuring of NWS field offices. This report argues for the continued evolution of observational and computational technologies to improve NWS forecasts and warnings and for the NWS to seek new avenues for partnerships with others to provide a range of environmental services. The report is an optimistic view of the advances that could enable the NWS to achieve the committee's vision of weather-related information services in 2025. This optimism depends, of course, on many assumptions, the most important of which are described at the beginning of the report.

This report was developed in parallel with another National Research Council report, prepared under the Board on Atmospheric Sciences and Climate and recently released as *The Atmospheric Sciences: Entering the Twenty-First Century*. Although the two authoring groups worked independently, their reports share a vision of exciting new opportunities in atmospheric science and atmospheric information services. They agree on the main strategies for achieving the resulting benefits for the nation. The present report focuses on the NWS and suggests how the evolution and improvement of its observing and prediction capabilities may evolve

Statement of Task

The purpose of this study is to provide guidelines for the National Weather Service (NWS) to effectively exploit emerging science and technology, incorporate modernization practices into operations, and continue to improve weather forecasting and related products and services for the nation well into the twenty-first century.

The project will result in a report with findings and recommendations on opportunities for the NWS to effectively exploit and incorporate emerging science and technology into routine operations on a continuing basis. In addition to addressing technical issues, the study will suggest criteria to establish priorities for science and technology initiatives that would foster improvements in NWS operations and services.

in the context of the projected advances in science and technology.

The panel drew on the scientific and technical expertise of its members, as well as on the experience of the present and past members of the NWSMC. I thank the NWS staff for their many presentations to this panel. I thank the experts in other government agencies, universities, and industry who contributed to this study in many ways. I also wish to express the panel's appreciation to Mr. Floyd F. Hauth, study director, Mrs. Mercedes Ilagan, study associate, and Carter Ford, project assistant, for their expert organizational and logistical support. Finally, I thank consultant Robert Katt for his assistance in preparing the report.

William E. Gordon, chair
Panel on the Road Map for the Future
National Weather Service

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Raymond J. Ban, The Weather Channel, Atlanta, Georgia
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Robert M. White, Washington Advisory Group, Washington, D.C.

While the individuals listed above have provided constructive comments and suggestions, it must be emphasized that responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

I WHERE ARE WE GOING?

II HOW WILL WE GET THERE?

Figures, Tables, and Boxes

FIGURES

TABLES

BOXES

Executive Summary

In this study, the committee explores ways the National Weather Service (NWS) can take advantage of continuing advances in science and technology to meet the challenges of the future. The predictions are focused on the target year 2025. Because specific predictions about the state of science and technology or the NWS more than 25 years in the future will not be entirely accurate, the goal of this report is to identify and highlight trends that are most likely to influence change. The Panel on the Road Map for the Future National Weather Service developed an optimistic vision for 2025 based on advances in science and technology. This vision is based on the seven assumptions explained in Chapter 1.

POTENTIAL BENEFITS TO THE NATION

The panel, which was established by the National Research Council to conduct this study for the National Oceanic and Atmospheric Administration (NOAA), predicts that in 2025 vastly improved weather information products and services will be substantially more useful to society than they are today. The formal NWS modernization and restructuring, now being completed, has provided the foundation for the NWS to lead the way in realizing enormous benefits to the nation. Advances in scientific understanding will enable advances in forecasting techniques. New observational, data assimilation, and modeling systems will be based on scientific advances and technological innovations. The resulting improvements in the accuracy of forecasts will foster markets for weather and related environmental information and will create new opportunities for providers of commercial products and services. To meet the challenges that lie ahead, the NWS must evolve in response to a rapidly changing user and technological environment.

Recommendation 1. The National Oceanic and Atmospheric Administration and the National Weather Service should more aggressively support and capitalize on advances in science and technology to increase the value of weather and related environmental information to society.

ENABLING SCIENCE AND TECHNOLOGIES

Based on improved scientific understanding, advances in observational and computational technologies will greatly improve the spatial and temporal density, accuracy, and timeliness of weather and climate data and information. Measurements of surface and upper air conditions will be made by automated surface observing networks, by airborne observing systems, by advanced Doppler radar processing technology, and by satellite-based observing systems. New methods of data assimilation will enable higher resolution numerical weather prediction models to represent accurately the physical processes responsible for weather and weather-related phenomena (atmospheric physics and hydrologic processes). New techniques will improve local forecasts by combining data from diverse observing systems taken at different times with results from large-scale modeling and local climate information (hybrid forecasting). Information about the accuracy of forecasts and measures of uncertainty in predictions will be more sophisticated, yet more understandable to users. Descriptions of the key physical processes and conditions at grid points over an entire basin (distributed modeling) will replace older methods of modeling the effects of precipitation and snow melt on streams and rivers.

Ongoing national and international scientific research and technology development will provide the foundation for these improvements, which will lead to a proliferation of user-oriented services and products. To realize these enormous opportunities, the NWS and NOAA must prepare to upgrade current observing systems and regain and maintain state-of-the-art computing facilities. They will have to keep abreast of research in the scientific community by actively supporting and participating in the U.S. Weather Research Program and other partnerships.

Recommendation 2. The National Weather Service should be an active partner and participant in national and international research enterprises in weather, hydrology, climate, and environmental sciences.

The NWS must adopt an evolutionary approach to upgrading its operational systems with new technology rather than relying on episodic overhauls. An evolutionary approach will avoid obsolescence and organizational trauma, minimize risks, and enable more timely implementation of improved tools. The rapid development, testing, and implementation of new algorithms and techniques will require sound science and proficient engineering.

Recommendation 3. The National Weather Service should commit to and plan for ongoing and timely incorporation of scientific and technical advances in the operational weather observation, analysis, and prediction system. To implement its commitment, the National Weather Service should take the following steps:

- Develop technologies, in cooperation with universities and the public and private sectors, that enhance systems for observing weather phenomena and for assimilating and analyzing resulting data.
- Evaluate, on a quantitative basis, alternative technologies and approaches for the development, testing, and deployment of a cost-effective system of synergistic observing instruments and platforms, incorporating the principle that integrated measurements taken by multiple sources using diverse techniques can provide a better estimate of a physical quantity than any one instrument alone.
- Test and evaluate new forecasting concepts and systems expeditiously, through rapid prototyping at the appropriate centers or selected forecast offices.
- Maintain a research staff of sufficient size and expertise at the national centers to develop new forecast techniques and products that further their broad national missions.
- Work with the National Oceanic and Atmospheric Administration to strengthen National Weather Service interactions with the National Environmental Satellite, Data, and Information Service and the Environmental Research Laboratories, ensuring that their combined activities are coherent, systematic, and mutually supportive.
- Work with the academic community on a continuous basis to improve numerical weather prediction models.
- Maintain a strong scientific capability at the field offices to conduct application-oriented research and development at the local level (for example, through the science and operations officers and development and operations hydrologists).
- Provide appropriate computing capabilities at field offices to ensure that new technologies can be tested and applied.

The future success of the NWS and the quality of its service to the nation will be determined in large measure by the capability of the computer resources made available to it. Improvements in forecasts will depend on the assimilation of timely data from a broad array of observing systems into computer-based models of the atmosphere, which are vital to modern weather and climate prediction. Running increasingly accurate models at higher resolutions quickly enough to produce useful forecasts will require increased computational power. Parsimony in purchasing NWS computer power is therefore a false economy that deprives the nation of valuable benefits.

Recommendation 4. Congress and the administration should provide the resources needed by the National Weather Service to regain and maintain the state-of-the-art supercomputing capability required to support the advanced analysis and modeling systems that are fundamental to the nation's weather and climate forecast systems.

MERGING WEATHER INFORMATION SERVICES INTO ENVIRONMENTAL INFORMATION SERVICES

The panel expects that continuing progress in weather forecasting, enabled by major changes in meteorology, hydrology, oceanography, and associated technologies, will combine with the continuing transformation of the United States to an information-oriented society to make weather and related environmental data increasingly valuable to a wide range of users. Consequently, the number and variety of participants in the national (and global) network that provides environmental information will increase dramatically. Consumers will use the information to meet their commercial needs and personal interests by integrating traditional weather data (probably in common gridded formats) with other data on the environment and on specific economic sectors. The increasing number and range of nonfederal public, private, and mixed public-private providers of these data and value-added applications will both respond to and create opportunities for new information services and products.

The NWS's role is expected to evolve as provider networks grow. First, the panel expects that the NWS will retain its lead role in issuing public forecasts and severe weather warnings. It must, therefore, constantly improve its dissemination system by exploiting new ways that information providers communicate with end users. Second, the NWS will increasingly provide observational data and gridded forecast products to other information providers, including the traditional disseminators of NWS products (emergency preparedness agencies and broadcast media), as well as public-sector and commercial producers of specialized products and services. Third, partnering with other governmental entities (federal, state, or local) as well as private entities will be essential for fulfilling the fundamental mission of the NWS.

Recommendation 5. The National Weather Service should collaborate with a variety of partner-providers to integrate weather and related information into comprehensive environmental information services.

ORGANIZATIONAL ISSUES

Enlightened strategic planning is critical to enable the NWS to interact with and serve its constituents. To meet the changes in user needs and efficiently upgrade its technology and operations, the NWS will require stable long-term funding that is adequate to implement long-range plans based on validated requirements. Irregular or inadequate support limits the quality and extent of services and denies potential benefits to the entire user community.

Recommendation 6. The National Weather Service should perform strategic long-range planning for orderly development of the infrastructure and technology that support the services for its constituents. Congress, the Office of Management and Budget, the U.S. Department of Commerce, and the National Oceanic and Atmospheric Administration should provide stable and adequate funding to the National Weather Service consistent with its needs and plans.

A rapidly evolving user community, advancing technology, and changing relationships among members of the weather community will require evolution in the organizational structure of NOAA and in the relationships among its components, including NWS, the National Environmental Satellite, Data, and Information Service, and the Office of Oceanic and Atmospheric Research.

Recommendation 7. The National Weather Service should routinely examine and anticipate the needs of primary customers and ultimate users. In the context of changing requirements, the National Oceanic and Atmospheric Administration should periodically adapt its organizational structure and operating processes to foster effective relationships among the National Weather Service, the National Environmental Satellite, Data, and Information Service, and the Office of Oceanic and Atmospheric Research.

Because the atmosphere and oceans transcend national boundaries, realizing the national weather and climate predictive capabilities envisioned in this report will require a free and open exchange of higher-quality and higher-resolution global observations. Creating the requisite global database will require improved cooperation among the major data-gathering nations.

Recommendation 8. The National Weather Service should maintain and strengthen its leadership role in seeking international cooperation for the free and open exchange of weather and climate data for the benefit of users in all nations.

The role of the forecaster will change as NWS personnel who have meteorological or hydrologic expertise spend less time preparing routine forecasts and more time interacting with customers and refining, extending, and validating the models and other tools of automated prediction. Interactions with other participants in the network that provides environmental information (the provider network) will be essential for incorporating environmental observational and forecast data into application-specific decision-support aids and for improving the dissemination of public forecasts and severe weather warnings. The heavy investment in technology for NWS operations will require a technical support staff that is expert in the operation, maintenance, and upgrading of this technology.

Recommendation 9. The National Weather Service should provide for the ongoing professional development of a knowledgeable, flexible workforce through continuing education and training, taking advantage of appropriate university resources.

Given the primacy of its role in the current provider network, the NWS could be well positioned to lead, and not merely react to, changes in the national and international systems for providing environmental information services. Both primary customers of NWS products and services (in the provider network) and ultimate consumers of the information should understand and appreciate the role of the NWS in sustaining and expanding the provider network.

Recommendation 10. The National Weather Service should participate with other public institutions, professional societies, and the private sector in educating the general public and specialized users about the causes and consequences of weather-related environmental phenomena; the utility and limitations of environmental observations, forecasts, and warnings; and the roles of the National Weather Service and its partners in providing this information.

At the end of Chapter 5, the panel lists criteria NWS can use in selecting science and technology initiatives. The list includes both general criteria, applicable to all areas, and criteria specific to observing systems, computer facilities, new NWS products, and education and training.

Part I

Where Are We Going?

Prologue

A Boston Christmas Carol
2025

The mayor of Boston, the director of emergency management, the chiefs of the police and fire departments, and three chief executive officers of major insurance companies arrive at Boston's central weather planetarium on December 19, 2025. The inside is dark except for faint lights blinking on the domed ceiling. The delegation, called together by the mayor, assembles around a meteorologist seated at a small console in the middle of the room. One window of the console contains options for space and time. The meteorologist enters "Boston" for the Location option and "December 24, 2025," for the Date/Time option. The display prompts the meteorologist for a more precise specification of the location and time. From the page-long list of locations in the prompt box, he selects the corner of Tremont and Main streets, an elevation of 800 ft. above the surface, and a time of 0600 EST. When he selects the View Weather option, the inside of the dome becomes faintly illuminated with a wintry scene. Through the swirling fog and snow, a few lights are occasionally visible. A text window in each quadrant of the dome reports heavy snow and fog, visibility of less than an eighth of a mile, temperature of 30°F, sea-level pressure of 997.7 mb and falling slowly, and winds from 030° at 25 mph with gusts up to 40 mph. The message also reports 4 to 8 inches of snow on the ground within a 5-mile radius of the site, with a mean depth of 5 inches.

The mayor asks the meteorologist to move forward in time. He presses the Slow Forward key, and the minute hand on the control panel clock spins forward. At 12 noon he releases the key. The view from central Boston has improved considerably. Breaks in the overcast are visible as the low clouds sweep across the sky from the north. The scene below is one of beauty as fresh snow blankets the city. Last minute Christmas shoppers drive slowly through the plowed streets. The text windows report broken stratocumulus clouds at 6,500 feet with scattered altocumulus clouds above, visibility 10 miles, winds 350° at 20 mph with gusts of 35 mph, temperature of 29°F, and sea-level pressure of 1002.5 mb and rising rapidly. Between 5 and 10 inches of snow are on the ground with an average of 8 inches. The Impacts window reports 3.5 on the EWIS (economic weather impacts scale) and 2.3 on the HWIS (human weather impacts scale).

Seeing that the storm is ending and the impacts are not severe, the mayor asks for the reliability of the "Most likely" forecast scenario she has just witnessed. A probability of 25 percent is returned. The mayor asks, "What is the worst possible case for this period of time?" The meteorologist selects an option in a display window; after a few seconds, another view appears on the dome. Now, only a fuzzy, diffuse white glow is visible. The blinking red text window reports extremely heavy snow and dense fog, visibility zero, winds 045° at 45 mph with gusts of 60 mph, temperature 27°F, and pressure 979.0 mb and falling rapidly. Between 5 and 28

Economic Weather Impacts Scale (EWIS)

EWIS = log (cost of event in $/100)

Cost of event	EWIS
$1,000	1
$10,000	2
$100,000	3
$1 million	4
$10 million	5
$100 million	6
$1 billion	7
$10 billion	8
$100 billion	9
$1 trillion	10

Human Weather Impacts Scale (HWIS)

HWIS = effect on human health and well being

1. *Nuisance*. Noticed/commented on/complained about by only a few people. Adverse effects on sensitive, careless, or unlucky people; fewer than 100 people per million (0.01 percent of the population) affected. Usually not mentioned in even the local news. Quickly forgotten. Examples: minor air pollution event; light rain; light fog. Occurs on about one-third of days. EWIS range 1–2.

2. *Inconvenient*. Noticed/remarked upon/complained about by many people. Adverse effect lasts a day or so for many people (greater than 1 percent). Major adverse impact on a few people. Mentioned in local newspaper and television stations but usually not in the national news media. Example: light snowfall slowing traffic, causing delays of up to several hours, many fender-benders, and a few serious accidents. Occurs about 30 days a year. EWIS range 2-4.

3. *Major*. Noticed and complained about by everyone. Some people frightened. Major adverse economic or health effect on most people lasting for several days or weeks. Life-threatening for a significant fraction (greater than 1 percent) of the population. Hundreds of serious injuries and/or health problems. Ten or more fatalities. Significant news story in the national media. Occurs once or twice a year, on average. Example: January 1996 East Coast "Storm of the Century." EWIS range 5–6.

4. *Severe*. Many people frightened. Thousands of serious injuries or health problems; up to 100 fatalities. Effects last a week or more. Makes headlines in the national media and a few international papers and news reports. Often an official disaster (declared by the president). Occurs a few times a decade in the United States. Remembered for the lifetime of those who experience the event. Example: January 1998 ice storm in northeastern United States and southeastern Canada. EWIS range 6–7.

5. *Catastrophic*. Entire population affected in significant adverse ways. Most people frightened, many terrorized. Life-threatening for more than 10 percent of the population. Featured in most international newspapers and news reports. Triggers major international relief efforts. Impacts may extend for a year or more. Hundreds or thousands of serious injuries or health problems and more than 100 fatalities. Occurs about once every decade. Examples: Hurricane Andrew, East Pakistan cyclone of November 12, 1970 (200,000–500,000 fatalities). EWIS range greater than 7.

inches of snow are on the ground with an average depth of 24 inches. Seventeen lightning strikes have occurred within 5 miles of the chosen location in the past 3 hours.

The mayor asks for the option to Delete Fog from the 360-degree field of view. As the fog disappears, millions of snowflakes become visible streaking nearly horizontally through the sky. A faint outline of a familiar skyscraper is visible about a quarter of a mile away. Selecting the "Remove Snow Precipitation option opens the view to the devastation below. Nothing is moving. Vehicles are stranded everywhere. The roofs of several buildings have been crushed by the weight of the snow. Fallen trees and power lines litter the landscape. In spite of the midday gloom, no lights are visible in any of the office buildings or department stores. Only dim emergency lights at the hospital break the gloom.

Selecting the Impacts window opens a long list of the probable damages from a storm of this magnitude: all airports within 500 miles closed, no roads passable, extreme danger to life and property, 400 fatalities, and $100 million in property damage and other economic losses. After weighing each item on the long list, the rating on the EWIS scale is 7.2 and on the HWIS scale is 4.6, or "Catastrophic."

The probability of the worst case is given as 18 percent, one of the highest probabilities ever forecast for a 5-day, worst-case scenario in the "Catastrophic" category of the HWIS. Based on this information, the mayor and her team begin immediate preparations and response measures.

Weather Services in 2025

FRAMEWORK FOR FUTURE STRATEGIES

As a framework for the evolution of weather services in the next quarter century, the Panel on the Road Map for the Future National Weather Service developed a vision of weather services and supporting technologies. This vision is not intended to be a prediction but is a reasonable scenario for future weather services. The outlook is optimistic and depends on significant advances in scientific understanding and in observational and computational technologies. But with a strong commitment by the National Weather Service (NWS), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Department of Commerce, Congress, and the public, the vision presented below could be realized.

A VISION OF THE FUTURE

In 2025, the basic components of the weather observing, forecasting, and warning process are similar to those of the late twentieth century—observations, analyses, prediction by numerical models, interpretation by humans, and delivery to the public and a variety of users with specialized needs through the media and private weather service companies. These components are so advanced compared to their predecessors, however, that the weather products and services are immensely more valuable to users.

Abundance of Data

Since the early days of meteorology, weather forecasters have sought more and better data. Even with the advent of weather satellites and other advanced remote and in situ sensors during the last half of the twentieth century, incomplete data coverage of the Earth and insufficiently accurate data were significant sources of errors in qualitative and quantitative weather forecasts at the end of the century.

In 2025, the data problem for weather prediction has been substantially solved. Geostationary satellites provide high-resolution (500 meters horizontal and 1 minute temporal) imagery in visible, infrared, and "water vapor" wavelengths on a nearly global basis. Diverse rapid scanning Doppler weather radars provide high resolution data on wind fields and the types and amounts of cloud water and precipitation.

The geostationary satellites also contribute to high-resolution vertical profiles of atmospheric water vapor and temperatures. They are assisted by a constellation of low Earth orbiting (LEO) satellites of the "GPS/MET" type (global positioning system and meteorological satellites). Each day, this constellation produces more than 100,000 accurate profiles of atmospheric variables in all weather, extending from the surface of the Earth to an altitude of 60 km. Low power lasers (developed in the first decade of the new century) carried on LEO satellites provide accurate measurements of global wind fields. The combination of geostationary and LEO satellite systems yields global analyses of wind, temperature, and water vapor pressures with accuracies better than 2 meters per second, 0.2 kelvins, and 0.25 millibars, respectively. Satellites observe cloud-to-cloud and cloud-to-ground lightning anywhere on Earth. No thunderstorm goes undetected.

Automated surface observing systems continuously record and transmit meteorological, hydrologic, and chemical data for the air over land surfaces. The basic meteorological and chemical parameters required for numerical weather prediction (NWP) models, including models that can predict "chemical weather," are supplemented by observations of precipitation type, rate, and amount, cloud cover, and visibility. Satellites measure soil moisture and vegetation characteristics four times a day to provide land-surface data for the models.

For less than $200 (in 1998 dollars), any home or office in 2025 can be equipped with an accurate, automatic, atmospheric observing system. These systems transmit data on meteorological conditions (temperature, atmospheric pressure, water vapor pressure, winds, and precipitation) and chemical trace constituents (e.g., ozone, ozone precursors, sulfur dioxide, carbon monoxide) to the National Centers for Environmental Prediction (NCEP). In 2025, one out of every hundred homes and offices has one of these systems. Augmented by similar state and local networks, the national surface network provides meteorological and chemical surface observations of unprecedented quality and density.

Thousands of softball players, golfers, and participants in other outdoor sports in Atlanta are warned of dangerous electrical storms an hour before the first lightning strikes.

Ground-based global positioning system (GPS) receiver stations provide the data to map the three-dimensional water vapor field for the atmosphere within 100 km (horizontal distance) of each station. Ground-based Doppler radar wind profilers at these stations, scanning horizontally and vertically, generate continuous vertical profiles of the three-dimensional wind over the same atmospheric volume.

Over the oceans, drifting and moored buoys, as well as ships of opportunity, carry instruments that measure surface air pressure, temperature, and water vapor pressure. Beneath them, remote-transmitting sensors measure ocean temperature, salinity, and current velocity at several levels, down to 4 km below the ocean surface. The exact location and depth of each instrument are included with these data. Surface wind observations are combined with boundary layer predictions from high-resolution global NWP models to determine surface winds accurately.

During the morning rush hour on December 15, 2025, drivers on Interstate 5 in the Sacramento Valley are warned automatically by their vehicle weather alarm systems (standard equipment on every car since 2010) that dense fog is present three miles up the road. They gradually slow down, averting a massive pileup where the highway disappears inside the fog bank.

Most commercial aircraft are equipped with sensors to measure winds, temperature, humidity, trace chemical species, and aerosols. These data are communicated to users through a global communications network.

"Smart" analysis and visualization software systems combine data from satellites, radars, and other observing systems to provide a composite view of the cloud, precipitation, and water vapor structure from a three-dimensional perspective in five-minute snapshots or movie images.

Uses of Weather Data

Timely, accurate, and complete data on weather, climate, and air quality are available in 2025 at a reasonable cost to anyone at any place and at any time, including people in all countries, through a global information network. The global array of observing systems described above transmits data instantly, without restrictions and free of charge, to international weather centers around the world and to anyone else who chooses to connect to the global network.

Emergency managers in the Midwest agree to move 1,000 snow plows from Illinois, Indiana, and Ohio to northern Mississippi just in time for the arrival of Mississippi's worst snowstorm in 100 years.

At the international centers, the data are used in two distinct but related ways. The first is the production of analyses of the present and recent past structure of the atmosphere and oceans. These analyses include four-dimensional (space and time) gridded digital meteorological and chemical data, as well as graphical depictions of cloud and precipitation systems, tropical and extratropical cyclones, thunderstorms, heavy rainfalls and snowfalls, icing, turbulence, electrical storms, air pollution, surface winds, surface water conditions, and other significant weather and chemical phenomena. Similarly, four-dimensional data fields depict the recent past and future evolution of the atmosphere for user-specified locations anywhere in the world. The information and associated derived images are used by the general public and by commercial, nonprofit, and governmental entities to improve the quality of life, avoid hazardous environmental conditions, and conserve economic, water, and energy resources. These highly accurate weather data are combined with other environmental data, such as hydrologic data, to produce forecast information of direct benefit to specific users. Accurate and quantitative forecasts of soil moisture, lake and river levels, and runoff are made two weeks in advance.

Energy resources are shifted from one region of the country to another in most months of the year, based on the next month's outlook for temperature, humidity, wind, precipitation, and cloud cover.

Major users of weather information go to "weather planetariums," rooms with projection domes for realistic depictions of past and future weather for a particular location, which can be specified for most places on Earth. The projections can show clouds, precipitation, fog, wind, and their effects on nearby landmarks. Policy makers, urban planners, emergency managers, businesses, and other parties with particular interests in the weather use these weather domes for a variety of purposes. In major cities, weather facilities are open to the public 24 hours a day, free of charge. Besides the planetariums, small personal visualization devices, worn by the users, are available at a reasonable cost. These "smart weather goggles" allow the wearer to view past and future weather in three dimensions at any place and time and from any viewing angle merely by facing in the desired direction.

> Every 10 minutes, a nonstop New World Airlines flight from Chicago to Sydney adjusts its heading and altitude automatically, based on the current global weather analysis, to avoid dangerous weather and take advantage of the most favorable winds. Meanwhile, the analysis is updated continuously through assimilation of new data and short-range forecasts.

The second major way that the international data centers of 2025 use global observational data is for high-resolution global NWP models. New observations are assimilated into the models throughout the day. Meteorological dependence on synoptic observation times (e.g., 0000 UTC and 1200 UTC) has become obsolete, and data pour into the NWP centers continuously. More than a billion quantitative pieces of information about global atmospheric structure, from the surface through the stratosphere, arrive every hour. Through the assimilation process, these observations, combined with improved physical parameterizations in the models, provide a nearly perfect and complete representation, at any time of day, of the atmospheric and upper ocean structure on horizontal scales greater than 100 km. These analyses no longer require radiosonde or other balloon observations.

> On May 10, 2025, the tenth anniversary of the last weather-related aircraft fatality in the United States passes without notice.

Global models with 1 km horizontal and 100 m vertical resolution are run for 30 days into the future in 10 centers around the world, and the results are used in a variety of deterministic and probabilistic forecast applications. For example, every six hours the runs are collected and grouped to form an ensemble of 200 forecasts.

> Hundreds of thousands of commuters in San Francisco leave their umbrellas and rain gear at home because the approaching rain is guaranteed not to arrive before 7 p.m. that evening.

The observational errors so common in NWP forecasts during the pioneer decades of the twentieth century have been virtually eliminated. Model predictions of the next three days' weather are nearly perfect; they are constrained only by the limits of predictability in chaotic systems. Predictions in the five to seven day time frame are about as accurate as two to three day forecasts were in 2000.

> On May 15, 2025, the Centers for Disease Control and Prevention issues an alert, based on the past month's temperature, precipitation, and wind speed and on present and forecast hydrologic conditions, for a major hatching of mosquitoes along the Gulf Coast during the next week. Scattered, recent reports of St. Louis encephalitis in the region indicate an increased probability that this disease could spread rapidly.

Probabilistic Forecasts

The ensemble of forecasts run by the international weather centers yields estimates of the variances, or uncertainties, in the NWP forecasts, as well as expected values for weather conditions. Thus, users have an indication of the *reliability* of a given forecast. For example, seven-day predictions of surface pressure, temperature, winds, and precipitation include estimates of the uncertainty in the predicted conditions. Users can view the most likely scenario, with a measure of how likely it is, and a range of extreme scenarios, each with its own measure of likelihood. Maps of forecast variables are color-coded to indicate the probability of the prediction.

> On Monday morning, January 21, 2025, an ensemble of more than a thousand forecasts from NWP model runs during the past two days shows a greater than 70 percent chance of a paralyzing East Coast blizzard during the coming weekend. Airlines announce schedule changes, including some cancellations and alternative flights, in response to the forecasts and make plans to divert airplanes away from the East Coast by Friday afternoon.

The probabilistic forecasts are also used to assess the likelihood that certain high-impact events will occur during a certain time period. These events include both severe weather and ordinarily benign but sometimes high-impact events, such as freezing or thawing conditions, sunshine, cloud cover, air stagnation, or any amount of precipitation. The planners of activities that would be extremely sensitive to one of these events—such as crop spraying, sensitive phases of major construction projects, and planting crops—use these forecasts to eliminate the risk from an unlikely but potentially catastrophic weather event.

Chemical Weather Forecasts

Because of the importance of air quality to human health and well-being, operational air-quality modeling is used in 2025 to provide detailed forecasts of the trace chemicals in the atmosphere that affect humans directly or indirectly. Rather than being derived from separate atmospheric chemistry or air quality models, these forecasts can be derived from special versions of the operational global NWP models, which include representations of detailed chemical processes. The daily ensemble forecasting conducted jointly by the international centers provides quantitative probabilistic forecasts for atmospheric chemical constituents, as well as meteorological conditions.

> Farmers in California and Oregon spend a billion dollars spraying a highly effective, environmentally benign but extremely water-sensitive chemical over a two-day period in April 2025, based on the forecast of "no chance" (less than a 0.1 percent probability) of any precipitation during that period.

Weather forecasts include information on ozone and other oxidants; ozone precursors, including volatile organic compounds; carbon monoxide; nitrogen oxides; sulfur dioxide and sulfates; aerosols; and other important chemical species. Predictions are also made for other chemical species that affect human or natural ecosystems, such as nitrate and sulfate deposition (acid rain), local visibility, and ultraviolet indices. The models calculate photolytic activity in relation to meteorological parameters that affect photochemical reactions, such as cloudiness and solar elevation angle.

> Based on the latest chemical weather forecasts, power companies in the Midwest shift to burning high-sulfur coal for three days.

The global chemical weather models predict large-scale and regional-scale trace chemical constituents in the atmosphere, including stratospheric and lower-tropospheric ozone, wet and dry acid deposition, aerosol distributions, and related chemical processes. On much finer scales, models covering a few hundred square kilometers at a resolution of 1 to 10 m capture the effects of point sources of pollutants and produce short-term forecasts of air quality for cities and urban areas to warn the public of dangerous levels of air pollution.

Reliable air quality predictions also depend on the atmospheric inventories for all significant natural and anthropogenic chemical emissions of interest. Inventories of chemical emissions are obtained from a national network of real-time emission monitors. Observations of atmospheric chemicals for initializing chemical weather models are obtained from sensors on board satellites (e.g., to measure stratospheric ozone) and commercial aircraft and from the national network of in-situ surface measurement stations. These data are assimilated into the global models in the same way as traditional meteorological observations.

Energy system managers and government officials use chemical weather forecasts to avoid dangerously high levels of pollutants or take advantage of the atmosphere's enormous dispersal and cleansing powers under appropriate conditions. The global chemical weather predictions include forecasts of both the amount and chemical quality of precipitation. Concentrations of trace nitrogen species that contribute to the decline of sensitive ecosystems are also monitored.

Climate Forecasts

> Fifty-year outlooks of changing climate and environmental conditions, such as water supplies, lake and sea levels, permafrost, monthly temperatures and precipitation, and frequency of extreme weather events, are factored into the design and construction of all major infrastructure components, including bridges, highways, major buildings, airports, and harbor facilities.

Once a week, "climate" versions of the global NWP models are run out for two years, again in ensemble mode. These model runs use somewhat lower horizontal and vertical resolution, but they incorporate all available atmospheric and ocean data for the past month into a quality-checked "super" data set. The resulting climate forecasts contain components representing interactions of atmosphere, ocean, ice, and land surfaces. The atmospheric component includes interactive parameters for chemical weather. The forecasts, which are expressed in probabilistic form, include not only estimates of variations in temperature and precipitation from seasonal norms but also frequency and intensity of extratropical and tropical cyclones, thunderstorms, and other weather and climate phenomena, by region and by month, for the next two years.

> In May 2025, farmers in Iowa plant relatively low-yield but highly drought-resistant corn, based on the three-month precipitation outlook from the National Climate Center. In the past 10 years, these outlooks have been correct 80 percent of the time.

Nowcasts and Warnings

The global NWP models in 2025 predict local atmospheric conditions conducive to the formation of severe storms (including thunderstorms and tornadoes, tropical cyclones, and winter storms). People affected by these storms typically receive at least two to three days' notice via outlooks, forecasts, and warnings that have been continually refined and updated as the event approaches.

> On April 3, 2025, a mother in Arkansas is awakened at 3 a.m. by her home ICE (information, communication, and entertainment) system alarm, which provides three-dimensional, virtual wraparound viewing. A "weather warning" window on the center screen displays a written message that a tornado is likely within a half-mile of her home in the next hour. Another window shows a map of the local area. Her house is at the center of the map, and familiar landmarks within 10 miles form the map background. Patterns on the map represent precipitation and the speed and direction of winds. The display shows a tornado on the ground four miles southwest of her home. Its past track, current direction, and forecast motion are clearly depicted in striking colors. An audio message summarizes the situation and urges her and her family to take immediate cover, specifying the best location in her home for shelter.

As the probability of a severe weather event during the next 12 hours reaches an action level, specialized ultra-high resolution models begin to run in real time. These models, which have horizontal and vertical resolutions of 10 m, typically cover regions of about 1,000 km^2 (roughly the size of a major urban area). They contain advanced physical parameterizations for cloud and precipitation water types (e.g., liquid water, supercooled water, snow, graupel, or hail) and are initialized with radar and satellite data. Although they are similar in concept to the primitive cloud and storm models of the 1990s, they include more complete and accurate physics, cover much larger areas, and are routinely updated through the assimilation of four-dimensional data. Because of the detailed, microscale data (including clear-air data) on the atmosphere available in 2025, these ultra-high-resolution models can predict the onset and severity of convective storms very accurately.

NWP models produce explicit forecasts of storm structures as well as probabilistic forecasts of precipitation types and amounts, wind speed and directions (including gusts), tornadoes, and electrical activity. These predictions are processed and communicated to users in a variety of ways, including text, audio, or visual products. They also provide input to hydrologic models of individual streams, rivers, lakes, and basins for a variety of water management, environmental monitoring, and emergency warning purposes.

> On September 3, 2025, the coastal zone from Miami to Fort Lauderdale is efficiently evacuated 36 hours before a Category 5 hurricane strikes Miami Beach. The hurricane causes extensive property damage but no loss of life.

Forecasts of Space Weather and Climate

By 2025, predicting space weather has matured into a cost-effective warning service for the electric power industry and an important design driver for power grids and communications and navigation systems. The Energy Conservation Center, which is operated by a consortium of power companies, was established at the beginning of the twenty-first century during the sunspot maximum that occurred about the same time that the energy industry was deregulated. The center's principal mission is to adjust the generation sources and distribution of electric power in the Northern Hemisphere grids to minimize fuel costs, conserve energy, and meet pollution constraints.

> February 21, 2025, is the twenty-second anniversary (two sunspot cycles) of the last major power blackout, which paralyzed the United States east of the Mississippi River from Virginia and Kentucky north. Cities were without power for two weeks or more, rural areas for nearly a month. The economic losses were estimated in the hundreds of billions of dollars. A quarter of the country was declared a disaster area, the largest ever. Despite massive relief efforts, thousands died. Congress pressed for the development of space weather services to prevent a repetition. By comparison, the Hydro-Quebec blackout in 1989 (3 sunspot cycles ago) had been a costly nuisance accepted by the public in good humor, with full recovery of the power system in two weeks.

When the Energy Conservation Center was first established, it also warned operators of wireless systems of impending solar events that could black out communications and upset navigation systems. These problems were solved by adding components to the systems that are not perturbed by ionospheric irregularities.

Space weather forecasts in 2025 are based on satellite and ground-based remotely sensed observations that are assimilated into models. Optical observations of the solar disk and corona, made with Sun-tracking satellite telescopes, measure the source of the solar wind and its variations (sunspot number and coronal mass ejections). For large gusts from the Sun's surface, these observations provide warnings, several days in advance, of possible consequences on Earth. Satellites in a gravitationally stable position between the Sun and the Earth measure the particle densities and waves in the solar wind as it passes them on the way to the Earth. Reports from these satellites provide an hour of warning time before a major solar wind fluctuation causes geomagnetic storms in the Earth's ionosphere.

The Energy Conservation Center announces in July 2025 that its quality assurance program has eliminated small surges in the electric power delivered to customers. These surges were causing up to $25 billion per year in damage to the sensitive computer and electronic equipment that has proliferated during the information age.

Gusts of solar wind produce beautiful auroras but also generate strong electric currents that previously devastated power grids and land communication systems, as well as radio communications and navigation (GPS) signals that travel through the ionosphere. Powerful diagnostic radars, together with radio occultation soundings from LEO satellites of electron density in the ionosphere, follow the propagation of electric currents around the globe.

Cost of Weather and Climate Services to Taxpayers

The total cost to taxpayers for the governmental part of the national weather information network in 2025 is a smaller fraction of the gross domestic product than it has been at any time since the major "modernization" of the NWS in the 1980s and 1990s (Chapman, 1992). Despite the near doubling of gross domestic product (in constant dollars), the cost per person in 2025 is no more than it was in 1998.

Part II

How Will We Get There?

1

Guideposts for the Road Ahead

In the twentieth century, a brief interval in human history, science and technology have made possible the automobile, air travel, space exploration, radio, television, nuclear energy, the transistor, integrated circuits, computers, three-dimensional medical imagers, GPS, lasers, fiber-optic communications, noninvasive surgery, the Internet, and satellite communications.

Modern meteorology began early in the twentieth century, when Cleveland Abbe in the United States and Wilhelm Bjerknes in Norway suggested independently that weather forecasting could and should become a mathematical science. Their vision, however, only began to be realized with the development of practical observing systems. The invention of the radiosonde (a balloon-borne instrument that measures air temperature, atmospheric pressure, and humidity) in the 1920s provided one of the first observing systems that moved meteorology toward an exact science. Meteorology has also benefited enormously from the invention of radar and has taken advantage of satellites in space for continuous observations of the Earth and its atmosphere. With advances in computing, more accurate and reliable NWP (numerical weather prediction) models, with finer and finer resolution, came to be used operationally. From the Second World War through the 1980s, meteorological and hydrologic science and technology made unprecedented progress.

Building upon this solid scientific and technological foundation, the NWS began a major modernization and restructuring in 1989. The modernization was an ambitious and bold program to replace aging equipment, implement new science and technology, and restructure the organization of NWS field offices and national centers. Interactions with universities were strengthened by locating some field offices on university campuses and by the Cooperative Program for Operational Meteorology, Education and Training (COMET) (Spangler et al., 1994). The intellectual resources of the NWS were also strengthened through a change in the mix of staff, so that by 1998 about two-thirds of the staff were professional meteorologists. The introduction of two new positions in field offices, the science operations officer and the development and operations hydrologist, has brought new pride and vision to NWS staff while expanding the scope of staff activities.

The formal phases of this modernization and restructuring are about to be completed. By 2000, all new equipment will be installed, all field offices staffed, and the forecasting and warning operations modernized throughout the NWS. The National Weather Service Modernization Committee of the National Research Council, which has observed, reviewed, commented on, and provided advice regarding the modernization and restructuring for the past eight years, will complete its work in 1999. The committee has examined virtually all facets of the NWS, including satellites, radars and radar coverage, surface observing systems, services, modeling advances, staff views and concerns, and interactive processing. It is appropriate, therefore, that the Road Map Panel of the committee, which comprises many current and former committee members, provide a vision for the NWS in 2025.

The panel has made a bold attempt to discern directions that the NWS should pursue over the next quarter century. Shorter-range objectives are being addressed by several other mechanisms, including the NWS strategic planning process, the study of technology infusion, and related NWS advisory committees. The primary tasks to pursue in the next few years are to consolidate the advances in technology provided by the modernization and restructuring, exploit the parallel scientific progress, and bring the technology and science together in the operational domain.

However, because technological change is an ongoing process that appears likely to accelerate, the NWS should also look beyond the next few years. In this report, the panel presents probable trends, opportunities, and scenarios. Some aspects of the panel's vision may be overly ambitious or optimistic. Some aspects may not be attained for technical, budgetary, or other reasons (NRC, 1998e). Nevertheless, the vision as a whole provides long-term goals worth pursuing

BOX 1-1
Mission of the National Weather Service

The National Weather Service provides weather, hydrologic, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy. NWS data and products form a national information database and infrastructure which can be used by other governmental agencies, the private sector, the public, and the global community.

Source: Jones, 1998

and delineates boundaries that NWS and NOAA decision-makers can apply to their strategic planning for the future.

ASSUMPTIONS

Within this general philosophical framework, the panel proceeded on the basis of seven assumptions, which are listed below with brief explanations.

1. **The broad NWS mission will be largely unchanged (see Box 1-1).** Access to weather and climate[1] information and warnings will continue to be vital to all facets of the U.S. economy, social structure, and civic services. It is reasonable that the federal government continue to provide a service that benefits so many of its citizens. Moreover, NWS observations, forecasts, and warnings provide the equivalent of a safety net for the lives and property of U.S. citizens. It is, therefore, necessary that these services be of uniformly high quality.
2. **The NWS and its parent organization NOAA (National Oceanic and Atmospheric Administration) will retain responsibility for an observational and data collection infrastructure that includes satellite, radar, surface, and upper air observing systems and the government applications from this infrastructure.** Whenever possible, the data will be made available free of charge or at minimum cost to the broadest possible cross section of society.
3. **The NWS will continue to be responsible for maintaining, developing, and operating a suite of analytical and predictive models and the supercomputers required to run them.**
4. **The boundaries between climate prediction and weather prediction will blur and eventually disappear.** Certain climate forecasting responsibilities will become increasingly important functions of the NWS. For this reason, many of the NWS's current obligations ought to be viewed in the context of their contributions to the long-range climate record for the nation and the world. To preserve these data for future generations, NOAA will continue to maintain appropriate climate record archives.
5. **The NWS, other federal agencies, state and local entities, and private-sector companies will increasingly form strong, interactive partnerships.** The types of partnerships and the functions of each partner will evolve as science, technology, and the industry evolve.
6. **The NWS and NOAA will provide observations, products, and services of the highest quality.** A dominant theme throughout the NWS modernization has been to avoid degradation of services—a minimal goal for an information age organization. The director of the NWS and the administrator of NOAA have stated that the NWS is committed to an evolutionary future, in which it will not merely maintain quality but will significantly improve its services (Baker, 1997; Kelly, 1998).
7. **The science and technology communities will make enormous advances in the next 25 years.** The global observing system will, therefore, no longer be limited to its current observations but will provide a rapid flow, and efficient storage, of highly diverse, asynchronous, high-resolution data. These data will be acquired from a multiplicity of sensors and platforms—some public, some private, and some operated jointly—that will allow unprecedented resolution in data assimilation and numerical prediction systems. Increases of at least several orders of magnitude in computing speed will provide for assimilation and modeling at high resolution with respect to both time and space.

The analyses, assessments, and suggestions offered throughout this report are intended to help the NWS achieve its near-term goals and continue along the road to the future. The

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[1] In this report, the terms "weather" and "climate" include the relevant aspects of related disciplines, especially hydrology and oceanography.

major theme can be stated succinctly: By applying the enabling science and technology (Chapter 2), merging and expanding weather information services into environmental information services (Chapter 3), and resolving organizational issues (Chapter 4), the NWS can realize the potential benefits to the nation reflected in the panel's vision for 2025.

2

Science and Technology

The products and services provided by the NWS are based on scientific understanding of atmospheric, hydrologic, and related phenomena. The NWS employs a diverse array of technologies to observe these phenomena, assimilate the data obtained from the observations into analytical and predictive tools, and apply the results in describing the present state of the atmosphere and predicting future weather. This chapter describes anticipated advances in science and technology between now and 2025. These advances will be the basis for improving forecasts of weather, climate, and related environmental conditions. For the NWS to increase the utility of environmental information, it will need more accurate and more precise predictions, based on higher resolution computer models that incorporate better observations and more accurate representations of the underlying physical processes.

OBSERVATIONAL SCIENCE AND TECHNOLOGY

Measurement Capabilities and Requirements

Meteorology depends on observations of many variables that jointly specify the state of the atmosphere, including measurements of winds, temperatures, atmospheric pressure, and humidity for NWP models. Together with observations of cloud types and amounts and precipitation types and intensities, they describe present weather. On longer time scales, climate is defined by these same quantities along with precipitation, land surface temperature, albedo, vegetation, soil moisture, ocean surface temperatures, and atmospheric constituents, such as trace chemical species and aerosols.

This section describes many important recent developments, and some that the panel anticipates will occur by 2025, in the observing instruments and systems that enable current hydrometeorological situations to be specified and future events predicted on all spatial and temporal scales. Representative examples are given of science and technology that could significantly affect NWS operations.

For example, current observing protocols rely heavily on synoptic (synchronous and globally distributed) rawinsonde observations to provide three-dimensional, synoptic-scale depictions of basic atmospheric quantities. It is possible that, before 2025, the rawinsonde observations will be replaced by measurements from ground-based and satellite-borne remote sensors, together with in-situ measurements from sensors on board cooperating commercial aircraft and autonomously piloted vehicles. In geographically remote regions, particularly over the oceans, sensors on aircraft may be augmented by dropsondes. Constellations of small satellites may complement or replace single large polar orbiters, and interesting concepts have been proposed for both larger and smaller geostationary platforms. Meanwhile, continuing strides in information technology will revolutionize communications, data processing, and computer modeling, thereby facilitating fundamental improvements throughout the observation, prediction, and warning system.

Although this section focuses on the atmosphere, atmospheric interactions with the oceans and the land are essential for accurate weather and climate predictions. The evolution of atmospheric phenomena depends on the state of the entire, coupled system of atmosphere, oceans, ice, and land, including the fundamental quantities needed to define that state at a given time. By contrast, some of the events most critical to human affairs in the near term—severe local storms and their consequences, such as tornadoes and low-level wind shear—are extremely localized in space and time. They require extremely detailed observations for analysis and prediction in near real time. To continue improving predictions of these storms, hazard detection and warning systems will require remote and in-situ sensing instruments.

BOX 2-1
Forecast Accuracy and Skill

Many elements of a forecast contribute to the overall perception of its accuracy. Meteorologists refer to an objectively measurable element (or sometimes a combination of elements) of a forecast as a *skill*. Thus, forecasts can be compared quantitatively on the basis of their skill scores or measures of skill. A set of *skill scores* may be used to approximate the overall or general accuracy of a forecast.

Throughout this report, the term "skill" refers to a defined, quantifiable element of a forecast that contributes to its accuracy. The term "accuracy" refers to the general or unspecified predictive value of a forecast or forecasting method.

Since World War II, a remarkable transformation has occurred in meteorological, hydrologic, and oceanographic observations. Some of the most dramatic changes have been the creation and rapid improvement of meteorological and oceanographic satellites, as well as the development of a wide variety of observing methods based on radars and lidars (Serafin and Wilson, in press). These systems enable one to view (in the sense of collecting the definitive data about) the entire structure of all kinds of storms, from large extratropical cyclones to tornadoes. The internal properties and motions of these storms can be measured, as well as the characteristics of the environment with which they interact. In parallel with these successes, major advances have occurred in the observing tools for more conventional meteorological quantities, ranging from sensors for measuring temperature, atmospheric pressure, and humidity to lightning detectors.

Some advances have been made in the sensors themselves; others have been in the platforms or the communications systems. For example, the rawinsonde has been greatly improved, and winds can now be measured with the use of sondes equipped with GPS receivers, enabling more accurate tracking of the sonde. High-flying aircraft have dropped GPS dropsondes into hurricanes to provide soundings for incorporation into NWP models. These dropsonde soundings noticeably increased the skill scores (see Box 2-1) for forecasts of hurricane motion and landfall, with concomitant reductions in deaths and in costs of hurricane evacuation and protection of property (Burpee et al., 1996; Aberson and Franklin, in press).

Many advances in measurement technology have come from fields outside the atmospheric and hydrologic sciences. The miniaturization of electronics, the digitization of communication systems, advances in computational capabilities, and the mass production of high resolution color monitors to display graphics and text have all improved observing systems and added to their value in the forecast process. The transfer of technology from other fields will continue, and a keen awareness of developments in supporting technologies can lead to early benefits for NWS operations.

Doppler radar observations have provided great insight into the structure and motion of hurricanes (Marks et al., 1992; Gamache et al., 1993). Ground-based Doppler radars, often with automated algorithms (Serafin et al., in press; Serafin and Wilson, in press), routinely provide measurements for warnings of severe weather, including tornadoes and hazardous wind shears near airports. Despite these advances, however, a perfect tornado detection and warning system has not yet been developed for two reasons. First, not enough is known about the processes by which tornadoes form and dissipate or about their localized effects. Second, the observing and communication systems for alerting the public are still inadequate.

The tornado detection and warning issue highlights the problem of detecting or forecasting small-scale phenomena of all kinds: detection and forecasting depend on observations at scales comparable to those of the phenomena. Partly as a result of the NWS modernization, but also because of regular improvements in observing systems, the temporal and spatial coverage and resolution of observations has continued to improve. For example, in just one decade, from 1985 to 1995, the number of measurements made in one state (Kansas) increased by a factor of 30 (MacDonald, 1995). This change illustrates a general trend throughout the United States and in much of the developed world toward dramatic increases in the spatial and temporal density of observations.

The combination of improved observational tools, computers, and numerical models has led to substantial improvements in the accuracy of forecasts, extended the lead times of forecasts, and enabled more accurate localizations of storm forecasts and warnings (Polger et al., 1994). Recent improvements in global analyses have also produced higher-quality data describing the global climate.

Soil moisture is an important factor in the surface fluxes of water and energy between land and air at a range of spatial and temporal scales. Subsurface moisture, which fluctuates more gradually than the precipitation rate, persists on seasonal to interannual time scales. Because soil moisture can be cumulative (in modeling terms, an integrated state), errors in NWP can lead to incorrect partitioning of surface water between land and atmosphere and of energy fluxes between sensible and latent heat. Accurate observations of soil moisture at the spatial resolutions needed for NWP models could therefore substantially improve the overall accuracy of the models (Houser et al., in press).

An accurate observational base for soil moisture is also essential for realizing the benefits of distributed hydrologic modeling (see Advanced Forecasting Techniques later in this chapter). For example, because the time constants for significant rate-controlled processes are longer than for precipitation rates, the soil water and groundwater components of the terrestrial hydrosphere create considerable lag times in the overall response time of a regional climatic or hydrologic system to abnormal weather events (such as marked fluctuations in precipitation or solar radiation). A distributed hydrologic model that includes an improved characterization of these components and accurate initializing observations could assess the longer-term response of a regional system to anomalous events.

The future network of observations will rely much less on synchronous global rawinsonde measurements. Modelers are developing methods of assimilating asynchronous and opportunistic measurements (see Data Assimilation later in this chapter). It will soon be possible to accommodate data from rawinsondes or dropsondes released at times and places selected by field office staff as being most useful for local forecasting.

Moreover, many observations will be available through partnerships between government and the private sector, such as measurements from commercial aircraft obtained through the Aircraft Communications Addressing and Reporting System (ACARS).[1] The federal government, states, county, and local governments, and segments of the private sector will all become rich new sources of data. For example, a state-operated network of surface meteorological instruments already in place in Oklahoma provides the basis for a broad spectrum of applications, including reports on road conditions and air pollution, as well as severe storm warnings (Brock et al., 1995).

Improved observations—more closely spaced in distance or time or made with more accurate instruments—will generally yield better four-dimensional analyses and lead to improved forecasts and warnings. Degraded observations may be less expensive, but they also degrade the quality of products and services. The trade-offs between changes in the value of products and services and changes in the costs of providing data must be frequently reevaluated because the benefits and costs are likely to change with time. Although the value of data and information is difficult to quantify, mechanisms such as the North American Atmospheric Observing System Program[2] could be used to assess trade-offs on a regular basis (McPherson, 1996; Shumbera, 1997).

Surface Observations

The core of the nation's current surface observing network consists of approximately 1,000 stations equipped with an Automated Surface Observing System (ASOS). These stations are supplemented by several thousand stations in the Cooperative Observer Network, which could be upgraded to provide automated measuring and reporting. Together with the various state-operated (e.g., Brock et al., 1995) and other special-function networks, these sites would form a network of about 10,000 stations. The ASOS and Cooperative Observer Network stations already provide the observational basis for the national climate database.

Incremental improvements in reliability or accuracy of surface observations may occur, as well as reductions in cost. Significant advances are likely in the capability of microprocessors to process measurements of the meteorological, hydrological, and other physical quantities in varied and flexible formats. Microprocessors can calculate derived statistical measures, such as the maximum, minimum, average, and standard deviation of selected phenomena over a standard time interval, as well as rates of change and other derived indicators. Microprocessors can also facilitate the transmission of observational data for incorporation into the NWS database. Improvements in automated sensing of present weather (e.g., clouds and precipitation) are also likely.

The Cooperative Observer Network provides the basic data for defining the climate of the United States and for monitoring climate change. Reports from this network also provide important information for mesoscale flood forecasting (NRC, 1998a). Greatly expanding the size of the Cooperative Observer Network and the timeliness of its data would improve mesoscale weather forecasts. Even with current technology at 1998 prices, homes or offices could be equipped with inexpensive, accurate, automated atmospheric observing systems that could transmit data to the NWS and national climate database on standard meteorological quantities (temperature, atmospheric pressure, water vapor pressure, winds, and precipitation) and even chemical constituents (e.g., ozone, ozone precursors, sulfur dioxide, and carbon monoxide). If a hundred thousand U.S. homes and offices had these systems with adequate siting, calibration, and maintenance, they would create a very dense nationwide network of meteorological and chemical surface observations, with average spacing of about 10 km.

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[1] ACARS was designed in the late 1960s and implemented in 1977–1978 by the commercial carriers through Aeronautical Radio, Inc. (ARINC). ACARS includes a VHF digital communication system with ground receivers, ground cluster controllers, and communication links back to ARINC in Annapolis, Maryland.

[2] This is a cooperative program supported by governments and universities in Canada, Mexico, and the United States to examine the scientific and economic value of upper-air observing systems over North America and adjacent waters.

The panel anticipates major developments in special-purpose, surface observing networks operated by public or private-sector entities. The Oklahoma Mesonet, which has already been mentioned, is one example. Many state highway departments operate observing networks to facilitate traffic flow and road-clearing operations. Airports, urban centers, and power generation facilities also operate special networks. As the value of specific weather and environmental data increases, the number and variety of these networks will also increase (see Chapter 3 for a discussion of the expanding role of non-NWS observing systems).

For surface observations on the oceans, drifting and moored buoys and ships of opportunity could carry instruments to observe the standard quantities. Underwater instrument systems on these platforms could use thermistor strings and radio positioning techniques to measure ocean temperature, salinity, and current velocity at several levels, down to several kilometers below the surface. To determine winds with great accuracy and high resolution for any location on the ocean, surface wind observations from these stations (or surface wind data from satellite scatterometer sensors) could be combined with high-resolution predictions of boundary layers from improved global weather prediction models.

In the future, other "platforms of opportunity" may prove similarly useful for increasing the density of surface (and in some cases upper-air or ocean subsurface) observations. Platforms might be ships, trains, buses, fleets of taxicabs or trucks, emergency response vehicles, and perhaps even personal vehicles.

Atmospheric Observations above the Surface

Data on the four-dimensional structure of atmospheric pressure, temperature, humidity, and winds from the surface to the lower stratosphere are the foundation of NWP models. Currently, the rawinsonde network is the backbone of the system for atmospheric observations above the surface (upper-air observations), although satellite-borne and surface-based remote sensors are becoming increasingly important. The rawinsonde network provides limited spatial and temporal samples, and rising costs could reduce the frequency of rawinsonde observations. In fact, surface-based remote sensors can provide better temporal continuity, and satellite-borne sensors can provide essentially contiguous spatial coverage.

The panel anticipates major improvements in surface-based remote sensors for upper-air observations. Current technologies include Doppler radars, such as the WSR-88D (commonly called NEXRAD) and wind profilers (see the section on Radar Systems below for details), microwave radiometers, acoustic sounders, and various lidar (light-wavelength radar) systems. These technologies provide profiles or path-integrated values of humidity, temperature, and wind, as well as quantitative measures of other weather variables, such as cloud liquid water. New concepts for inferring path-integrated moisture using existing Doppler radars may prove to be operationally feasible (e.g., Fabry et al., 1997).

Ground-based GPS receivers that view several GPS satellites at once can generate temporally continuous profiles of integrated water vapor content along each slant path from the ground station to a GPS satellite in view (Ware et al., 1997). Tomographic inversion techniques applied to these profiles can be used to construct accurate and complete three-dimensional water vapor fields for the atmosphere within 100 km (horizontal distance) of the station. Ground-based horizontally and vertically scanning Doppler radar wind profilers at these stations could provide continuous vertical profiles of the three-dimensional wind for the same atmospheric volume.

Airborne Systems

Observing systems carried on aircraft can provide both in-situ (immediate vicinity of the sensor) measurements and remote sensing. Thus they can be used for both upper-air (in situ) and surface (remote sensing) applications. In addition, dropsondes can be released from aircraft at precise locations.

In-situ observations of wind and temperature, which are made routinely as part of an aircraft's flight information, are now being transmitted in real time from many commercial aircraft via ACARS. The data are sent from ARINC to the various air carrier dispatch centers for aviation use and to NOAA's Forecast Systems Laboratory and NCEP for use by the meteorological community.

More than a dozen major air carriers and delivery service companies operating out of the United States and Canada participate in the ACARS program. Approximately 10,000 reports of winds and temperatures are made each day, and this number is expected to increase. Although more than 90 percent of the data from these reports are at cruise levels (near 9 km), Benjamin et al. (1991) have shown that using these upper-air observations in NWP models has improved wind and temperature predictions. ACARS coverage over North America is almost complete, and the system is expanding. Other countries are developing or have developed similar communication systems.

If water-vapor observations could be added to the ACARS data stream, an exact pressure-height relationship could be computed from observations taken during ascents and descents. This approach would provide data equivalent to radiosonde observations. Better definition of water vapor fields would also lead to better forecasts of precipitation. A multiyear demonstration program is now under way to confirm that water vapor can be measured from commercial aircraft conveniently and accurately. If the demonstration program is successful, next-generation water vapor sensor systems are likely to be installed on a substantial portion of the domestic air carrier fleet.

The future ACARS program may include greater numbers of commercial aircraft, global coverage, an ACARS-type package for general aviation, and sensors to measure atmospheric turbulence and trace chemicals. Dropsondes may also be released from commercial aircraft in selected areas to provide vertical profiles of key weather elements. Downward-looking remote sensors that can measure soil moisture or snow pack water content from commercial aircraft may also become practical. They will become more important as the capabilities evolve for modeling coupled atmosphere-surface processes.

Radar Systems

Ground-based and airborne Doppler radars provide a wide range of observations. These systems include the Next Generation Weather Radar (NEXRAD) systems and wind profilers, which have demonstrated their ability to detect localized phenomena, such as downbursts near airports and mesoscale cyclonic rotations, which are precursors to the development of tornadoes. The more routine observations of the vertical profile of horizontal wind and its changes with time have also proven to be of great value for forecasting, particularly for aviation forecasts and NWP models.

Measurements of precipitation by properly calibrated radar have many hydrometeorological purposes. Although many of the existing algorithms for measuring rainfall by radar can be improved, present methods already provide values for areal accumulations that could otherwise be provided only by expensive, dense networks of gauges (networks this dense are available at only a few experimental sites). Promising methods have been developed for a wide spectrum of Doppler radar applications, ranging from the nowcasting[3] of flash floods to mainstem hydrologic predictions and even calculations of monthly, wide-area, accumulated precipitation for monitoring climate.

One of the candidate modifications proposed for NEXRAD radar is polarimetry (Bringi and Hendry, 1990), a technique that uses the differential reflectivity between two signals polarized at right angles to measure the mass-weighted mean size of drops of precipitation. Other polarimetric variables can also be measured to infer other characteristics of the precipitation. Polarization techniques can provide more accurate precipitation rates than can be measured by a singly polarized radar beam. Differential echoes and related parameters can be used to distinguish between rain, hail, and snow, as well as to distinguish precipitation from other reflectors, such as airplanes, birds, and insects.

A very different technological approach to improving radar measurements of rainfall is based on novel quasi-statistical methods. Some of these techniques use the physical properties of radar echoes to classify precipitation by type and then, based on prior observations of that precipitation type, select an appropriate rain algorithm from a computer library of algorithms (Rosenfeld et al., 1995). Technological and statistical approaches may even be combined to yield more accurate estimates of precipitation. Improvements in measuring snowfall accumulations by conventional Doppler radar are also being studied (Super and Holroyd, 1997; Xiao et al., 1998).

Present-day NEXRADs are the basic tools for detecting severe thunderstorms and mesoscale vortices, the precursors of tornadoes. Some tornadoes are so small and short-lived that they are missed by the NEXRAD detection algorithm. But the majority of severe tornadic storms are detected, and warnings are issued with sufficient lead time to save lives and reduce injuries (Polger et al., 1994; Bieringer and Ray, 1995). In the future, it will be possible to equip emergency response vehicles and aircraft with simple Doppler radars. These mobile radars will be able to get closer to suspicious storms than a fixed-site radar can. The higher resolution of the velocity structure would make these observations more reliable and increase confidence in the tornado warning system. This concept has already been demonstrated with advanced experimental airborne Doppler radar (Hildebrand et al., 1995) and with truck-borne "Doppler on wheels" (Wurman et al., 1997).

NEXRAD is but one of a number of current weather and aviation Doppler radars. Others include wind profilers that are used to measure winds up to the tropopause, the Terminal Doppler Weather Radar for detecting microbursts and low-level wind shears in airport terminal areas, and the airport surveillance radar (ASR-9) for both air traffic control and limited weather surveillance. Various research radars are being used for Doppler observations, polarimetric measurements of precipitation, and cloud detection—the latter typically at very high frequencies of 35 to 94 GHz. Many television stations also operate their own Doppler weather radars.

An imaginative recent development is a multistatic Doppler radar (Wurman et al., 1995), which uses a basic radar, such as NEXRAD in normal operation, plus associated low-cost, wide-beamwidth passive receivers at nearby locations. As the basic radar scans, each receiver receives the echoes from a different perspective and measures a different component of the wind. The combination of two or more measurements gives the full wind vector, which is an important aspect of localized convective storms, which have highly variable winds. A single Doppler radar receiver can measure only the radial component of the wind velocity.

Doppler radars have not yet been exploited to their full potential. Methods are being investigated to determine the full wind vector with a single radar (Wilson and Megenhardt, 1997). The resulting wind fields could be used to reconstruct the temperature and pressure fields that drive the motion of the air. These derived fields could then be assimilated into storm-scale numerical models to predict the evolution of storms (Sun and Crook, 1998). These and other advances in

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[3] Nowcasting is the process of making rapid, near-term predictions (roughly six hours or less) from recent or current observations.

the numerical modeling of convective storms (e.g., Kopp and Orville, 1994) promise real-time predictions of storm behavior on scales as small as 100 m and time intervals of a few minutes. The anticipated tremendous increases in speed and computational capacity of computers will make it possible to model the microphysics (particle types, phases, and size distributions) and dynamics of storms with unprecedented detail and accuracy in real time.

An important question is whether a multipurpose radar can be designed to provide most, if not all, of these diverse weather observations, as well as non-weather-related functions (see Box 2-2). Putting aside issues of particular site locations and operational control, a multipurpose radar of this kind is certainly feasible. For example, a system might radiate at three wavelengths (e.g., 3, 10, and 70 cm) at high power from a five-sided phased array (facing in the four ordinal directions and vertically), obviating the need for mechanical scanning. High transmitted power, a high-gain antenna, and sensitive receivers would ensure the detection of clouds and clear air echoes. Pulse compression would provide a sufficient number of independent signal samples to obtain rapid, accurate measurements of reflectivity and velocity of the entire hemisphere overhead in less than a minute. A combination of polarimetry and wavelength dependence could distinguish rain, snow, and hail from one another and from aircraft, birds, and insects. Lightning detection would also be possible with the rapid scan. This system could be used simultaneously for aircraft tracking and control and taking observations of weather-related phenomena. Although this radar is still visionary, studies of less ambitious radars are already in progress (OFCM, 1997). However, considerable research, development, and testing will be needed in order for advanced multipurpose radars to become operational.

Satellite-Based Observing Systems

In 1960, well before the dramatic views of storm systems provided by Doppler radar were available, the public and the meteorological community were enthralled by the images provided by TIROS (television and infrared observation satellite), the first U.S. weather satellite. In contrast to those pioneering, qualitative weather pictures, satellites now provide magnificent color-enhanced images spanning the globe. Satellites also provide a broad range of quantitative measurements that are used routinely in preparing forecasts and severe storm warnings and are assimilated into NWP models. Time-lapse sequences of the whirling clouds of hurricanes are familiar to virtually every U.S. household. Current satellites are operated by the National Environmental Satellite, Data, and Information Service (NESDIS) and its counterparts elsewhere in the world.

Along with the NESDIS programs, a wide range of Earth-observing systems deployed by the National Aeronautics and Space Administration (NASA) have important applications for operational meteorology and hydrology. Data from these spacecraft also enable the analysis and modeling of broad environmental phenomena and systems, of which weather and climate are components. Even the GPS satellites, which were intended for positioning and navigation, have important emerging uses in observing fundamental weather variables. To cover this wealth of satellite-based technologies, this section is divided into four categories of current and future systems: (1) geostationary and polar-orbiting satellites like those currently operated by NESDIS, (2) satellite-based radar systems, exemplified by the new tropical rainfall measuring mission (TRMM) satellite, (3) GPS (or similar positioning constellations) for occultation measurements, and (4) the NASA Earth observing system (EOS) and its potential future extensions.

Geostationary Operational Environmental Satellites and the National Polar-Orbiting Operational Environmental Satellite System

Only a combination of geostationary and polar-orbiting satellites can provide the spatial and temporal coverage required to measure the atmosphere and Earth system for weather and climate. Geostationary satellites provide images at high horizontal and temporal resolution, of clouds and total water vapor in tropical and middle latitudes but not over polar regions. Although some progress has been made in deriving vertical soundings of temperature and water vapor from geostationary satellites using infrared and

BOX 2-2
Beyond NEXRAD

NEXRAD, known also by its technical designation WSR-88D, may be the last radar system deployed operationally and dedicated to weather surveillance. Radars require large segments of valuable electromagnetic spectrum bandwidth, and they cannot provide uniform coverage, even over land. To conserve spectrum bandwidth for other purposes, multifunction radars serving varied users, meteorology among them, may become mandatory in the future.

microwave channels, the soundings have relatively low vertical resolution. Polar orbiters provide observations for all latitudes and longitudes, including polar regions, several times a day, and radiometric temperature and water vapor soundings derived from polar orbiters have better vertical resolution than the soundings from geostationary satellites. However, the vertical resolution of radiometrically derived soundings from both geostationary and polar-orbiting satellites is not high enough for accurate initialization of NWP models.

Current soundings do not adequately resolve important structures in the atmosphere, such as the tropopause and upper-level fronts. They are also generally limited to clear or partially clear regions of the atmosphere and have to be calibrated on a regular basis. In contrast, soundings derived by the radio occultation technique on polar orbiters (discussed below) have lower horizontal but higher vertical resolution than radiometric soundings. Radio occultation soundings are not affected by clouds, precipitation, or aerosols and are self-calibrating. Thus, radiometric and radio occultation sounding methods are synergistic, as are geostationary and polar-orbiting satellites. A combined system would provide high-resolution global coverage, spatially and temporally, of cloud images, temperatures, and water vapor.[4]

In a report on the continuity of spatial and temporal coverage by the weather satellites in the NESDIS program, the National Weather Service Modernization Committee evaluated NOAA's plans for continuing operations of the geostationary operational environmental satellite (GOES) program and the national polar-orbiting operational environmental satellite system (NPOESS) (NRC, 1997). These satellite systems will remain an integral part of NOAA's national and global observing systems and will constitute critical observational tools for NWS operations well into the twenty-first century. The linkage of NPOESS with European polar-orbiting satellites, called METOP, in the near future will be an important step toward the creation of an integrated global observing system comprising the geostationary and polar-orbiting satellites of many nations. If NOAA assigns appropriate priority to this program, an integrated system is likely to be operational before 2025.

Geostationary satellites are important for monitoring the tropics and middle latitudes, especially when near-continuous monitoring of the Earth's surface or atmosphere is necessary, in the case of rapidly evolving severe storms, for example. Progress continues to be made in the analysis, display, and uses of GOES data for a variety of research and operational applications. For example, the digital data from GOES that are now used in NCEP's numerical models include high-resolution observations of winds from time-lapse water vapor and cloud imagery. Work is under way to incorporate the three-layer precipitable water and clear-air radiances from the GOES sounders as well. Digital satellite information available at NWS field offices includes a product that specifies low-clouds derived from GOES imagers. Other products include an index of atmospheric stability and an indicator of the amount of precipitable water above a location derived from GOES imagers and sounders.

The most valuable products from GOES satellites are cloud and water vapor images. The highest NWS priority for improving these products is frequent, high-quality, full-disk imaging to support its forecast and warning operations. GOES satellites also provide some useful information on the horizontal and vertical distribution of temperature and water vapor, as well as some useful information on winds based on rapidly sequenced images of cloud and water vapor features. However, complementary low Earth orbit (LEO) satellites are needed to provide the most important observations for improving NWP model forecasts: wind observations from laser systems and temperature and water vapor soundings with higher vertical resolution and greater accuracy, which could be obtained with the radio occultation technique.

For the next decade, the NWS has set a goal of determining the value of real-time lightning mapping from geostationary orbit. Most cloud-to-cloud lightning can be observed from space at any time of the day. These observations of the development of vigorous storm and energy release typically provide valuable indicators of the onset of convective precipitation. The observations are particularly valuable in areas not covered by NEXRAD radars, such as the Gulf of Mexico and mountainous regions. The lightning mapper (LM) is now successfully operating on TRMM (see below). With adequate support, a version of LM designed to fly on a GOES could be built within two years.

In the past, data from NOAA's polar orbiters have been used mostly as quantitative input for numerical models, which are used primarily for longer-range weather and climate predictions. The data from geostationary satellites have been used mostly in a qualitative mode by local forecasters for issuing short-term forecasts and warnings of hazardous weather. With advances and improvements in NPOESS sounders, as well as in weather and climate forecasting, the use of NPOESS data by local and regional offices for computing specialized products, such as soil moisture, precipitable water, and winds, has greatly increased. Satellite constellations and clusters could provide significantly better coverage and open new approaches for calibration and data continuity (NRC, 1998c). Data from geostationary satellites are being used in numerical predictions and by local forecast offices for specialized products, such as stability indices and estimates of total precipitable water (potential rainfall). Thus, it is becoming increasingly apparent that GOES and polar-orbiting satellite data sets will have to be used as a "mix" of observations throughout the NWS, at both national centers and local forecast offices.

Full exploitation of the synergism between geostationary and polar-orbiting satellites will provide the full spatial and

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[4] Stankov (1998) has recently argued for combining different observational systems to get better atmospheric soundings than can be provided by any one system.

temporal coverage for monitoring and predicting changes in the land-ocean-atmosphere system on both short (weather) and long (climate) time scales. Together these satellites can provide the data to address NWS's priorities for better forecasts and warnings, as well as the scientific priorities of NASA and NOAA.

Future generations of environmental satellites will benefit from a number of synergies: from a partnership among nations leading to a global observing system; from combinations of measurements from instruments on a single satellite or on multiple satellites; from advanced analytical systems that can combine satellite, radar, and other related in-situ observations to produce refined, accurate values for standard meteorological quantities; and from numerical models that can assimilate data and interact with the observing systems.

Satellite-Based Radar Observing Systems

The TRMM satellite, which was launched in November 1997, illustrates the coming of age of radar as a *space-based* environmental observing system. TRMM carries the first meteorological radar in space, along with a multichannel microwave imager, a visible and infrared (IR) radiometer, an Earth radiation budget sensor (the Clouds and Earth's Radiant Energy System [CERES]), and a lightning imaging sensor. The purpose of the TRMM is to estimate precipitation in the tropical regions of the world. TRMM observations can distinguish between convective and stratiform rainfall and are expected to provide mean vertical profiles of latent heating and evaporative cooling. When assimilated into models, this information is expected to improve both synoptic-scale and long-range forecasts. Future observations will enhance forecasts of weather phenomena, such as the El Niño Southern Oscillation.

GPS Radio Occultation Measurements

One attractive approach to atmospheric profiling is limb scanning of the atmosphere during the occultation of the signals from the GPS satellites as received by polar-orbiting LEO satellites (Melbourne et al., 1994). The measurements relate directly to the refractivity of the atmosphere and, therefore, to electron densities in the ionosphere and temperature and moisture in the stratosphere and troposphere. Results of the proof-of-concept GPS/MET (GPS/Meteorology) experiment demonstrated the high accuracy (1 K) and high vertical resolution (approximately 500 m) retrieval of temperature soundings in the upper stratosphere and the capability to derive water vapor profiles in the lower troposphere, given reasonably accurate independent temperature information (Kursinski et al., 1997; Rocken et al., 1997). The characteristics of GPS/MET observations complement the soundings derived from radiometric measurements by GOES and NPOESS satellites.

The Earth Observing System and Potential Extensions

Additional satellite capabilities will be provided by NASA's EOS missions. Table 2-1 lists 24 measurements that will be made by EOS. Although these measurements are intended primarily for monitoring climate and global change, virtually all of them are directly or indirectly relevant to short-term and medium-term weather predictions. For example, greatly improved atmospheric temperature and humidity soundings, which will come from the advanced infrared sounder (AIRS), the advanced microwave sounding unit (AMSU), and the high-resolution dynamics limb sounder, could provide basic data for regional and synoptic weather predictions. AIRS alone is expected to provide radiative fluxes and profiles of temperature and moisture that are substantially more accurate than current measurements. It will also provide the mean boundary layer temperature and column water vapor up to about 1 km, both of which are important for forecasts of clouds, precipitation, and severe storms.

Versions of some of these instruments will also be aboard NOAA's operational environmental satellites. The NOAA K satellite in the polar-orbiting series (launched May 13, 1998) carries a version of AMSU with 15 channels near the 56-GHz oxygen band for temperature sounding and 4 channels near the 183-GHz water vapor band for humidity profiles. Present NPOESS plans call for the flight of a high-resolution sounder with capabilities similar to the AIRS sounder on NOAA N′, the polar-orbiting satellite that will follow L, M, and N, around 2010.

Combinations of instruments, such as AIRS and the moderate resolution imaging spectrometer, promise to provide accurate observations of surface skin temperature, which can be used to estimate sensible and latent heat fluxes over the ocean (in combination with simultaneous measurements of surface winds by a scatterometer). Heat fluxes are important forcing factors in the development of intense cyclonic storms. NPOESS plans to fly a conical microwave imager sounder about 2010, which will use both a high-resolution sounder and a multichannel microwave instrument to estimate ocean surface winds and determine ocean heat fluxes.

A variety of modeling experiments with both real and simulated data have shown the great value of accurate wind observations over the oceans. For example, the assimilation of data from a NASA ocean wind scatterometer (NSCAT) aboard Japan's advanced Earth observing satellite into general circulation models has significantly improved the skill scores of operational marine weather forecasts. Among other phenomena, these observations have detected fronts and extratropical cyclones that ordinarily might have gone undetected (Atlas et al., in press). NOAA intends to use the NSCAT data to monitor ocean-atmosphere phenomena, such as the El Niño Southern Oscillation and sea ice in the polar regions (NOAA, 1998).

One of the missing observational links has been an accurate and reliable measure of the winds throughout the entire

TABLE 2-1 Earth Observing System Measurements

	ACRIM	AIRS	AMSR	AMSU	ASTER	CERES	DFA/MR	EOSP	ETM+	GLAS	HIRDLS	HSB	LATI	LIS	MHS	MIMR	MISR	MLS	MODIS	MOPITT	NSCAT-2	ODUS	SAGE III	SeaWiFS	SeaWinds	SOLSTICE	TES	TOPEX
Cloud properties		■	■		■			■		■							■		■				■					
Radiative energy fluxes	■	■	■		■	■				■							■		■				■					
Precipitation			■													■												
Tropospheric chemistry											■			■				■		■			■				■	
Stratospheric chemistry											■							■				■	■				■	
Aerosol properties								■		■	■						■		■				■					
Atmospheric temperature		■		■							■							■	■								■	
Atmospheric humidity		■		■			■				■	■						■	■				■				■	
Lightning														■														
Total solar irradiance	■																											
Ultraviolet spectral irradiance																										■		
Land cover and use change					■				■				■				■		■									
Vegetation dynamics					■				■				■				■		■									
Land surface temperature		■			■				■										■									
Fire occurrence					■				■										■									
Volcanic effects					■				■								■		■									
Surface wetness			■																									
Ocean surface temperature		■	■																■									
Phytoplankton and dissolved organic matter																			■					■				
Ocean surface wind fields			■				■														■				■			
Ocean surface topography							■																					■
Land ice					■				■	■			■															
Sea ice			■		■		■		■				■						■									
Snow cover			■		■				■				■						■									

Notes: EOS instruments recommended for early period (1997–2001)

ACRIM=active cavity radiometer irradiance monitor
AIRS=advanced infrared sounder
AMSR=advanced microwave scanning radiometer
AMSU=advanced microwave sounding unit-A
ASTER=advanced spaceborne thermal emission and reflection radiometer
CERES=cloud and Earth's radiant energy system
DFA/MR=dual-frequency radar altimeter/microwave radiometer
EOSP=Earth observing scanning polarimeter
ETM+=enhanced thematic mapper

GLAS=geoscience laser altimeter system
HIRDLS=high-resolution dynamics limb sounder
HSB=humidity sounder Brazil
LATI=Landsat advanced technology instrument
LIS=lightning imaging sensor
MHS=microwave humidity sounder
MIMR=multifrequency imaging microwave radiometer
MISR=multi-angle imaging spectro-radiometer
MLS=microwave limb sounder

MODIS=moderate-resolution imaging spectrometer-nadir
MOPITT=measurements of pollution in the troposphere
NSCAT-2= NASA scatterometer
ODUS=ozone dynamics ultraviolet spectrometer
SAGE III=stratospheric aerosol and gas experiment
SeaWiFS=sea-viewing wide field-of-view sensor
SOLSTICE=solar stellar irradiance comparison experiment
TES=tropospheric emission spectrometer
TOPEX=ocean topography experiment

troposphere. Observing system simulation experiments have shown that a wind profiler with an assumed accuracy of 1–3 m/s RMS (root mean square) would improve forecasting skill more than any other proposed space-based measurement (Atlas, 1997). Several alternative techniques for making these measurements have been discussed (Abreu et al., 1992; Baker et al., 1995). A Doppler lidar wind measurement system called the space readiness coherent lidar experiment (SPARCLE), based on new solid-state laser technology, is scheduled for flight in 2002 on the space shuttle (NASA, 1998). If it performs successfully, a lidar wind profiler may be flown on the NPOESS generation of operational polar-orbiting satellites.

Other quantities that would be especially beneficial for weather prediction on a variety of scales are cloud properties, radiative energy fluxes, and precipitation. These quantities will be measured by AIRS, AMSU, CERES, the advanced spaceborne thermal emission and reflection radiometer (ASTER), and the stratospheric aerosol and gas experiment, among others. Measurements of snow cover and sea ice, which are expected from ASTER and the advanced microwave scanning radiometer, are related to surface albedo and heat transfer, two important quantities in NWP models. Estimates of snow pack properties, such as coverage and thermodynamic properties (e.g., temperature and equivalent water content) derived from satellite sensors using multispectral observations, could be developed further and integrated into hydrologic and regional atmospheric assimilation and forecasting systems.

Soil moisture is an important measurable quantity that is not currently included in EOS plans. However, a soil moisture mission is one of several satellite observing missions that have been proposed independently of EOS. Remote sensing of soil moisture—for example, by a synthetic aperture passive microwave sensor, as proposed for the HydroStar program (Cavalieri and St. Germain, 1995)—offers the possibility of routine, gridded data that could be assimilated into soil moisture representations for better NWP models.

Because continuity in the NESDIS operational satellite program is essential for studies of climate and global change, the National Weather Service Modernization Committee recommended that climate research, such as research being conducted under EOS, be integrated with the NESDIS operational satellite programs (NRC, 1998b). Similarly, the research satellites operating under NASA's Earth Science Enterprise and the research satellites planned in the EOS program (NASA, 1995) offer a wide range of new and exciting measurements that will be beneficial for operational environmental predictions and warnings. Research satellites of the European Space Agency, such as the European Remote Sensing satellites ERS-1 and ERS-2, which are already in flight, the forthcoming environmental satellite ENVISAT, and the Canadian radar satellite RADARSAT could also provide useful data. The many opportunities for improving and expanding observations are indicators of the rapid evolution of the operational satellite system.

NUMERICAL MODELING AND DATA ASSIMILATION

Introduction and History

The foundations of quantitative modern NWP are the Newtonian laws of motion, the conservation of mass, the laws of classical thermodynamics, and the laws of electromagnetic radiation transfer and interactions with matter. Numerical approximations to these laws describe the atmosphere system, including the oceans, land, and ice surfaces, and are solved on computers as initial value problems. The scientific and mathematical basis for NWP, which will be even more important in 2025 than it is today, was predicted by Lewis Fry Richardson in *Weather Prediction by Numerical Process*, published in 1922. (The history and scientific basis of NWP are summarized in Tribbia and Anthes [1987]).

Over the years, model representations of the behavior of the real atmosphere have become more and more accurate (Kalnay et al., 1998). The first experimental NWP model was run in April 1950 for a region encompassing North America on a primitive computer called the ENIAC (electronic numerical integrator and calculator), which was far less powerful than today's hand-held calculators. This first model, which later became the first operational forecast model run at the National Meteorological Center (now NCEP), was based on a single conservation principle and equation and gave answers only at one mid-troposphere level. Current models describe the large-scale dynamics of the atmosphere, as well as physical processes, such as radiation, cloud formation, precipitation, energy dissipation, and interactions between the atmosphere and the surface of the Earth. They now cover many levels of the troposphere, giving a nearly complete picture of the atmosphere.

Observations and Analysis

Observations provide the basic information that NWP models require to make forecasts. An NWP model describes the temporal evolution of the atmosphere from an initial state. It requires knowledge of the value of each state-defining variable at that initial time. In the early years of numerical predictions, individual observations were "analyzed" by fairly simple mathematical techniques to derive the initial values of variables. The analysis process was based on subjective procedures, often involving human decisions and interventions, to eliminate "bad" observations. The principal purpose was to produce, from irregularly spaced weather observations, an array of values of atmospheric variables at model grid points. As part of the analysis process, data were often modified slightly to reflect certain assumed "balances" in the atmosphere; adjustment of the data is referred to as "initialization." Analyses and initializations were, in general, produced twice each day, corresponding to the global rawinsonde observation times of 00 and 12 UTC. Changes in the methods of atmospheric data analysis are reviewed in Daley (1991).

Data Assimilation

In recent years, the analysis and forecast portions of the NWP process have become much more closely linked through the direct assimilation of data into models. Observations are used to "correct" or adjust model predictions wherever and whenever the observations are available. Some of the advantages of data assimilation over the older analysis process are (1) more effective ways of dealing with the asynchronous nature of the vast majority of new observations (such as those from aircraft and weather satellites), (2) the use of an observation of one or several model variables to modify and improve the values of all variables through physical adjustment processes, and (3) the use of the variable itself (e.g., radiances from satellites) rather than derived quantities (e.g., temperature profiles derived from observed radiances). This latter capability has only recently been developed operationally and has led to significant improvements in forecast skill (Eyre et al., 1993; Derber and Wu, 1998). Preliminary studies have shown that the assimilation of atmospheric refractivity (Zou et al., 1995) or radio wave bending angles (Zou et al., 1999) obtained through the radio occultation technique will cause the model variables to adjust toward the actual state of the atmosphere.

A powerful, though computationally expensive technique for data assimilation is the four-dimensional variational data assimilation, or 4DVAR (Lewis and Derber, 1985; Errico, 1997). With the 4DVAR process, observations over time for any model-predicted variable (or observations over time for a function of a model variable, such as radiances or refractivities) can be assimilated into the model. As these observations are assimilated, the model's physical adjustment processes allow the impact of the observations to be spread throughout the model. With this approach to assimilation, the system of model equations plus observations produces a better data analysis than could be obtained from the observations alone. This assimilation process is the basis for the retrospective "reanalysis" of past atmospheric data using modern models (Kalnay et al., 1996).

Predictability Limits

The atmosphere is a nonlinear fluid system and hence, as shown by chaos theory, has limited and variable predictability (Lorenz, 1963; Thompson, 1983). No matter how accurate the models or how precise the observations, the temporal limits to predictive skill (which are not yet known for all weather phenomena) cannot be exceeded. Small errors in initial conditions, errors generated by the numerical approximations to the model's differential equations, and errors introduced by imperfect physical approximations grow with time and ultimately limit the accuracy of forecasts.

Originally, low resolution and the difficulty of representing physical processes, such as radiation, latent heat release, and boundary layer processes, were the principal sources of errors in numerical forecasts. As models have improved in the past several decades, the situation has changed, and deficiencies in observations have become the major source of errors. As observations become more accurate and complete, and as models become more highly resolved, it seems likely that the dominant errors will again be produced by errors in the model's physical approximations.

The predictability of many atmospheric phenomena, especially mesoscale and smaller phenomena, are limited (although these limits have not been quantified). In general the largest scales of atmospheric motion, such as the long-wave patterns at the jet stream level, are more predictable than smaller scales of motion, such as those associated with thunderstorms. Thus, although jet stream patterns can be forecast routinely with some skill for a week or more, individual thunderstorms are usually predictable for only a few hours beyond the latest observation base.

Quantitative estimates of predictability generally refer to the predictability of medium and large-scale waves in the atmosphere (wavelengths of 1,000 to 40,000 km). Although these estimates have been made in a variety of ways (Thompson, 1984), the estimates are all similar. Errors, no matter how small, typically grow at a rate that causes forecasts to become inaccurate in the range of 10 to 20 days.

Although the atmosphere is predictable for only a few weeks, the coupled ocean-atmosphere system may be predictable for a year. For example, the Tropical Oceans Global Atmosphere Program of the World Climate Research Program has demonstrated that the El Niño phenomenon in the tropical Pacific Ocean and the associated Southern Oscillation are to some extent predictable a year in advance (Trenberth, 1997). Anomalies in the sea-surface temperature, which may persist for months, modify the precipitation distribution over the Pacific, and the modulated latent heating distribution affects the jet stream and associated weather patterns over regions of the atmosphere far from the source of the sea-surface temperature anomaly. Coupled ocean-atmosphere models have been able to predict these shifts in global weather patterns, and it is likely that further improvements in models and initial data will lead to significantly better climate predictions in the next several decades. Trenberth (1997) reviews the scientific basis for interannual predictions based on long time scales associated with atmosphere-ocean interactions and recent progress in the development of operational climate forecast models.

Forecasting Skill

History has shown that new operational forecast models

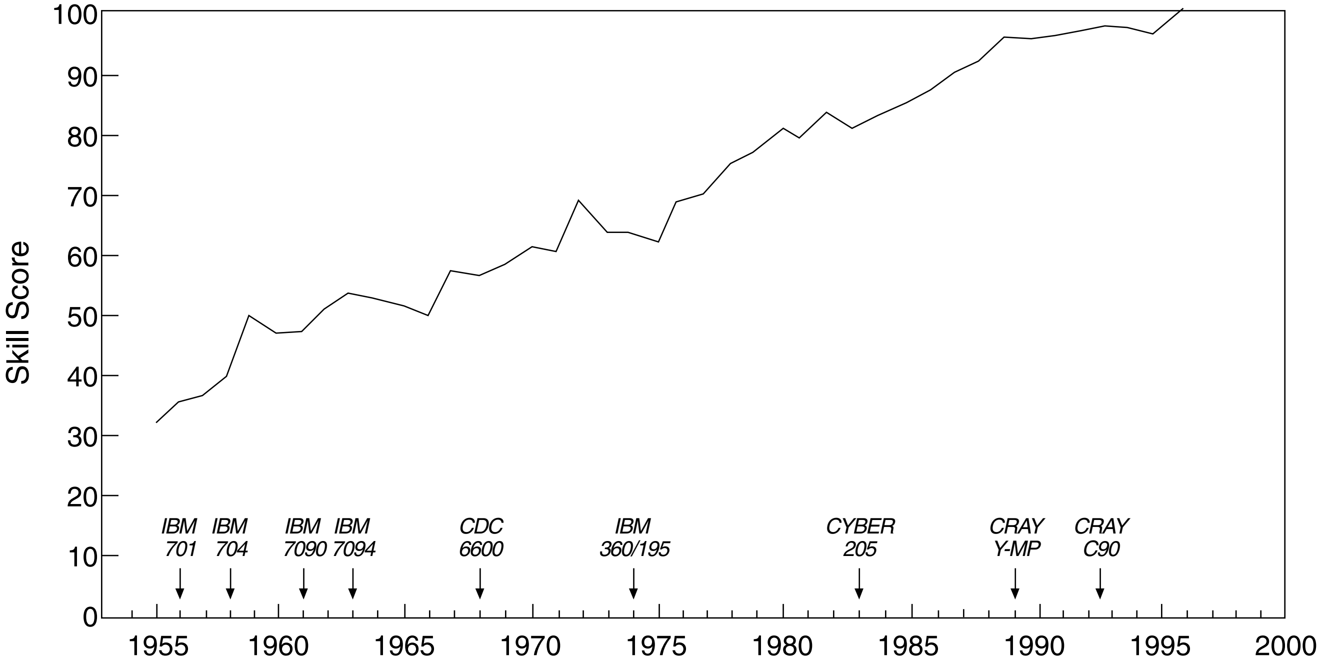

FIGURE 2-1 The variation since 1954 at NCEP (formerly the National Meteorological Center) in the skill score for 36-hour forecasts for the 500-mb geopotential height field over North America. On this scale, a score of zero represents an essentially worthless forecast (one with little or no skill). A score of 100 represents a highly accurate (nearly perfect) forecast. Also shown in the figure are the times of major computer upgrades at NCEP and the names of the computers. These upgrades in computer power were essential for increasing forecast skill. Source: NCEP, personal communication.

with improved resolution and physics, new observing systems, and new methods of assimilating data have increased the accuracy of forecasts. Figure 2-1 shows the increase in skill of NCEP forecasts since 1955, using one simple measure of forecast skill: the forecast height of the 500-mb constant pressure surface over North America 36 hours after the initialization time.[5] Figure 2-2 shows the corresponding skill in forecasting sea-level pressure.

Figure 2-3 shows the increase in skill at NCEP in forecasting the 500-mb geopotential height anomalies over the Northern Hemisphere in winter. An anomaly correlation of 0.6 or better is generally considered to represent a fairly accurate forecast. According to this measure, forecasting skill has more than doubled since 1972; a five-day forecast in 1998 is as accurate as a two-day forecast was in 1972.

The increases in forecast skill shown in Figures 2-1 and 2-2 are somewhat misleading because the weather of interest is far more complex than the behavior of the heights of the 500-mb pressure surface or the sea-level pressure field. There is a long way to go before forecasts of rain, snow, severe weather, and other phenomena will be as accurate as is theoretically possible. For example, the skill score for 24-hour forecasts of precipitation amounts of 0.5, 1.0, and 2.0 inches has increased only modestly since 1961 (Figure 2-4). However, progress is being made, as shown by the increasingly frequent forecast successes that would have been impossible 25 years ago. Box 2-3 describes the remarkable five-day forecast of the East Coast superstorm on March 12–14, 1993.

This issue of forecast success raises some serious questions. Given the improvements in NWP in the past 50 years, what can one reasonably expect in the next 25 years? How will weather services and the manner of delivering these services be affected? The panel believes that an ambitious but achievable goal for 2025 is that the forecast skill of global NWP models will approach the theoretical limit of skill as described by predictability theory.

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[5] The *skill scores* are based on the so-called S1 score, which measures the accuracy or skill in predicting the horizontal gradient of a scalar field, such as geopotential height of a constant pressure surface or sea-level pressure (Teweles and Wobus, 1954). Because of the strong relationship in middle and high latitudes between the pressure gradient and large-scale (or synoptic-scale) wind flow, the S1 score for geopotential height and sea-level pressure is also a good measure of skill in predicting the synoptic-scale winds.

If the forecast and observed pressure gradients are identical, the S1 score is zero. However, forecasters in the 1950s noted that for practical purposes, an S1 score of 20 represented an extremely good or near-perfect forecast, while an S1 score of 70 represented an essentially worthless forecast. Thus it became common practice to express the skill score as 2(70 – S1) so that an extremely good forecast would have a score of 100 and a worthless forecast would have a score of 0 (Shuman, 1989). Although this convention is arbitrary, the long record of measuring forecast skill this way makes it useful for showing trends in the accuracy of large-scale forecasts.

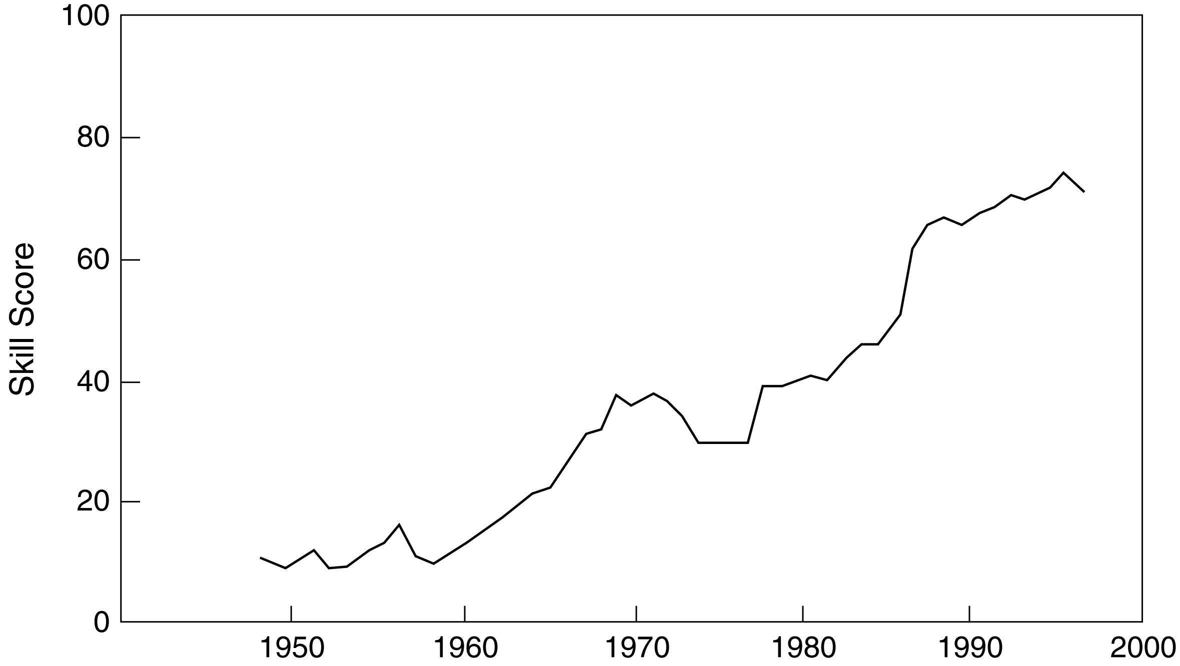

FIGURE 2-2 The variation since 1949 at NCEP in the skill score of 36-hour forecasts for the sea-level pressure field over North America. The skill score is on the same zero to 100 scale as Figure 2-1. Source: NCEP, personal communication.

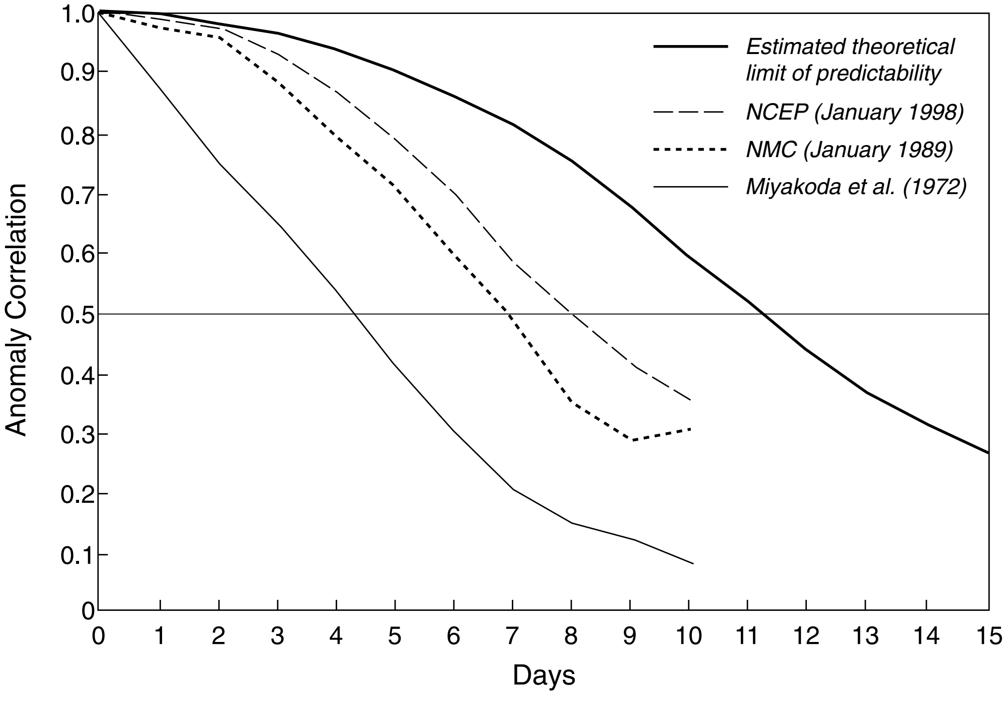

FIGURE 2-3 Anomaly (variation from seasonal climatic norm) of the height correlation for 500-mb forecasts. The curves labeled "Miyakoda et al. (1972)" and "NMC (January 1989)" are from Bonner (1989). The curve labeled "NCEP (January 1998)" was provided by Ronald McPherson of NCEP. The curve labeled "estimated theoretical limit of predictability" is a subjective and possibly optimistic estimate by the Road Map Panel, based on various quantitative estimates of the predictability of synoptic-scale waves in the atmosphere, such as Simmons et al. (1995).

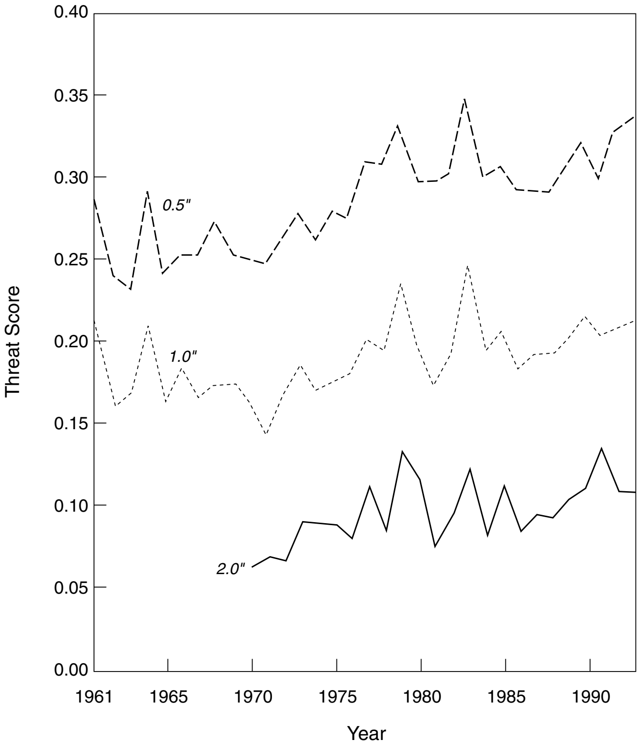

FIGURE 2-4 Skill in forecasting precipitation amounts over the United States (0.5, 1.0, and 2.0 inches) one day in advance. Each line represents the *threat score*, which is based on the degree of agreement between the forecast and observed area coverage of precipitation isohyets (lines of equal amounts of precipitation). If the area of a given forecast amount of precipitation is denoted by Af, the area observed by Ao, and the area correctly forecast (overlap of Af and Ao) by Ac, then the threat score is given by Ac/(Af +Ao–Ac). The threat score varies from zero (no area correctly forecast) to 1.0 (perfect overlap between forecast and observed areas of precipitation amounts). Source: Olson et al., 1995.

Current Status

The current status of several representative operational and research models is summarized in Table 2-2. Operational global models are being run daily out to more than two weeks at approximately 100 km horizontal resolution at NCEP and 60 km at the European Centre for Medium-Range Weather Forecasts (ECMWF). The regional Meso-Eta model at NCEP is being run at 32 km horizontal resolution out to 48 hours. Fully coupled atmosphere-ocean climate system models with approximately 300 km horizontal resolution in the atmosphere and 200 km horizontal resolution in the ocean are being run to simulate several hundred years of the Earth's climate (Boville and Gent, 1998).

Mesoscale and microscale research models with horizontal resolutions much higher than the operational models are being run to simulate and study a wide variety of nonhydrostatic atmospheric phenomena, including thunderstorms, tornadoes, hurricanes, other precipitation systems, and clear air turbulence and fires (see Table 2-2). For example, the Clark-Hall model developed by the National Center for Atmospheric Research (NCAR) has realistically simulated forest fires with an 84 x 84 x 160 grid using a resolution of 20 m.

Projections for 2025

Today's large-scale weather forecasts are useful for 7 to 10 days. Thus, current NWP forecasting techniques are probably about half way to the predictability limit. Reaching the limit will require improved model physics, significant improvements in global observations, and higher model resolutions. Although programs to improve the global observations are progressing well, they must be accompanied by advances in scientific understanding and computational power.

NWP has been one of several driving factors in the push for more powerful computers. The panel assumes that this will be true in the future and that the computer power available for NWP will continue to reflect the state of the art in processing capability. Figure 2-5 shows the increase in computer speed for a number of computers that have been used at NCEP and other weather prediction centers, as well as some projections into the future based on the accelerated strategic computing initiative (ASCI), an ambitious research and development program of the U.S. Department of Energy. Also shown in this figure are projections to 2025 listed in Box 2-4.

The differential equations used by NWP models are nonlinear and can only be solved analytically for highly simplified problems. In order to solve the equations on computers, equations are expressed either in finite difference form and solved algebraically at discrete locations (model grid points) or they are expressed as a series of wave functions (e.g., Legendre polynomials). Both methods introduce errors. In the first case, errors arise from the estimation of continuous derivatives by finite differences between data at discrete points. In the second case, errors arise through ending the series representation at a finite number of waves. In both cases, numerical errors grow as the forecast proceeds.

The resolution of grid point models is expressed as the spatial distance between calculation points. The resolution of spectral models is expressed in terms of the type of formulation (rhomboidal or triangular, denoted by *R* or *T*) and the number of waves that are used to represent a field. Even in spectral models, vertical structure is represented in finite difference form through operations on variables at discrete model levels.

High resolution in models is important for two reasons, to reduce truncation errors and to resolve finer scale phenomena. Resolution determines the scale of phenomena that the models can resolve and predict. The limiting factor in model resolution has always been—and will continue to be—available computer power.

BOX 2-3
Storm of the Century

On March 12–14, 1993, the eastern third of the United States was hit by a major winter storm. The storm produced the most extensive distribution of heavy snow across the eastern United States in modern times., generated severe coastal flooding, spawned tornadoes and damaging wind squalls in Florida, Cuba, and other Caribbean nations, sank several ships, closed major roadways, and stranded thousands of people at airports throughout the United States. The forecasts of this historic storm by the NWS were remarkably successful. The formation of the storm was forecast five days in advance. The unusual intensity of the storm was forecast three days in advance, allowing forecasters, government officials, and the media ample time to prepare the public and marine and aviation industries to take precautions for the protection of life and property. The amounts and areal distribution of snowfall were predicted two days in advance. The coordination of forecasts within the NWS, and between the NWS, private forecasters, and media meteorologists was the most extensive in history.

Source: Uccellini et al., 1995.

TABLE 2-2 Examples of Current Numerical Models

Numerical Model[a]	Horizontal Resolution	Number of Vertical Levels	Period of Forecast or Simulation
Operational, Global Models			
NCEP medium-range forecast	105 km	28	16 days
ECMWF medium-range forecast	60 km	31	10 days
Canadian global	100 km	28	10 days
Operational, Regional Models			
NCEP Meso-Eta	32 km	45	48 hours
Air Force MM5[b]	36 km (12 km inner nests)	10	24 hours
Canadian regional	24 km	28	48 hours
Research, Regional or Storm-Scale Models			
ARPS SAMEX	3 grids (32, 9, 3)	—	36 hours
ARPS coupled hydrology	4 grids (64, 16, 4, 1)	49	36 hours
ARPS lake effect	5 grids (64, 16, 4, 1, 0.25)	41	24 hours
CSU RAMS, supercell thunderstorm and tornado	6 grids (120,40,8,1.6,0.4 and 0.1 km)	32	13 hours
CSU RAMS, cirrus simulation	150 m	115	30 minutes
CSU RAMS, derecho	4 grids (80,40,10, 2 km)	38	24 hours
MM5 (1987 TAMEX) IOP13 rainbands)	6 grids (90, 45, 22.5, 7.5, 2.5, 0.83 km)	27	48 hours
MOZART (chemical transport model)	~300 km	25	2–3 years
NCAR MM5 (Supertyphoon Herb, 1996)	4 grids (60, 20, 6.67, 2.23 km)	27	48 hours
NCAR Clark-Hall, clear air turbulence	5 grids (25.6, 6.4, 1.6, 0.4, 0.2 km)	—	7 hours
NCAR Clark-Hall, fire	20 m	160	~30 minutes

[a] ECMWF = European Centre for Medium-Range Weather Forecasts; NCEP = (U.S.) National Centers for Environmental Prediction; MM5 = Mesoscale Model Version 5 (developed by Pennsylvania State University and NCAR); ARPS = Advanced Regional Prediction System (originated at University of Oklahoma); SAMEX = storm and mesoscale ensemble experiment; CSU = Colorado State University; RAMS = regional atmospheric modeling system.

[b] The U.S. Air Force has recently begun to use a version of the MM5 model on an operational basis. Other versions are used for research.

BOX 2-4
Available Computer Power

Moore's Law, which is actually an empirical generalization, predicts that computer power will double, on average, every one to two years, and computer power available at major weather prediction centers has roughly followed that law ([URL: HtmlResAnchor www.hedweb.com/nickbb/superintelligence.htm]). If this trend holds, computer power will double approximately every 18 months, or quadruple every three years, from now until 2025. The table below uses the Moore's Law relation to estimate computer speed through 2025, given the *peak* speed for the world's fastest computers, at present approximately 1 teraflop (10^{12} floating point operations per second). Figure 2-5 is a graph of historical values for peak speed, plus an extrapolation out to 2025, using the data in the table below.

Year	Speed (teraflops)
1998	1
2001	4
2004	16
2007	64
2010	256
2013	1,024
2016	4,096
2019	16,384
2022	65,536
2025	262,144

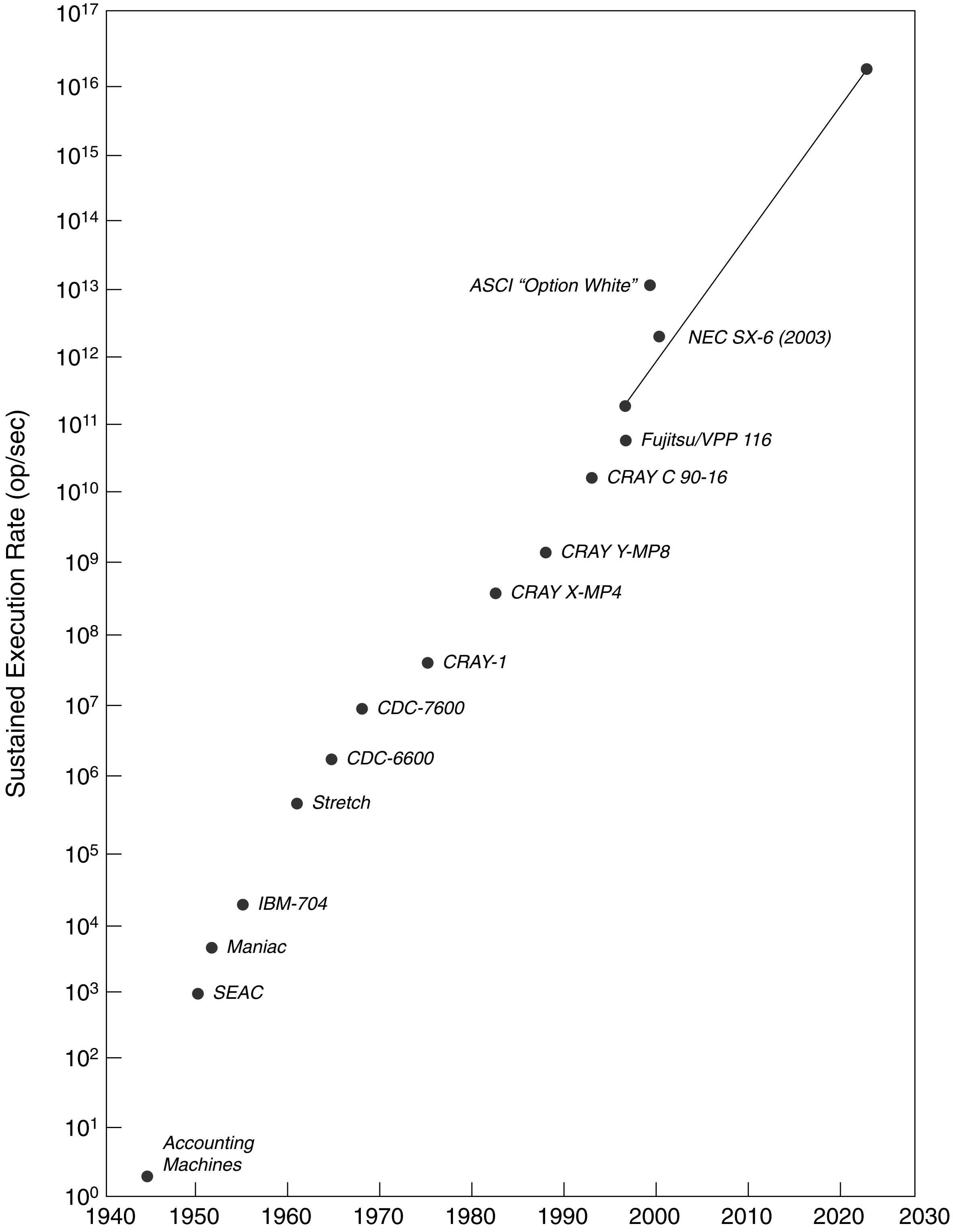

FIGURE 2-5 Trend in total system computational performance. Estimates are of total system performance (not peak performance) on NWP models. Adapted from Hack Fig. 9.1 in Trenberth (1992).

Global Models in 2025

Global weather predictions and climate models in 2025 will include the ocean, land, and atmosphere in a single system. These models will be used for routine daily weather forecasts and, in a somewhat lower resolution version, for much longer periodic climate forecasts used as the basis for forecasts of anomalous weather conditions associated with large-scale, persistent ocean features, such as the El Niño Southern Oscillation.

To estimate the possible horizontal resolution of global NWP/climate models in 2025, one must make assumptions about the types of models that will be run, the available computer power, and the relationship between model resolution and computer speed. The panel anticipates that there will be three types of global models in 2025:

- coupled ocean, atmosphere, land, and sea ice models, also called atmosphere-system models (ASMs)
- coupled atmosphere-chemistry models
- space weather models

The estimates in Boxes 2-4 and 2-5 relate to ASMs; the panel assumes that the requirements for the other two types of models will be approximately the same. However, resolution is not the only factor that limits forecasting skill. Errors in initial conditions caused by incomplete observations, observational errors, and inadequate representations of atmospheric physics also contribute significantly to forecast errors. Advances in computer technology are likely to solve only the resolution problem. With advances in observational technologies, errors in initial conditions may become small enough that they no longer prevent NWP models from reaching the theoretical limits of predictability. Eliminating errors in the physical parameterizations of the models, the remaining constraint to reaching the predictability limit, will require significant increases in the basic understanding of the coupled atmosphere system and in translating this understanding into better model physics. This constraint is likely to be the greatest challenge to overcome, if the forecast skill of global NWP models is to reach the fundamental predictability limits by 2025.

Storm-Scale (Microscale) Models

The greatest advances in operational NWP in the next 10 to 20 years may be in storm-scale predictions. One can envision NWP systems with ultra high resolution (e.g., 1–10 m) that can capture features on time and space scales ranging from the scale of individual thunderstorms (roughly one hour) to the scale of organized features, such as squall lines, precipitation bands in cyclones, and mesoscale convective systems, that may last for several hours.

Based on the current state of research and projected computer capabilities, the NWS of the future will probably depend heavily on the operational use of limited area storm-scale models for short-range forecasts and warnings. By 2025, models with explicit representations of cloud and precipitation processes and horizontal resolutions of roughly 10 m will be capable of reliably predicting the life cycles of individual thunderstorms. With adequate initial conditions, these models will be able to predict the development and motion of individual storms for tens of minutes to perhaps a few hours. Storm-scale model forecasts will provide a basis for forecasters to issue site-specific warnings of flash floods, severe thunderstorms, and tornadoes. Small-scale features that are induced by topography and strongly affect local weather, such as land and sea breezes or mountain and valley winds, will also be predicted by these models.

In 2025, microscale models of air quality run by local environmental forecasters will contain appropriate representations for cloud, aerosol, and precipitation physics. Real-time data on industrial emissions of key trace chemicals (particularly the oxides of nitrogen and sulfur) will be assimilated into these local air quality and deposition models. Emission rates from traffic and natural sources, such as vegetation, will be added to the evolving emissions database, using specialized descriptions relating emission rates to external controlling factors. These models will be capable of predicting air quality for urban areas, where people susceptible to exposure to smog, and to air pollution in general, will be able to take protective action.

The models run by NCEP and other forecasting centers will include sufficient chemical detail to yield accurate forecasts of air quality affecting cities and other densely populated areas. The chemical weather forecasts will be tailored to provide requisite information for small-scale, area-specific air quality models run by commercial industries for forecasting local air quality. The predictions of these commercial vendors will constitute “value added” products that derive from NCEP chemical weather forecasts but that have been refined with information specific to the local topography, natural features, and built environment.

SPACE WEATHER

Causes and Consequences

The importance of space weather forecasts stems from the potential economic consequences of strong transient electrical currents in the ionosphere.[6] These currents occur when a strong solar gust is captured in the Earth’s magnetic field, rather than being repelled from it. The resulting damage to

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[6] Space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Adverse conditions in the space environment can cause disruptions of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socioeconomic losses (OFCM, 1995, pp. v, 1).

BOX 2-5
Relationship between Model Resolution and Computer Power

For a given set of physics, the computer speed required to run a model for a given forecast period increases linearly with the number of vertical levels and the cube of the horizontal-resolution parameter, N, where the horizontal resolution, $R=dxo/N$, and dxo is the reference horizontal grid spacing for $N = 1$.

Although required computer speed varies with the cube of the horizontal resolution, as horizontal resolution increases, the vertical resolution does not usually have to increase by the same factor. A useful approximation for increasing resolution is that the required computer speed increases exponentially with N and requires approximately a tenfold increase in computer power to double the horizontal resolution. This approximation allows for some increase in vertical resolution and some increase in the complexity of model physics as the horizontal resolution increases. From these assumptions, an approximate relationship between required effective computer speed and horizontal resolution factor N is

$$S(N) = S(N=1)\ N^{3.3223} \qquad (1)$$

For $S(N=1)$ the calculation uses actual data from Boville and Gent (1998) on the time required to run the NCAR climate system model (CSM). Assume that the CSM is run on a CRAY-90 (C-90) computer in 1998. For a nominal horizontal resolution of 312 km, it takes 5,200 C-90 CPU seconds (1.44 hours) to run the model for 10 days (Hack, 1998). The speed of a single processor on the C-90 is 340 megaflops or 0.34 gigaflops. The table below shows the resulting estimate of the computer speed required to run an ASM model like the CSM for a 10-day forecast in 1.44 wall-clock hours at various horizontal resolutions (dx), using Equation 1 with $S(N = 1)$ equal to 0.34 gigaflops.

N	$N^{3.3223}$	dx (km)	S (gigaflops)	S (teraflops)
1	1	312	0.34	0.00034
2	10	156	3.4	0.0034
4	100	78	34.0	0.034
8	1000	39	340	0.34
20	21,009	15.6	7,143	7.14
100	4.412E6	3.12	1.50E6	1,500
200	44.1E6	1.56	15.0E6	15,000
300	170E6	1.04	57.8E6	57,700
500	926E6	0.62	315.E6	315,000

E=mathematical notation for exponent.

The conclusion from this analysis is that, using the "business as usual" assumptions of Moore's Law, in 2025 it should be possible to run quite a few 10-day global forecasts using resolutions of less than 5 km. Thus, the panel projects that resolution should not be a limiting factor for global forecast skill in 2025.

power generating and transmission equipment can lead to a cascading breakdown of the infrastructure that supports modern, technology-dependent societies, including water supplies, heating and cooling systems, industries, and transportation systems. Depending on the area affected by the blackout and the extent of equipment damage, the economic costs could be as great as a billion dollars, and full recovery could take as long as a year. Living conditions in a blacked-out area could be stressed to the point that evacuations were required. "The magnitude of the disturbances triggered by solar flares is capable of disabling entire utility systems, and the worst is yet to come . . ." (Douglas, 1989). This comment was made in reference to the blackout in the Northeast United States in 1989 (the year of the last sunspot maximum in the 11-year solar cycle). A blackout in New York City in 1977 cost an estimated $290 million (OTA, 1990).

Solar gusts can disturb the Earth's upper atmosphere, which acts as a mirror and scatterer for over-the-horizon high-frequency (HF) transmissions and a medium for satellite signals. Radio communications, both ground-to-ground HF transmissions and satellite-to-ground links could be disrupted. During ionospheric disturbances, HF reflectivity could be lost in some regions, and satellite signals could scintillate, causing data errors. The GPS and GLONASS (Russian counterpart to GPS) navigation systems could be adversely affected in some geographic areas.

Satellite operations are also affected by gusts in the solar wind. In 1996, during the passage of a solar gust, a $200 million communication satellite was destroyed, presumably by electrical short circuits caused by high differential charge densities between the antenna and the satellite frame. Although this problem can be eliminated by changing the satellite design, astronauts in space during the passage of solar gusts will have to take extra safety precautions to protect themselves from the high charge densities and the high levels of radiation associated with solar flares.

Observing and Forecasting Space Weather

In January 1997, the Space Environment Center, which is operated by NOAA and the U.S. Air Force, successfully tracked a coronal ejection from the Sun as a solar wind gust to a violent magnetic disturbance on Earth (Peredo et al., 1997). The center's forecasts and other services cover ionospheric conditions; energetic particle fluxes at satellite orbits; solar events, including solar flares, solar particle fluxes, and geomagnetic storms; density variations in the upper atmosphere; and conditions affecting the propagation of HF radio waves. The center also provides detailed post-event analyses of problems in operational systems to determine the extent to which the space environment was a contributing factor (OFCM, 1997).

Current thinking about the need for observations of solar weather forecasts is based on solar wind gusts that originate at the Sun and travel through space to and beyond the Earth. The particle flux from a gust enters the Earth's upper atmosphere at the polar caps and propagates to lower latitudes in the ionosphere. To measure the sunspot activity on the disk of the Sun and the ejections of particles and plasma waves from the corona, solar observations will be made at and near optical wavelengths and in the microwave region. The solar wind in space will be observed by probes on the Advanced Composition Explorer (ACE) satellite at the Lagrangian point (about a million miles from the Earth in the direction of the Sun). Satellites of the Solar Terrestrial Physics "observatory" will supplement the ACE observations.[7] The entry of a gust into the upper atmosphere can be observed and the motion tracked by a chain of diagnostic radars in the arctic region. The technology for these observations is already in place. The National Science Foundation and the Air Force plan to build radars near the magnetic pole and near the auroral oval. GPS signals can be measured with space-based or ground-based receivers to provide information on the electron density structure of the ionosphere.

The data, in the form of plasma densities and their variations, solar wind speeds, and ionospheric electron densities as a function of time and position, will be fed to the Space Environment Center for assimilation and analysis. A model of the Sun's activity on the disk and in the corona, starting with current data, will project solar activity for one or two rotations of the disk. Outputs from the model of the Sun's activity will be the inputs for the model of the solar wind, which will predict the speed and density of the solar wind from the Sun past the Earth and estimate the arrival times of gusts at the Lagrangian point and at the Earth. The motions of solar gusts in the polar upper atmosphere will be validated and modeled as circulating winds and storms on the quiescent models of the polar cap (Matuura and Kamide, 1995). The Space Environment Center will use the models to prepare nowcasts and forecasts of space weather (Spotts, 1998).

Operators of satellites for communications and navigation, operators of high latitude HF communications systems, and the electric power consortia (the Electric Power Research Institute and the National Energy Research Center) will then be able to take appropriate remedial actions. The Space Environment Center will provide information on current space weather, warnings with an hour lead time, watches for the next few days, predictions of solar activity for the next month, and predictions of the 11-year sunspot cycle. The next sunspot maximum is expected to peak in late 1999 or early 2000, when annual average activity is expected to be the highest in the 128-year record. Severe geomagnetic storms are likely from 1999 to 2005 (Joselyn et al., 1997). Timely research on solar-terrestrial physics by universities and applications to impacted systems in industrial consortia and laboratories might mitigate the life-threatening and economic consequences of these storms.

ADVANCED FORECASTING TECHNIQUES

This section highlights four of the emerging techniques in forecasting that are closely linked to recent advances and unresolved issues in meteorology and hydrology: hybrid forecasting, probabilistic forecasting, distributed hydrologic modeling, and quantitative precipitation forecasting (QPF). Not every emerging technique is covered here. The selected techniques would substantially improve forecasting but will require advances through research or development, or both, to realize their full potential.

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[7] The satellite-based observing systems that will observe solar storms and solar wind gusts are described in more detail in a recent National Research Council report, *Readiness for the Upcoming Solar Maximum* (NRC, 1998d).

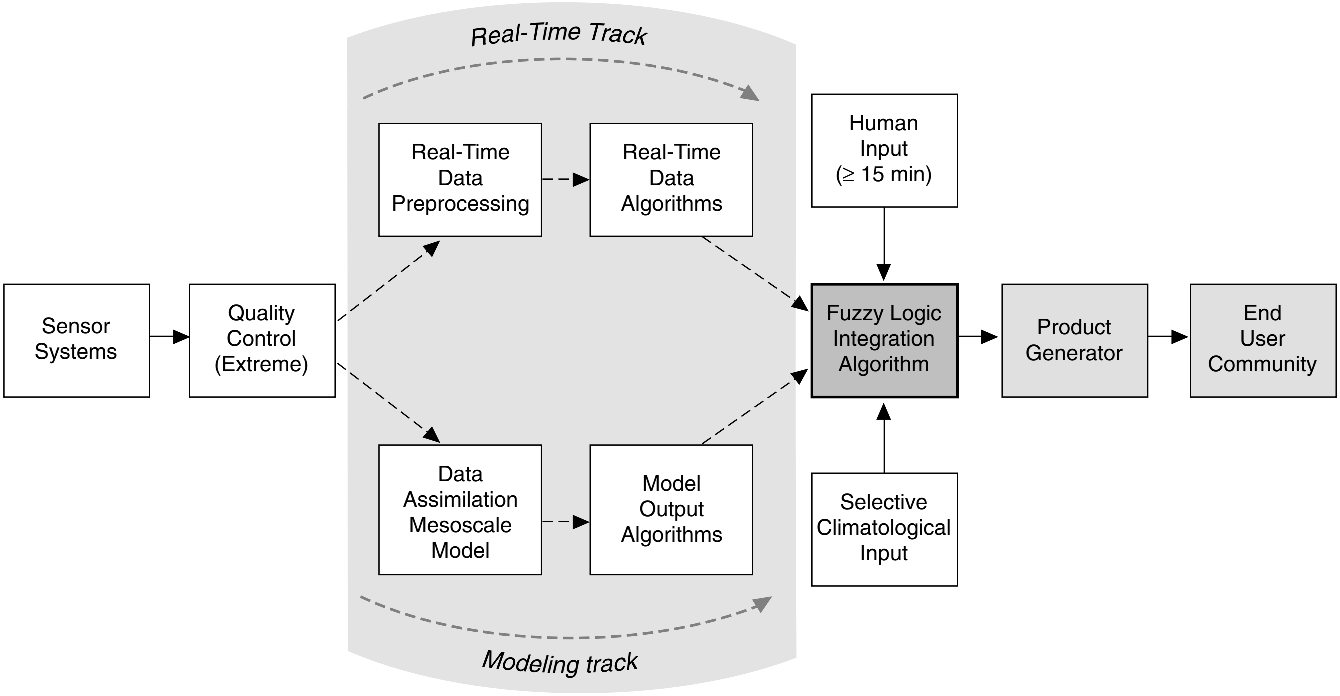

FIGURE 2-6 Using rule-based logic to develop specialized forecasts. Source: Wagoner, 1998.

Hybrid Forecasting

Innovative forecasting techniques combine observations, mesoscale NWP guidance, numerical modeling, climatology, and human input in expert systems that use rule-based or fuzzy logic interpretive schemes to develop specialized weather forecasts and products. Figure 2-6 illustrates this approach to hybrid forecasting. These *expert weather analysis and forecast systems* tend to eliminate the distinctions and separations among types of weather data and instead produce weather-related decision aids of direct interest to specific users.

An example of an expert system used for hybrid nowcasting is the Integrated Terminal Weather System (ITWS), which is being implemented by the Federal Aviation Administration for short-term, high-resolution forecasts and warnings in the vicinity of major airports (OFCM, 1997). This system uses data from multiple Doppler radars (NEXRAD, Terminal Doppler Weather Radar, and airport surveillance radar), surface observations from the Advanced Weather Observing System and Low Level Windshear Alert System, a lightning detection network, and measurements from sensors on aircraft. Observations from these sources are assimilated by the ITWS processor, which transmits forecast products directly to air traffic controllers as simplified graphic displays. These near-real-time displays are used to identify microbursts, low-level wind shears, gust fronts, storm location and motion, tornadoes, and strong winds in the terminal area. This type of integrated approach could be tailored to meet the needs of other users, such as the construction industry, road authorities, and managers of sporting events.

Another prototype for a hybrid nowcasting system for local or regional applications is the Automatic Thunderstorm Nowcasting System, which is under development at NCAR (NCAR, 1998a). This system integrates observations from radars, satellites, surface mesonets, and sounding data, together with numerical guidance, to predict convective activity every 30 minutes. Another system is the Wind Shear and Turbulence Warning System (WTWS), which is used at the new international airport in Hong Kong (NCAR, 1998b). Designed to produce forecasts and nowcasts of terrain-induced turbulence and wind shear, the WTWS uses the Terminal Doppler Weather Radar, wind profiler and other local observations, mesoscale model runs, and empirical results.

The promising results from these early systems indicate that hybrid forecasting will expand to serve a variety of users' needs. Expert weather systems could relieve forecasters at NWS field offices of the burden of examining diverse, asynchronous, rapidly changing observational data. Applications for hybrid nowcasting systems could include producing flash flood advisories, predicting the ground track for hail, or predicting the location of convective storms. In aviation, expert weather systems could quantify icing potential and forecast clear-air turbulence. In agriculture, one can envision the microscale management of water resources for irrigation based on soil moisture, precipitation measurements and forecasts, as well as hydrologic and crop models. Even with these expert analysis and forecast systems, people will play an important role by adjusting data inputs and exercising overall quality control. Moreover, their experience with the use of these systems will be a key element in the continuing development of improved systems and new applications.

Nowcasting systems that assimilate multisensor estimates of precipitation fields and then make statistical extrapolations can quickly produce multiscale estimates of near-term precipitation. With an expert weather system for nowcasting, the season of the year, local topography, and local climatology can all be factored into the nowcast of precipitation. These precipitation estimates will in turn provide crucial input to local and regional hydrologic models.

Probabilistic Forecasting

NWS has issued probabilistic forecasts of precipitation for more than 20 years and of hurricane strikes for nearly 10 years. In the future, probabilistic forecasts will become increasingly important because of both the growing number of uses for which probabilistic information will be beneficial or even essential (application pulls) and the capability to produce better forecasts (technology pushes). The panel foresees rapid growth in this area fostered by a combination of more sophisticated forecasting techniques and better ways of presenting probabilistic forecasts to decision makers.

The enabling technologies for probabilistic forecasting include improvements in modeling. For example, models could provide confidence limits as part of the gridded forecast results. Ensemble forecasting will improve as multiple model runs based on slightly different initial conditions become available.

Probabilistic representations of observational data—for example, radar data—will be available for direct use by customers. Probability data will also be used as input for meteorological and hydrometeorological models by NWS and other forecasters in the expanding weather information network.

Customer demand will determine which forecast results are represented as probability distributions and how distributed results are represented. Emergency managers, who are becoming skilled in risk management based on probabilistic decision aids, will be looking for probabilistic results from NWS that can be used as direct inputs to these computer-based tools. The business and financial communities can be expected to take the lead in developing new risk management techniques that incorporate probabilistic observations and forecasts. The increasingly sophisticated models used by insurance companies, commodity futures brokers, and transportation and energy companies (to name a few examples) will require large domains of information, including weather observations and forecasts.

Potential uses of probabilistic warnings include predictions of flood stages based on hydrologic modeling for river and larger stream systems, and flash flood warnings. Probabilistic forecasts of the severity of large-scale winter storms can be communicated to public authorities who have to decide whether or not to make emergency preparations. Forecasts of seasonal variations from climatic norms will become increasingly important for business planning. Climatic trends, such as "global warming" or changing regional precipitation patterns, will be represented in probabilistic terms, first to establish the existence of the trend, then to describe the amount of change over a given period.

Advanced Hydrologic Forecasts and Warnings

Hydrologic hazards, such as flooding rivers and flash floods, will continue to pose serious risks to people and property. New user requirements will also emerge, especially in terms of assessing and ensuring water quality and long-lead predictions to facilitate decisions for managing sectors and activities that are sensitive to hydrologic variations. To take advantage of the opportunities created by advances in science and technology, the NWS should continue the integration of meteorological and hydrologic data and modeling that began during its modernization and restructuring.

Ground Hydrology Modeling Based on Spatial Distributions of Physical Conditions

Recent scientific advances and technological innovations have led to a fundamentally new approach to operational hydrology and the difficult problem of hydrologic forecasting. A new generation of hydrologic models will be based on characterizing the spatial distribution, over a drainage area, of physical hydrometeorological and hydrologic processes. Distributed hydrologic modeling should replace the spatially lumped soil moisture accounting approach still used by the NWS. Besides being more realistic, the next generation of models will yield an entirely new suite of forecast products.

By assimilating recent observations of soil moisture, groundwater level, and snow pack conditions from monitoring sites into mathematical representations of the controlling physical conditions, the stage or flooding level in streams and rivers can be forecast with spatial and temporal continuity. In other words, a forecast over time can be made for any node or link in the drainage network. This approach to hydrologic forecasting will provide a unified and consistent approach for forecasting both mainstem floods and flash floods of smaller streams. Forecasting of flood hazards would be continuous, from flash floods with lead times measured in hours, to river floods, with lead times of days or, for snow melt, weeks.

Distributed hydrologic models can be scaled to both smaller and larger basins and can be transferred to other basins, if the same physical processes apply. Differences related to scaling or transfer would be captured in the observational data sets used to initialize the model, rather than being expressed intrinsically in the modeled relationships, as they are in soil moisture accounting.

Another advantage of distributed hydrologic modeling is its capability to assimilate estimates of precipitation fields derived from radars, satellites, and surface observing systems. These estimates, which will have high spatial and temporal resolution, can capture the mesoscale structure of rain intensity, which will have significant implications for estimating the magnitude and timing of floods.

Broader Applications of Distributed Hydrologic Modeling

In addition to mitigating flood risks, distributed hydrologic information (e.g., soil water contents, snow pack conditions, groundwater levels, and river stages) will become much more useful to customers. Forecasts of river discharge at every link in a drainage network will help water resource managers and utilities to optimize delivery operations. Detailed predictions of water levels and flows for an entire drainage system will help managers ensure the quality of water and protect habitats (e.g., fish populations and wetlands). Distributed models of soil moisture can be fed into hydrologic analyses of groundwater levels to manage the transport of environmentally significant chemicals (e.g., nutrients, pollutants, and indicators), as well as to support models of the ecological roles of soil moisture and waterborne chemicals.

Distributed hydrologic modeling could also significantly improve meteorological forecasts. Mapping and monitoring soil water across the landscape will improve the utility of NWP models by providing initialization fields for land surface, as long as the variables in distributed hydrologic models and NWP land surface parameterizations are compatible. The results of a run in one model would provide initializing and boundary conditions for the next run of the other model type. Atmospheric and soil moisture models would be especially beneficial during the summer months when convective storms are affected by buoyancy near the surface. Correct initializations for soil moisture will improve predictions of surface flux (e.g., latent heat and sensible heat) and changes in meteorological and climatological forcing factors on virtually all scales. The NWP model will produce ensemble fields for QPF, which will extend the lead time of hydrologic forecasts and make probabilistic forecasts feasible for both precipitation and drainage flow. Even fire weather forecasts will be improved by information on soil water and vegetation status, which can be derived from the distributed hydrologic model.

Potential Extensions to Models of Physical Processes

Sophisticated distributed hydrologic models will include soil physics and vegetation processes. Thus, auxiliary sets of data relevant to soil science and terrestrial ecology, such as surveys of soil texture and remotely sensed conditions of vegetation canopy (structure and photosynthetic function), could replace the empirical fitting parameters of soil moisture accounting models. Spatial snow pack conditions in a distributed model, as well as the soil moisture fields, could be initialized and updated using satellite measurements

Ultimately, distributed hydrologic models will be fully integrated with regional NWP and nowcasting models for atmospheric processes. Data assimilation (input) and forecast integration (output) could be made fully compatible across this suite of interactive models. The regional land-atmosphere or hydrometeorological system could also incorporate, or could be linked seamlessly to, user applications, such as models of water quality, reservoir operations, and urban hydrology.

Quantitative Precipitation Forecasting

Although QPF is not a new forecasting technique, the utility of these high-resolution forecasts of the geographic and temporal patterns of precipitation intensity and type could be greatly improved. Although skill scores for QPFs have steadily increased over the past 30 years as a result of improvements in both NWP and the characterization of atmospheric fields, the scores are still relatively low (Olson et al., 1995; see Figure 2-4). Emerging observational technologies and advances in modeling will significantly improve the accuracy and reliability of QPFs in the next quarter century.

Multisource upper-air observing systems will capture more of the small-scale features and sharp variations in atmospheric conditions that are critical for accurate representations of thermodynamic fields in storm-scale models, which could predict the track and evolution of precipitating systems. These small-scale features are essential for extending the time of short-term precipitation forecasts beyond their current limit of several hours. Better characterizations of three-dimensional water vapor may be the largest single contributor to improving QPFs. If radar and satellite precipitation measurements could be included in data assimilation schemes, the tightly coupled system of observations and high-resolution, storm-scale models would improve forecasts of precipitation between the one-to-two hour nowcasts and the one-to-three day forecasts based on NWP models. For longer forecasts, the specifications for surface-condition parameters and boundary conditions would increase skill scores for QPFs of less than 12 hours.

IMPLICATIONS FOR THE NATIONAL WEATHER SERVICE

Advances in three essential areas—observational technologies, computational technologies, and scientific understanding—will contribute to the development of more sophisticated analysis and forecasting techniques and more accurate, precise, and reliable numerical forecast models (NRC, 1998e). To realize the enormous potential of these capabilities for providing weather, climate, and other environmental information to a variety of customers, the NWS and NOAA must address a number of issues related to new observational systems, the acquisition of state-of-the-art computer systems, scientific research, and the development of advanced forecasting techniques (Dutton et al., 1998).

Upgrading Observing Systems

Despite the sophistication and elegance of existing observational systems, they cannot meet the growing need for accurate forecasts and warnings at higher spatial and temporal resolutions. *In fact, no single instrument or platform will be able to provide all of the necessary meteorological observations.* A combination of instruments and platforms will provide the most cost-effective and accurate total system. Recent studies (e.g., Stankov, 1998) have shown that systems that integrate measurements from multiple, diverse, remote sensing and in-situ instruments provide a better estimate of the true state of the atmosphere than any single instrument. Thus, emphasis at the NWS should be on developing a total system of synergistic, cost-effective instruments and platforms.

This development effort should begin by obtaining maximum benefit from the existing suite of remote and in-situ measurement systems. In pursuing this goal, the NWS must achieve four objectives:

- Make the resource commitments necessary to ensure that all data are of the highest possible quality and accuracy. For example, NWS must receive and commit the resources necessary to maintain and calibrate all of its sensing systems in accordance with the standards set for their performance.
- Develop new single and multiple parameter interpretative techniques applicable to the existing observing systems and the full suite of observations obtainable from them.
- Develop more comprehensive methods for assimilating the entire suite of observations into coupled NWP models that make full use of this information.
- Provide sufficient fiscal and staffing resources at NWS field offices and centralized facilities to progress rapidly in realizing the full potential of the technical systems already in place.

Realizing the panel's vision of weather services in 2025 will also require many improvements in observing systems:

- Future observing systems must fill the existing gaps in data fields, including data from remote regions, especially over the oceans and the poles. New systems and techniques, such as observations from GPS/MET satellites, should be considered and tested. In addition, much higher resolution NWP models will require a higher density of point observations and higher resolution of remotely observed fields in all three spatial dimensions and in time.
- Techniques for making quantitative observations of certain variables or characteristics that are now observed poorly, or not at all (e.g., vegetation, soil moisture, or the amounts of water and ice in clouds), will have to be improved or developed.
- Asynchronous data and observational information from "platforms of opportunity" will have to be used more effectively. Better ways are needed for using directly observed, measurable characteristics (such as satellite-observed radiances or atmospheric refractivity) in the forecast process.
- The evaluation of existing and potential observing instruments individually or as part of an integrated instrument suite should be conducted systematically. These evaluations are generally conducted by means of observing system simulation experiments, in which the observations from one or more instruments are assimilated into NWP models to determine the improvements in predictive skill.

To facilitate evolutionary, incremental upgrades in technology and the transfer of new observational developments into operations, the NWS will have to improve its capabilities for rapid prototyping and system testing. One of the lessons from the NWS modernization is that an evolutionary approach to upgrading technology is preferable to the NWS's past approach of making radical overhauls after years of minimal improvements. An incremental approach will require that the NWS, as well as the research and user communities, be willing to give up obsolete, or sometimes still useful, operational technologies or practices to free human and fiscal resources for newer, more effective technologies and practices.

Regaining and Maintaining State-of-Practice Computer Facilities

The panel is concerned that NWS computer capabilities at NCEP have fallen well behind the state of practice as represented by the capabilities of meteorological centers of many other industrialized nations (Table 2-3). One ominous consequence is that NCEP can no longer develop, test, and run the NWP modeling systems with the highest resolution and greatest accuracy and completeness in representing important physical processes, such as precipitation, radiation, turbulence, and atmosphere-ocean interactions. The issue is not one of "keeping up with the Joneses," in the sense of merely indulging national or institutional pride in having at least as much new technology as other weather services. Rather, the issue is the value of having adequate computer power to provide the most beneficial information to the U.S.

TABLE 2-3 Supercomputing Capabilities at Operational Weather Prediction Centers, March 1998[a]

Meteorological Forecast Center	Vendor	Machine	Number of Processors	Effective Speed (gigaflops)
North America				
U.S. NWS (NCEP)	SGI/Cray	C916	16	5
US. Navy NAVOCEANO[b]	SGI/Cray	T3E-900 (primary)	544	47
	O200	128	13	
	T932	12	15	
U.S. Navy (FNMOC)[b]	SGI/CRAY	C916	16	5
Canada	NEC	2 SX-4/32	64	48
Europe				
European Union (ECMWF)	Fujitsu	VPP-700	116	80
Denmark	NEC	SX-4/16	16	10
France	Fujitsu	VPP-700	40	28
Germany	SGI/Cray	T3E-LC400	432	26
United Kingdom (U.K. Met Office)	SGI/Cray	T3E-900	840	76
Asia-Pacific				
Australia	NEC	SX-4/32	32	24
Japan	Hitachi	S-380	4	10

[a] Sustained performance is calculated as 31.25 percent of peak performance for vector machines and 10 percent of peak for the massively parallel T3E machines.

[b] NAVOCEANO = Naval Oceanographic Office; FNMOC = Fleet Numerical Meteorology and Oceanography Center.

Sources: The information was compiled by members of the panel from information provided by Bill Buzbee, Director, NCAR Scientific Computing Division, from various websites on the Internet World Wide Web, and from personal communications with individual forecast centers.

public and to U.S. economic interests through state-of-the-art operations for centralized data assimilation and forecasting.

History shows that improvements in NWP forecasts are directly related to increases in computer power. Unless the NWS is committed to maintaining state-of-practice computer capabilities in NCEP operations, it will be unable to meet the needs of users for more accurate and precise weather forecasts, especially for longer forecast periods. Consequently, the nation will not reap the full benefits of its ongoing investment in weather observations and weather forecast research. Failure to invest in NCEP computers will limit the availability and accuracy of day-to-day forecasts (one day to the limits of deterministic predictability) and forecasts of large-scale climatic events, such as the El Niño Southern Oscillation and its associated weather patterns. Because of the importance of using accurate boundary conditions from global models to run local or storm-scale models, these limitations will also affect the entire forecast and warning system.

There appear to be two principal obstacles to relieving the computational bottleneck: (1) delays in budget appropriations for the acquisition of NCEP computers, and (2) fewer technology options for NCEP than are available to forecast centers in other countries. These are serious problems, and the NWS must work with NOAA and the U.S. Department of Commerce to communicate the consequences to the administration and congressional authorizing and appropriating committees. A common understanding among these parties will be essential for exploring effective, practical, politically acceptable solutions.

Advances in Scientific Understanding

The major requirements for accurate NWP forecasts are more improved model physics, more complete global observations, and adequate computer power. If computer power continues to double about every 18 months, and if the NWS has access to the world's most powerful computers, the first requirement would be met. The only feasible way to obtain accurate observations worldwide, at the required temporal and spatial densities, is through remote sensing. Thus the NWS should support the rapid development, testing, and deployment of innovative remote sensing concepts, including those based on microsat technologies. The expeditious implementation of these technologies will require that NCEP's research staff be able, first, to develop and test the data assimilation schemes for using the new observations, and second, to evaluate their impact on forecasts. In the judgment of this panel, based on familiarity with NCEP staff and budget resources, current NCEP resources in the critical area of research and implementation on data assimilation are woefully inadequate. To reap the practical benefits of the nation's substantial investments in satellite and ground-based remote sensing systems, data assimilation capabilities at NCEP and other operational weather centers will have to increase significantly.

To address the limitation in model physics, the NWS should take advantage of extensive research at universities and national laboratories on realistic, accurate parameterizations of physical processes. Known limitations in NWP models include the treatment of the physics of clouds and precipitation, long-wave and short-wave radiation, boundary layer processes, and most important, the interactions among them. The NWS need not take the lead in research, but it should enter into partnerships with the research community, through programs such as the U.S. Weather Research Program (USWRP), for the development and rigorous testing and evaluation of promising new data sources, models, analysis techniques, and physical parameterizations.

The forecast techniques and models for predicting both chemical weather and space weather are much less mature than those for predicting conventional weather and for issuing warnings. Improving forecasts of chemical weather and space weather will require significant research in observational techniques, data assimilation, and model development and testing. The NWS roles should be to: (1) work with the research communities in developing and evaluating prototype numerical forecast models and (2) as soon as possible, begin making and verifying experimental forecasts based on the best available models. For chemical weather predictions of air quality, NOAA and the NWS should coordinate and expand partnerships with the Environmental Protection Agency and other federal, state, and local governmental entities to determine observational and forecast needs and the best ways of disseminating chemical weather information and air quality warnings.

Advanced Forecasting Techniques

Advances in artificial intelligence and knowledge representation have led to the development of smart weather information systems, which combine data from many sources, model predictions, climatology, and statistics to produce more accurate forecasts than can be produced by a single model or forecasting technique. The panel expects that hybrid nowcasting methodologies, as well as probabilistic forecasting techniques, will proliferate in the years ahead. The NWS should support (with budgetary and personnel resources, as appropriate) and strongly encourage the development, testing, evaluation, and implementation of these systems.

The NWS will have to adopt innovative approaches to the development, implementation, and support of distributed hydrologic models; the assimilation of data into these models from the full suite of radar, satellite, and surface observing systems; and the integration of hydrologic models with atmospheric models. In an earlier report, the National Weather Service Modernization Committee recommended that the NWS increase its efforts to meet these objectives (NRC, 1996a). The NWS should look forward to what needs to be accomplished, rather than looking back to what has been considered acceptable. The computer technology required to implement and run these large numerical models is at hand. The scientific basis for the models has been advanced by the research community. But the implementation of advanced forecasting systems will require greater support and commitment by NWS managers and greater attention to operational applications and training of NWS field staff.

3

Providing Weather and Environmental Information Services

"Environmental information" includes not only meteorological and hydrologic observations, analyses, and forecasts but also other indicators of physical, chemical, and biological phenomena relevant to the functioning of ecological systems, including human communities. The panel expects the value of environmental information to increase greatly as it becomes more useful and reliable in meeting the diverse needs of a broad base of sophisticated users. These users will depend on advanced information technology to select and receive information of interest. As science and technology improve the accuracy of environmental forecasts, the market value of environmental information will increase. There will be major consequences for the NWS and other organizations in the public and private sectors, as well as for individuals. The chapter includes scenarios to illustrate four factors that will influence which consequences occur: (1) the rate of progress in science and technology, (2) the economic value of environmental information, (3) government policy and budgets, and (4) international cooperation on information exchange.

If current trends continue, a broad range of environmental information services may soon be available. As computer modeling and the automated processing of meteorological data advance, the workforce, both public and private, in the weather-related sciences will change. Partnerships among government organizations and private-sector companies will become more widespread and will alter the roles for the NWS and its partners in providing environmental information to the nation.

Although the panel does not expect the mission of the NWS to change (see Assumptions in Chapter 1), the resolution, quality, and reliability of weather observations, forecasts, and warnings will improve dramatically. The amount of data available to users will increase by many orders of magnitude, by virtue of much higher spatial and temporal resolution and the integration of complementary environmental information. These vast data resources will be widely available, as the capacities and capabilities of local, regional, national, and international information networks expand.

The availability of this information base will set the stage for a great expansion in the number and diversity of secondary providers, both public and private. As the services of secondary providers expand, the NWS will need to participate in diverse partnering relationships. The partnerships will range from collaborations for integrating national and global data with local and regional data to agreements establishing new data interfaces, based on emerging technology, through which NWS services and products can be disseminated.

In the following sections, the term "provider network" refers to the totality of governmental, commercial, and nonprofit outlets for environmental information that supply users in both the public and private sectors. The terms "user" and "customer" are used interchangeably.

CUSTOMERS AND PROVIDERS OF WEATHER INFORMATION

As the recent modernization of NWS technology and operations nears completion, the various communities of information users are already reaping benefits from the improved observations, data assimilation, and modeling. The print and television broadcast media, often with the help of private meteorologists, have been instrumental in communicating NWS forecasts to the general public via increasingly sophisticated and effective graphical representations of weather information.

Weather information has also become a more serious competitor for consumer attention. Weather reports, which were once a few lines of text buried in the daily newspaper or a brief announcement at the end of a television news program, are now major features in both media. Responding to media coverage of the current debate on global climate change, the consequences of the latest El Niño cycle, and the relation between severe storm warnings and risk reduction, the public is more aware than ever of the importance of weather and climate to our daily lives and economic well-being.

NWS products also reach a variety of user groups with differing information needs: emergency managers at all levels of government, economic sectors that are heavily dependent on weather (for example, aviation and agriculture), and private firms that use weather information in conducting their business. The issue of who should provide services to these emerging market segments is being debated, especially in terms of the appropriate "service territories" for the NWS, other federal and state agencies, and private providers of meteorological services. The debate is likely to intensify as the economic value of environmental information increases and market incentives for new, specialized products and services become strong enough to interest commercial providers. Programs for new applications, such as intelligent-highway initiatives, are beginning to combine weather-related information with other application-specific data in their planning and decision making. The emergence of customers in the transportation sector has led to new customer and provider coalitions that include state and local governments and a variety of private businesses. The needs of emerging customers have created enormous opportunities and challenges for the private and government sectors to work together to provide services for the protection of life and property and to further economic growth.

The panel foresees the following outcomes as reasonable projections of these trends. Services and products from the provider network will multiply and proliferate in response to growing demands from existing customers, while new customer segments will emerge as new and improved products and services become available. As the NWS improves its capabilities to observe and forecast the weather, a major challenge for the environmental information system will be to disseminate this information quickly in forms that a diverse and segmented public can understand and respond to rapidly.

Customers in 2025 will be considerably more knowledgeable about weather and environmental forces than their counterparts in 1998, and they will be more sophisticated in using this information in their professional and personal lives. Future customer communities will demand access to a wide range of information from multiple sources. Graphics combined with text and audio communication will provide information to the general public, as well as to decision makers in government agencies and businesses. More individuals and businesses will use information networks to select what they need from widely distributed information sources. In addition to receiving prepackaged information products intended for broad dissemination, these information consumers will be able to select highly processed information tailored to meet their personal or institutional needs (NRC, 1996a).

Environmental information, both global and local, will become part of the international information infrastructure that individuals and organizations use on a daily basis. Business customers will use worldwide environmental information to plan operations in the global marketplace. At the same time, customers will also require information for specific times and places. Location-specific business decisions, such as when to start pouring concrete in a construction project or whether to shut down operations in response to tornado or hurricane warnings, will be made with the help of decision support systems that include environmental data targeted for a specific place and time.

The burgeoning customer base for weather and environmental services will include new economic sectors and populations; customers who are underserved in 1998 will become active consumers of new services made possible by the continued growth of the information economy. Health-related environmental forecasts will be available to help vulnerable individuals manage illness, disability, and their daily activities. The banking and commodities sectors will use sophisticated algorithms to manage speculative risks. Resource managers in the public and private sectors will routinely use weather and other environmental information to allocate physical resources, such as water and power, as well as public services, such as emergency room facilities and police forces. Economic sectors that are already active users of weather forecasts, such as the aviation, marine and agricultural sectors, will develop even more sophisticated ways of using weather and environmental information.

Environmental information services will develop as markets, applications, and public needs emerge. As the services and products become more complex, organizations will increasingly function as both providers and customers in the flow of information through society.

WEATHER INFORMATION IN AN INFORMATION ECONOMY

Given the rapid changes of the past three decades in information technology and in the ways this technology has transformed how we communicate and use information, one can expect that future weather information services will differ from today's in ways we can scarcely imagine, much less predict with confidence. However, two major driving forces are already present and will continue to have a substantial influence at least until 2025.

First, the United States and much of the world are shifting from an industrial economy to an information economy. Second, with progress in meteorology, hydrology, oceanography and associated technologies, weather observations and forecasts are becoming products with substantial economic value in everyday decisions. In the information economy, the major component of economic growth will be *information* *as an item of commerce*, information that is gathered, packaged, and distributed according to its economic value to various markets.

During the past decade, attention has focused on constructing an *infrastructure* to support the flow and use of information. This infrastructure will continue for at least another decade and will result in a strengthened infrastructure that will include computers as sophisticated information handling nodes in communications networks; a global Internet for the low-cost transport of information; microprocessors that add "intelligence" to the growing range of products, tools, and services; the World Wide Web as an electronic medium for the global village; and the fusion of audio, graphical, video, and digital communications through interchangeable, interconnected modes of transmission (e.g., digital telephony and interactive video, wireless digital communications, and computer-mediated multimedia messaging). Almost everyone in 2025 will take this infrastructure for granted, just as we now take for granted indoor plumbing, household electrification, and the national highway system. Their attention will focus on the information that passes via the infrastructure, rather than on the infrastructure itself.

Signs of the growing economic value of weather and climate information are less often acknowledged, but they are pervasive. Individuals and organizations are increasingly willing to make significant economic decisions based on weather forecasts that, even a decade ago, were not reliable enough to "bet on." In 1997 and 1998, many energy companies made significant investment plans based on predictions of the effects of El Niño on weather conditions in the eastern United States. In some cases, newspapers in New England have printed headlines about a coming winter storm, even though the source of the storm was still in the Gulf of Mexico, several days away. On a smaller scale, individuals are more likely to alter weekend or travel plans based on three-day to five-day forecasts than they were just a few years ago.

User Needs

To understand how and why the uses of environmental information will change over time, one must move beyond thinking of information in terms of what it is *about* (e.g., meteorological and hydrometeorological information) and think of it in terms of *how it will be used*, that is, the uses that will develop into economic markets for information as a commercial item. For example, commercial providers of weather observation and forecast data already think of users in terms of economic sectors, such as aviation, energy, agriculture, or surface transportation. Although the accuracy of three-to-five-day forecasts as represented by reductions in forecast errors may be a useful benchmark for measuring meteorological forecast skill, these measures may mean little to a potential information consumer who only wants to know how the information can help solve a problem or improve business. Thus, traditional measures of the quality of forecasts or warnings may not capture the utility of information for customers. As weather information becomes more accurate, the familiar weather forecast products will be augmented, or even superseded, by *information in the form of decision-support aids* tailored for business, public, and personal decisions.

The What and How of Information

For application-specific products and services, weather information will be integrated with other environmental, economic, and technical data to produce information products that (1) describe the current status of a relevant situation, (2) forecast relevant conditions, or (3) provide a combination of observational and probabilistic data to aid in decision making. This integration represents a marked change from the past.

Integration of Gridded Data Types

Until recently, weather data and other environmental data were separate data sets based on the type of environmental phenomena observed (for example, weather data as distinct from data on vegetation and soil moisture, which were distinct from data on air and water quality). These data sets remained distinct (in separate "stovepipes") throughout the process leading from the base observations through assimilation and prediction to information products that contained predictions about *phenomena of the same type*. These data on diverse phenomena are relevant in various combinations to specific applications. In the future, they are likely to become available in a gridded format linked to one or more common frameworks.

Computer-based data processing will be essential for integrating gridded data sets that describe diverse phenomena. As the algorithms at the core of the model become better at representing (or at least providing a quantitative analog for) the underlying physical, biological, and socioeconomic processes being simulated, and as the computational power of the hardware increases, *computer-based modeling will become the best way, and eventually the only way, to produce high-quality, useful products*.

The channels through which information commodities will pass from provider to user and the formats for representing the information will continue to evolve. Gridded data, including observations, analyses, and forecasts, are likely to become a powerful and convenient way to transfer information from a provider to the next user in line without losing spatial and temporal specificity. Graphical representations of forecasts, particularly moving representations like the time loops used in forecast workstation displays and on television weather reports, can be readily created from gridded data to meet the needs and interests of consumers. Digitized imagery—similar to current satellite images, graphical displays of radar data, or forecast workstation composite images—will be another format for transmitting large volumes of high-resolution data.

Spatial and Temporal Scales

The spatial and temporal scales at which data are needed will depend on the application. For example, probabilistic forecasts of deviations, on seasonal and interannual time scales, from climatic norms on a regional scale will be valuable for businesses with seasonal variations in supply or demand. By contrast, forecasts of severe weather tracks will be on time scales of hours (for mesoscale storms, whose spatial scales are several kilometers or less) or days (for tropical storms, forecast at scales of hundreds of kilometers). But these examples only reflect the spatial and temporal scales of weather-related information. Other data being integrated for a specific application may be on the same or different spatial and temporal scales as the weather data. Data sets for an integrated model may describe environmental parameters, such as soil and plant moisture levels, vegetation or crop types, or pest and vector populations. Economic and business data may relate to the supply of, and demand for, affected products or to the risk distributions associated with the utility of the product.

Implications of Automation

The history of numerical modeling in the NWS forecast process illustrates the evolution of computer-based information processing. As computer power has increased and human experts have developed better algorithms (software), the meteorological models routinely run at NCEP and the hydrologic models run at river forecast centers have become more precise on finer spatial and temporal grids. Local forecast meteorologists or hydrologists can still add value to the predictions produced from these models. However, the time interval within a forecast for which human experts add value by modifying the model output is becoming shorter.

Automation will change but not eliminate the role of people in weather observation and forecasting. In the future, highly skilled experts will be needed for interpreting nonrepetitive data or for ensuring that unusual circumstances (those not covered by the processing rules) are taken into consideration. Many complex modeling processes, whether implemented as algorithms or as sophisticated rule sets and inference engines, could fail under previously untested conditions. Human quality control will therefore continue to be necessary to check the basic realism of the output, especially in situations involving unusual or catastrophic weather. Most important, of course, continued refinements and improvements of the models will depend on human expertise.

Implications of the Increasing Commercial Value of Environmental Information

As the commercial value of weather information increases, the current debate about the public versus private delivery of information will be settled in part by economic realities. As the information (particularly forecast information) *becomes reliable enough to make a difference in economic decisions*, individual and corporate buyers will demand more specialized services. A broad range of commercial providers will step in to supply these needs.

New and more sophisticated means of providing individuals with information specific to their needs will create new commercial opportunities. The resulting new channels for communicating information can also be used to communicate relevant emergency weather warnings to targeted audiences. Individuals and organizations can thus receive information they want without being overloaded with irrelevant information. One can easily imagine, for example, an electronic "personal assistant"—a sophisticated descendent of today's pagers, cellular phones, and palm-top computers—that would receive emergency weather alerts along with many other types of information. Weather alerts would be based on the user's current location and other user-specified locations of interest, such as the locations of family members or business interests.

Sources of Uncertainty

The major driving forces arising from the information economy and progress in science and technology will dominate the evolution of weather information services for the next three decades. Nevertheless, no one can predict with certainty the consequences of these forces because significant sources of variability and uncertainty will influence the responses to the creation of information commodities in an information economy. In Boxes 3-1 through 3-4, the panel uses alternative scenarios to illustrate four sources of uncertainty: (1) the rate of progress in science and technology, (2) the change in economic value of reliable environmental information, (3) government policies and expanding or shrinking budgets, and (4) the degree of international cooperation on exchange of observational data. These scenarios are provided to alert planners to the range of variations in scientific, economic, political, and international conditions relevant to the panel's vision for 2025.

PRESENT AND FUTURE ROLES OF INFORMATION PROVIDERS

To illustrate how the creation and distribution of weather information products and services are likely to be affected by increases in the value of environmental information, the panel developed a description of how such information is currently provided and a vision of how environmental

BOX 3-1
Progress in Science and Technology

A strong market for environmental information products and services will develop only if the information is reliable enough to influence choices with real economic consequences. Once that point is reached and the market "takes off," the financial resources available in the private sector for providing reliable information will dramatically increase. The panel believes that scientific and technological progress will be rapid.

In the panel's scenario for *rapid scientific and technical progress*, this change will occur soon (within the next decade) for forecasts of a variety of key weather and climate-variation factors. The quantity and variety of products and services increases as new providers enter the market, which is driven by the demand for reliable information. Initially commercial providers continue to use observations and model data from NWS, other government agencies, and entities supported by foreign governments. When better forecast data or better (e.g., more timely, denser coverage) observational data can be acquired through more capacity or advanced technology (observing instruments or platforms, computing capacity, model resolution, etc.), commercial suppliers may take on new roles, such as operating observing systems or providing specialized numerical forecasts of the environment. NOAA and the NWS (as well as other suppliers of environmental information) may decide to purchase some observational data or model output from commercial vendors. For the environmental provider network as a whole, and for the NWS, products and services of greater economic value are produced and disseminated at lower cost.

In the panel's scenario for *slow scientific and technical progress*, the reliability of weather and climate-variation forecasts improves only marginally over time. The national (and global) network for providing weather services and products grows modestly. Some companies survive as they do now, by tailoring application-specific forecast products from NWS observational data (radars, satellites, and surface observations) and NCEP model output. The cost of operating observational systems and state-of-the-art modeling capacity on a global or regional scale is too high, relative to the expected return on investment, to stimulate private-sector growth, except for niche markets and high-value specialized services.

information and services may be provided in 2025. At present, weather forecast offices (WFOs) provide observations, forecasts, and warnings to entities in both the public and private sectors and to the general public. The NWS national centers provide products (observational data and model output) to the WFOs and to public and private entities. Direct dissemination to the public is limited essentially to NOAA Weather Radio and, recently, Internet services. NWS forecasts, warnings, and watches are disseminated to most of the public through private broadcast and print media.

In addition to the broadcast and print media, other markets for commercial providers of weather information have emerged in recent years. Commercial providers now sell several hundred million dollars worth of specialized products and services annually. These providers rely largely on the NOAA Family of Services (described below) as their source of observational and forecast data.

Public-private partnerships are increasing and are providing better service to the public. Most of them are involved in planning for and responding to emergency situations, but there is also an emerging market for specialized services, such as the Oklahoma Mesonet (Brock et al., 1995) or the provision of weather information for special events like the Olympic games.

Changes in information provider roles will depend on how the developing information economy and the rate of progress in science and technology affect the existing network. One significant change will be a greatly expanded role for providers of application-specific products and services to customers in a broad range of market segments, most of which do not yet exist in the 1998 network. A second significant change will be new dissemination nodes, which will be distribution hubs on the national infrastructure for electronic communication, the descendent of today's Internet. These dissemination nodes will provide more than weather or climate information; they will resemble "supermarket" versions of present sites on the World Wide Web. For example, a dissemination node might include information on road construction schedules, soil moisture and vegetation conditions, air quality, and traffic congestion. Many of the commercial providers of application-specific products and services will probably use these dissemination nodes for distributing and marketing their products to customers.

The overall network will be many times larger than today in the quantity and diversity of information flowing through it, the categories of providers or consumers, and the number of participants in each category. Sources of data will increase to supply consumers' demands for integrated information

BOX 3-2
Economic Value of Environmental Information

Uncertainty about the future value of environmental information is an important reminder that scientific and technical progress alone cannot give commercial value to information. Based on the trend of the past 50 years, the panel believes the future will more closely resemble a scenario of increasing economic value than one of decreasing economic value, although some technological or societal changes might decrease the potential economic impact of environmental fluctuations.

In the panel's scenario for *increasing economic value*, more and more ways are found or created to use information profitably. For example, airlines and the Federal Aviation Administration demonstrate that real-time nowcasts, incorporating data from local and aircraft sensors and combined with differential-GPS navigation aids, substantially improve the safety and reliability of instrument landings, thus helping increasingly busy airports to avoid delays. Climate-variability forecasts, improving on the success of the 1997–1998 predictions of the El Niño cycle, have a significant economic impact on the deregulated power industry. Users of the information learn to assess their exposure to economic consequences, positive and negative, of the conditions being forecast. For example, insurance companies find a competitive advantage in being able to price real estate insurance, and even motor vehicle insurance, according to interannual climate-variation forecasts. The increasing value of this information spurs development of new uses for environmental information and new market segments. The environmental information infrastructure grows in response to the perceived value of the available information products.

In a scenario with *decreasing economic value*, new technology or societal trends make environmental information less valuable by decreasing the sensitivity of economic decisions to environmental information, even when reliable information is available. For example, radical changes in national and state policies restrict or reverse floodplain development, while the U.S. Army Corps of Engineers devises more effective ways to control river flood damage through expanded wetlands and "controlled flooding" of undeveloped floodplains. Changes in building codes, together with new construction technologies, substantially reduce heating and cooling demands for power, as well as the likelihood of wind and hail damage in all but the most severe storms. One effect of this scenario on the environmental information network is much slower differentiation of markets for specialized products and services. Although more reliable observations and forecasts have increased value in established applications, there are fewer opportunities for profiting from new kinds of decision aids.

that meets their personal and business needs. Innovative partnerships that integrate diverse data sets to meet specific customer needs will probably be the norm. Channels for providing data to consumers will also be more diverse, including not only the media and the successor to the Internet, but also "point casts" via wireless communications, to users in homes, businesses, and vehicles. There will also be sophisticated computer programs, tailored to meet a single consumer's needs.

Role of the National Weather Service

The NWS today supplies multifaceted data and valuable information to the public and private entities that provide weather and emergency management services. The nearly completed modernization of NWS observing systems, systems for processing and communicating data, and staff structure has improved the quantity and quality of NWS services. New forecasting algorithms can be devised at any of the distributed WFOs and easily incorporated into the system. The information system for the modernized weather service, called the Advanced Weather Interactive Processing System (AWIPS), can easily accommodate new algorithms and data sources. This capability allows for timely implementation of locally developed and locally targeted methods of forecasting.

NWS forecasters at WFOs prepare public weather forecasts and warnings for their geographical areas of responsibility. They combine national data (model data from NCEP and satellite data from NESDIS) with their personal knowledge of local geography and climatology (e.g., terrain effects, lake effects, and coastal currents) and a variety of local observational data, such as NEXRAD radar products, hydrologic data (stream and river gauges), spotter reports, and observations from the Cooperative Observer Network. Flood warnings are based on all these data plus information from river forecast centers. The NWS chooses algorithms for forecasting based on a variety of sources, including research conducted at NOAA laboratories (under the Office of Oceanic and Atmospheric Research), NWS headquarters organizations

BOX 3-3
Government Policies and Budgets

In the panel's scenario for an *expanding government budget*, public opinion (and therefore public policy) favors social policies in which the federal (and state or local) government provides more services. Sustained economic growth and public acceptance of tax burdens produce the substantial tax revenues needed to fund the increase in government-supplied services. In this scenario, the environmental information network offers better products and broader services, provided principally through governmental agencies and many forms of public-private partnering. Government agencies, including the NWS, have the budgets and staff to expand their services and product offerings quickly and to adopt new technology far more rapidly than they could during the difficult decades at the end of the twentieth century. The number of commercial providers who offer differentiated, specialized products could grow more slowly, and the market value of economic information might not be high enough for commercial suppliers to invest in providing new kinds of services. However, the panel believes that, instead, the increased variety of services provided by the government in this scenario would stimulate even greater demand for specialized services in new and diverse markets.

In the scenario for *contracting government budgets*, the recent trends toward decreasing budgets (in constant dollars) and reducing staff at government agencies continue. Budget constraints and antitaxation sentiment also prevail at the state and local levels where, for example, emergency warning services are maintained but agencies have great difficulty expanding into preparedness programs. Funding is not available for initiatives that would apply environmental information to highway programs, agriculture, or tourism. In this scenario, growth and improvement in the information provider network depend increasingly on (1) the development of commercially viable markets served by commercial providers and (2) the ingenuity of public information providers like the NWS in leveraging their limited fiscal resources through intergovernmental and public-private partnering. In its most extreme form, in which the economic value of the information is not high enough to attract commercial partners, this scenario could lead to reductions in vital public services.

BOX 3-4
International Cooperation

Substantial growth in commercial environmental information services will require taking advantage of global opportunities, rather than serving only a domestic market. Weather is a global phenomenon, and most of the initial customers supporting the expansion of commercial services will be either multinational companies or companies that operate internationally. In addition, low-cost communications networks will make global service economically feasible. Because of low costs and guaranteed access to data from national observing systems, commercial providers today have little incentive to compete in that area (as long as government-provided data are near the state of the art). However, recent trends by foreign governments to support state-owned or state-favored information providers by restricting access to observational data may favor the entrance of privately owned remote sensing platforms. Once these systems have been acquired, using them to provide products in the domestic market will be economically feasible.

In the panel's scenario for *strong international cooperation*, open access to observational data and even modeling data at a reasonable cost to all parties regains the support of the established industrial countries. Industrializing nations join this regime of environmental cooperation because they recognize the need for joint efforts to deal with their serious environmental problems. In the environmental information network, this broad base of shared, high-quality observational data at low cost encourages the expansion of value-added products and services. Overall, the global environmental infrastructure produces a wider variety of products and services more cost effectively.

In the scenario for *restricted international access*, the recent trend toward controlling access to observational data intensifies, and the high cost of data restricts the growth of the global information provider network. Eventually these restrictions raise the market value of alternative sources of observational data. Depending on how quickly technology and other economic factors reduce the cost of setting up privately owned systems and on the perceived return on investment from application-specific products, national weather agencies eventually find themselves competing against state-of-the-art commercial systems. In countries with a strong tradition of market-oriented economies (such as the United States), this situation leads to pressures for the government to leave the field because industry can now do it better and cheaper. For the network as a whole, however, the artificially high barriers to new uses for observational data hinder the rise in value of the network's products and services.

such as the Techniques Development Laboratory and the Office of Hydrology, and research and testing by field office staff. New techniques and algorithms also result from staff interactions with the academic community, NCAR, and other national research facilities.

NWS data are accessible to all NWS customers, which include emergency management organizations at the federal, state, and local levels; specialized customers, such as the Federal Aviation Administration; commercial entities; and the general public. Some of the information channels NWS uses to distribute data and products are described in Box 3-5. Some NWS services (e.g., NOAA Weather Radio) are intended primarily for ultimate consumers (or end users), while others (NOAA Weather Wire Services and the Family of Services) are intended primarily for intermediate users who facilitate the dissemination to the ultimate consumers and may add value.

In the future, NWS products will continue to be accessible to all NWS customers, but the ways in which these products are created and disseminated will improve. With the growth of information infrastructure, the NWS will be called upon to provide more information to a greatly expanded public and private provider network. NWS products will include environmental observations; high-resolution regional and national gridded data sets for present and future environmental conditions; and forecasts, warnings, and watches. The future NWS will continue to play a critical role in providing technical support (information and expertise) to its governmental and private-sector partners. Assuming that moderate progress is made in modeling algorithms and computing capacity, the regional models will run quickly and routinely on grids of a kilometer or less. National and regional forecasts will be distributed as gridded data sets, much like the national model runs are now. Some forecast products will also continue to be distributed in graphical or text formats. The gridded data sets will facilitate the development of representations, including interactive displays, that focus on the locations and interests of specific customers. These customers will include the broadcast, cable, point cast, and print media, which will still be the principal distributors of environmental forecasts to the public.

NWS observations and forecasts will be the essential base products that feed many other environmental information providers. Because this information will be critical to the overall functioning of this network of providers, the leadership exercised by the NWS in promoting partnerships and

BOX 3-5
NWS Information Channels

The NOAA Weather Wire Service is the primary telecommunications network for distributing NWS forecasts, warnings, and other products to the mass media and emergency management agencies. NOAA Weather Radio provides voice broadcasts of weather information, including present weather reports, forecasts, watches, and warnings. Cable television weather channels and local traveler information services often rebroadcast the information. The broadcasts are also available through a commercial (900 code) telephone service operated by a private company under contract.

The NEXRAD Information Dissemination Service provides radar products to users outside the NWS (primarily the academic community and commercial providers of weather information, including the broadcast media) on a fee-for-service basis. This service is provided by several commercial companies, under contract to NOAA, which have access to all commissioned NEXRAD radars.

The NOAA Family of Services uses the NWS Telecommunications Gateway to provide dedicated telecommunications lines for users of NWS data, including private-sector data resellers and value-added resellers. Users pay a connection charge and annual fee. The services available include access to the NWS products for public distribution, domestic and international observations, data from NOAA/NWS forecast models in gridded binary format, and graphic products from NCEP in vector format. The older land-line telecommunications link will soon be supplemented by NOAAPORT, a satellite broadcast available to NOAA staff, partner-providers, and end users of weather information. The NWS Internet site provides up-to-date weather information in both text and graphical formats.

Climate data from the Climate Analysis Center of NCEP are available for a fee through dial-in access. Weather satellite imagery is available through either the GOES-TAP data service for a connection charge and annual fee or without charge by connecting to an existing GOES-TAP circuit to an NWS field office. Private vendors also sell weather satellite imagery.

Since the mid-1980s, the NWS has been replacing its automated telephone announcement systems for public forecasts with contractor service by local vendors who offer equal or better service. Some of the remaining in-house systems still provide dial-in service by which callers can speak directly to a forecaster in the local office.

innovation will significantly influence how the provider network evolves.

Roles of the Private Sector

In 1998, the private sector plays two principal roles in providing weather services:

- the dissemination of weather data to the public (examples are The Weather Channel, which provides national and local weather forecasts throughout the day, and the many local television and radio weathercasts, all based on data from the NWS)
- the provision of weather data to specialized communities (e.g., agriculture, energy, and financial services), usually with value-added information

Some for-profit providers produce their own forecasts using various combinations of public and proprietary observations and model data. Others, such as value-added resellers of NWS forecast data, add value to forecast data by providing specialized graphical presentations or data formats for specific customers. As the weather information industry grows, many more private-sector organizations will join the provider network.

The boundary between public service and private enterprise is becoming blurred as new relationships and activities are developed. For example, some state governments are becoming involved in partnerships that generate revenue. These partnerships, which have limited government financial support, cover their costs with fee-for-service charges. In time, some of them may evolve into for-profit enterprises. On the other side of the boundary, some for-profit companies contribute to information services for their communities as a form of advertisement. Other forms of public-private collaboration include advisory groups, coalitions, and community partnerships that bring businesses with common interests into semi-official relationships with local and state governmental bodies.

In the future, the private sector will include increasing varieties of for-profit information services that provide value-added products for specific customers based on observational and forecast data provided by the NWS. Detailed point-to-point highway travel forecasts, for example, will require that a number of "public" data sources (map and terrain data, highway conditions, local weather observations, near-term weather forecasts) be quickly integrated into a format suited to individual circumstances and priced according to the value to the consumer. An example of a for-profit, value-added service that goes beyond integrating and tailoring public data is an environmental conditions forecast that incorporates such data as soil moisture and absorption/runoff parameters and predicts runoff conditions to help farmers decide when to fertilize.

Vendors of Specialized Commercial Applications

The growing economic value of environmental information will promote the development of proprietary software applications that use weather observation and forecast data as input. The input data might be acquired from public data providers (the NWS or, for local surface observations, local and regional mesonets), the value-added private weather services described above, or proprietary observation and modeling systems. The developers of these tools for using information can be considered as either *providers* of information processing tools or *enablers* of the dissemination of value-added environmental information from public and private providers. However they are viewed, these tool developers will have a synergistic relation with information providers (including the NWS). If the data are available and a need for them has economic value, there is an economic incentive to develop the tools. If the tools already exist or can be easily adapted from existing tools, the economic incentives to improve the data increase.

Private Broadcast Media

Radio stations, broadcast and cable television, and public displays will continue to provide advertisement-supported dissemination of "public weather information." Television, and to a lesser extent radio and print media, will continue to try to gain a competitive advantage by adding value to the observation and forecast products provided by the NWS or others.

In some broadcast media, such as The Weather Channel, the NWS is already explicitly identified as the source of observations, forecasts, and warnings for specific areas. As the provider network becomes more extensive and complex, this demarcation will become increasingly important for the following reasons:

- To maintain public support for the tax-supported government activities of the NWS, the public must be made aware of the services it receives for tax dollars. Standard statements of attribution can clarify the extent of NWS involvement (e.g., satellite or radar data from NOAA-operated systems and NWS model output) in creating the final product.
- As providers of forecasts proliferate, the source of the observational basis for the forecast, as well as the model used and any interpretation or analysis applied to the model output, will become an increasingly important part of the information used by sophisticated customers. The statements of attribution that identify the NWS role in providing an information product could inform potential buyers of the source of observational data, NWP models, and other inputs.

Partnerships in the Provider Network

Federal agencies are under increasing pressure to justify their existence and their budgets through strategic planning, annual performance plans and evaluations, and objective performance measures. Partnering is often promoted as a way of leveraging limited, and often decreasing, agency resources. In this context, agency partnerships can be characterized in three ways. First, partnerships may involve only public entities, such as federal agencies or state and local entities (intergovernmental partnerships). Second, partnerships may include private-sector partners, which may be for-profit (commercial companies), nonprofit organizations, or both. Third, regardless of who participates, partnerships may be short term (with definite end points) or ongoing (with indefinite end points).

As of 1998, NOAA is involved in many partnerships. among which is the USWRP (U.S. Weather Research Program), a multi-agency partnership. Others include the Partnership Research Programs under the Office of Global Programs, the Coastal Ocean Program, and the Advance Short Term Warning and Forecast Services (a research program on new observing capabilities).

The NWS has service delivery partnerships with several traditional federal partners, including the Federal Aviation Administration for aviation weather services and the Federal Emergency Management Agency for responding to severe weather events and weather-related disasters. Other traditional partnerships produce and disseminate marine weather information and weather information for planning large controlled burns or dealing with wildland fires on public lands.

State and local partnerships are vital to the NOAA and NWS mission because most emergency weather information must be disseminated to state and local governmental agencies to effect timely responses. As federal–state partnerships become more common, the state and local partners are taking on more and more decision-making responsibilities. With the evolution of new information dissemination channels widely used by the public, the NWS, NOAA, and FEMA will have opportunities to work with state and local emergency preparedness and public safety officials to improve the alert system. Despite major improvements, much remains to be done to ensure that those at risk receive useful information in time to act.

An interesting example of the role of the NWS and other federal agencies (in this case, the Federal Highway Administration) in providing information resources and processing capability for making decisions is the Weather Information for Surface Transportation Systems. The Federal Highway Administration, which is the lead agency for the program, plans to serve all modes of transportation (including highway transit, rail, and intermodal interfaces, such as airports and truck-rail transfer points) and all transportation decision makers, including transit operators, travelers, shippers, planners, and builders, as well as highway departments and safety agencies (Pisano and Nelson, 1997).

In partnerships with for-profit companies at the national level, the NOAA and NWS roles have been limited to contractor-disseminator and providing access to data for a fee. Mechanisms for outreach and interactions between the NWS and private weather services and commercial media are provided principally through the Office of Industrial Meteorology. Public-private partnerships for developing new services (not merely a hand-off of public data to a disseminator or value-added reseller) are springing up in areas such as transportation weather.

One recent public-private partnership is the FORETELL project, in which the Iowa Department of Transportation is the public sector lead and Castle Rock Services is the private sector lead. FORETELL will deploy service centers to disseminate road and weather information in a five-state region of the Midwest (and western Ontario). The project's vision description cites research from the NOAA Forecast Systems Laboratory and the distribution capabilities of the modernized NWS as key public-sector contributions to the long-term success of the project (Davies et al., 1998).

In addition to the enduring partnerships discussed so far, there are also event-based or relatively short-term collaborations among interested parties. The focus of these partnerships may be a single event or a specific problem. An example of an event-driven partnership in which the NWS collaborated with a private nonprofit organization and commercial partners was the establishment of weather support offices for the Atlanta Olympic games (Box 3-6). In the future, short-term partnerships will be fostered by the new dissemination nodes for environmental information because much of the special-purpose information offered at these nodes will be provided by sources outside the NWS.

IMPLICATIONS FOR THE NATIONAL WEATHER SERVICE

The principal future roles of the NWS in providing environmental information will be extensions of its current roles. First, public forecasts and severe weather warnings will continue to be a government responsibility. The NWS will retain the lead role for issuing warnings and ensuring their dissemination. Second, the NWS will continue to provide information-rich observational data and gridded forecast products to other information providers, including not only the traditional disseminators of NWS products (emergency preparedness and broadcast media) but also a wider range of private-sector providers of specialized products and services.

Partnering with government and private-sector entities will be the principal means by which the NWS fulfills its broad mission to disseminate public forecasts and warnings and meet the increasing needs of the nation for weather information. The NWS can continue to provide the best

BOX 3-6
Weather Support Offices for the Olympic Games Peachtree City and Savannah, Georgia

In response to a request from the Atlanta Committee for the Olympic Games (ACOG) for information about local weather conditions at each Olympic competition venue, the NWS established two Olympic Weather Support Offices. To obtain the most accurate and current weather data, the NWS collaborated with the University of Georgia, the Georgia Forestry Commission, the University of Auburn, the South Carolina Forestry Commission, the Florida Forestry Commission, and the U.S. Fish and Wildlife Service to create a comprehensive mesonet of monitoring stations throughout Georgia, Tennessee, and the Carolinas. In addition, several outside agencies and private companies agreed to lend much of the equipment used to provide weather support for the Olympic Games. The various agencies and ACOG worked together to determine the most effective placement of monitoring equipment; ensure that observing stations were erected in locations that did not have observation sites for local conditions; and calibrate, maintain, and perform quality control checks on the observing stations. During the Olympics, 50 to 60 observing stations were polled every 15 minutes. The collected data were then processed by the NWS and used as input to fine-scale numerical models. The observations and model results were sent to a variety of Olympic participants, including coaches, athletes, and the media, through ACOG's information system.

possible weather information to the nation by developing partnerships that involve it in the emerging markets for environmental information. The expertise of the NWS staff will be an essential resource that NWS brings to these partnerships, in addition to the data it provides. Opportunities can be sought for participating in newly emerging entities, such as quasi-governmental organizations that blur the boundaries between the public and private sectors, particularly at the state and regional levels.

NWS partnerships with private-sector and government entities in the provider network will continue to be shaped and constrained by government policies and budget allocations (NRC, 1998e). Recent legislative attempts to define these relationships, such as the debate over funding for agricultural weather services, have taken an "all or nothing" approach to whether a given service should be provided as a public service or a market-provided commercial item. A better approach would be to consider NWS responsibilities in terms of potential partnerships and collaborations, which could provide better private-sector or mixed public-private services over time. Statutory and administrative changes may be necessary to allow this change.

Focusing on Primary Customers

In the future environmental information network, data and information will often flow from one information provider to another before they reach their ultimate consumers, or end users. The length and complexity of these information chains will increase as the network of providers expands and diversifies through a range of specialized applications and services developed as decision aids for market segments and individual customers. For the market to be efficient, all providers, including the NWS, will have to focus on serving their primary customers, defined as *whoever immediately receives their products*. The primary customers of the NWS will often be other information providers, not end users.

Based on the panel's review of NWS documents and discussions with NWS personnel, the NWS does not distinguish adequately between customers of the entire provider network and the primary customers of the NWS. Box 3-7 lists the user sectors identified in recent NWS planning documents (e.g., NWS, 1994; Kanawha Institute, 1997). The list is a summary of all the users of weather information, who will in the future be served by the provider network. But it is not a list of NWS primary customers. The NWS cannot serve all of these information users well by trying to serve them all directly. It will either stretch its resources too thin and fail to do most things well enough to excel or it will retreat to "one size fits all" products (e.g., zone forecasts) that do not adequately meet any users' needs.

To determine how well its products and services are being used, the NWS will need to understand the needs and capabilities of providers and users who are not its primary customers. Nevertheless, in providing quality service the imperative to "focus on the customer" pertains first and foremost to existing and potential primary customers.

Requirements Definition and NWS Leadership in the Network

Rapid growth of the provider network for environmental information during the next quarter-century will mean that the primary customers for NWS services and products will

BOX 3-7
Current National Weather Service Users

The general public
Aviation (e.g., FAA, pilots, Air Weather Service)
Marine (e.g., Naval Oceanographic Command)
Emergency management (e.g., FEMA, state and local emergency managers)
Fire, police, safety (e.g., local fire and police departments)
Agriculture (e.g., U.S. Department. of Agriculture)
Transportation (e.g., U.S. Department of Transportation)
Land conservation and environment (e.g., Environmental Protection Agency, Bureau of Reclamation, Soil Conservation, Bureau of Land Management, U.S. Geological Survey, U.S Army Corps of Engineers)
Forestry (e.g., Forest Service)
Water resources (e.g., state divisions of water resources, flood control districts)
Media (e.g., The Weather Channel, Associated Press, Radio and TV News Directors Association)
Law (Forensic services)
Travel and recreation (e.g., National Park Service)
Energy (e.g., Department of Energy)
Education (e.g., U.S. Department of Education, state and local jurisdictions, local schools)
Health (e.g., Centers for Disease Control and Prevention)
Private meteorological companies (e.g., The Weather Channel, Accu-Weather, WSI)
Universities and research institutes (e.g., National Center for Atmospheric Research)
Professional meteorologists and hydrologists
Elected officials (e.g., Congress, local elected officials)
Other industries (e.g., construction, insurance)

be changing more rapidly than in the past. Even the needs of continuing customers will change more rapidly, as they develop new products or find new ways to use detailed environmental information. Therefore, the NWS will need a requirements definition process that allows for frequent, structured reassessments of its goals and activities. The "reverse end-to-end" requirements definition process used by the NWS Office of Meteorology and frequent meetings with user groups are two excellent first steps toward a flexible process for defining and updating requirements.

But these are only first steps. The NWS process for defining requirements could become a tool to help define the roles of various members of the provider network, including the roles of private-sector participants, as well as the roles of other federal and nonfederal public-sector providers. By providing a forum for diverse providers to come together, with the NWS playing a leading role as the dominant information provider, meetings with its primary customers could do even more than help the NWS formulate its own requirements. These meetings could contribute greatly to the development of a shared view of what ought to be done, in what time frames, and how the parties could work together to meet the needs of everyone served by the network. In fact, the broad mission of the NWS to provide weather services to the nation requires that it take a leadership role in this process.

An ongoing, periodic process for defining requirements should have an accompanying response process. The NWS will need a mechanism for sorting through the diverse and often conflicting inputs from partners and customers, so that short-term and long-term priorities can be clearly defined. This process should include defining the criteria for meeting the needs of primary customers; that is, how the NWS and its partner-providers will know if the requirements are being met and if the requirements need to be updated. For example, as the primary source of weather data and models, the NWS can play a key role in facilitating the integration of environmental data sets by taking the lead in establishing standards for data formats and quality.

4

Education and Training

Well educated and well trained people will continue to be essential for fulfilling NWS missions. Two issues the NWS will face in finding and retaining qualified scientific and technical personnel, at least in the near term, are the changing role of scientifically educated forecasters and the tight labor market for technical support professionals in telecommunications, software development, and related fields. To retain valuable professionals and fully develop its human resources, the NWS will need a comprehensive career-path program that includes flexible career progressions within the NWS and exchanges of personnel with universities, the private sector, and other providers in the environmental information network. To keep up with changes in technology and in the workforce, the NWS must keep its educational and training curricula current and broaden its in-house programs. The NWS should also work with other providers in the network to improve the "weather information literacy" of end users.

CHANGING ROLE OF FORECASTERS

The main focus of human forecasters in the forecast/warning process is now trending toward accurate predictions at smaller and smaller spatial and temporal scales. Moreover, there is greater dependence on explicit science, captured in forecasting tools and routines, rather than relying on the tacit knowledge or skills of individuals. As a consequence of this trend, new scientific concepts and techniques will continue to be introduced into NWS operations. New and existing staff will need education and training to use the new technology and scientific knowledge effectively.

As forecast and warning operations become increasingly automated, the roles of meteorological and hydrologic professionals will change, but their importance will not diminish. At one end of the process, more effort will go into refining, extending, and validating the models and other tools of automated prediction. At the other end, an increasing portion of staff time and resources will be invested in close interactions with users of NWS products and services. Interaction with the emergency response community will continue to be critical. The proliferation of new dissemination channels will create new opportunities to get the right weather-related warnings and information to the right people in time for them to act on them.

The emphasis on incorporating environmental, observational, and forecast data into products for specific applications will increase the demand for meteorological and hydrologic applications specialists throughout the provider network, as well as in the NWS. These professionals will understand how to integrate data sets and information on weather, water, climate, air quality, and other environmental factors. In addition to an undergraduate or higher level education in meteorology, they will need an in-depth understanding of one or more disciplines in which these environmental factors have important consequences, such as human health and performance, hydrology, agronomy, entomology, or engineering. These next-generation *environmental information specialists* will be sought after by individual companies and consulting firms, as well as by the NWS and other government agencies.

TECHNICAL SUPPORT STAFF

The supply of university graduates is expected to be sufficient to meet the needs of the NWS for meteorologist-forecasters and hydrologists. However, the supply of electronics technicians has diminished noticeably. Historically, the military services have been the primary source of these trained technicians. Major reductions in troop strength during the past decade, which have forced the military to outsource more technical support to contractors, have decreased the labor pool of trained technicians to meet the needs of civilian agencies like the NWS.

A similar supply problem exists for the technical staff to support information systems. This broad category, which will become increasingly important in the future, includes both hardware support and the development and maintenance of NWS-specific software. The current demand for personnel in these technical support categories is high, and market competition is intense. Therefore, the NWS may find it necessary to contract with the private sector for some of its technical support staff.

The panel expects that each field office will need a computer system specialist on staff, either full time, part time, or under contract. At present, the science and operations officers (SOOs) at WFOs and the development and operations hydrologists (DOHs) at river forecast centers often serve in this capacity because they typically have enough technical expertise with computer systems and application software to satisfy some of the demand. However, this is not a sound long-term solution because the SOOs and DOHs have too many other operational and research responsibilities.

CAREER PROGRESSION

The NWS must establish and maintain visible, logical career paths for all its staff. Alternative ways to progress should enable qualified NWS personnel to move from one career track to another, in accordance with personal career objectives. For example, a person who aspires to a management position should have opportunities to develop leadership skills while maintaining his or her technical skills and gaining the necessary breadth of experience.

The development of career paths will require the following components:

- describing clearly the functional requirements, including required prior experience, for each staff job
- distributing information regarding career development to the NWS workforce
- encouraging and mentoring personnel with the potential for growth and leadership
- identifying staff members who embrace the full range of environmental forecasting practices and encouraging their development as the next generation of NWS leaders

The trend in the private sector away from lifetime careers with a single employer will become increasingly common in government service in the coming decades. This change will result in a continuing flow of personnel back and forth between the universities, the private sector, and the NWS. Given the expanding role of the private sector in the national environmental information network and the evolving role of the NWS in relation to other providers, this exchange of professional personnel could improve both the NWS and the provider network as a whole and ultimately provide better environmental information to the nation. However, the NWS must take this new situation into account in structuring its job requirements, education and training programs, and rewards.

EDUCATIONAL AND TRAINING CURRICULA

Anticipating and adapting to change requires a long-range outlook and an evolutionary approach to training that is based on understanding the current situation and appreciating new concepts and technologies that could affect NWS activities or users of its products and services. The NWS must apply this long-range, evolutionary approach to assessing its education and training needs. The assessment should include all staff training categories, such as training for new staff, refresher courses, cross-training, and upgrading capabilities. It should evaluate the capabilities expected of new staff who enter with different levels of prior professional experience. The required and desired capabilities of those who have completed a course of training should also be clearly specified.

Besides the education and training of field office personnel (the meteorologists, hydrologists, and technical support staff at WFOs and RFCs), the NWS should offer a personalized curriculum for all other personnel, including:

- technical personnel who develop or maintain software
- management personnel
- staff of national centers

In developing its curricula, the NWS should consider the experiences and talents of weather services in other countries. The NWS might also consider including non-NWS personnel in some of its training activities, which would facilitate the cross-fertilization of ideas, as well as promoting economies of scale. The recent participation of personnel from the Canadian Atmospheric Environment Service in some of the COMET programs run by the University Corporation for Atmospheric Research is a constructive example.

PROGRAMS

Universities or technical schools provide most entry-level NWS staff with basic education and training. Operational training for NWS meteorologists and hydrologists is provided at the National Weather Service Training Center in Kansas City, Missouri, the NEXRAD Operational Support Facility in Norman, Oklahoma, and the COMET program in Boulder, Colorado. An extensive cooperative/intern program for university students also provides valuable training for entry-level staff. Most training in equipment maintenance takes place at the training center in Kansas City.

In the past, training center students remained in residence at the facility for most of their training, but economic and other pressures have forced the NWS to adopt more distance-learning activities. Similar trends are apparent in other fields where continuing professional education and training are essential. Most approaches to distance learning used by the NWS thus far have involved passive (one-way communication) learning through video, CD-ROM, and similar media. However, with the advent of the Internet and two-way video systems, opportunities are increasing for more interactive learning activities (NRC, 1994).

On-the-job training, which takes place informally all the time, will continue to be an important part of the continuing education and training of NWS staff. In addition to their other functions, SOOs and DOHs are an invaluable resource for educating and training staff on the job. A more formal journeyman/apprentice arrangement would have advantages for learning and would also recognize the contributions of the trainer, as well as the accomplishments of the trainee.

Conferences and meetings are also very important to education and training. Regular conferences organized by professional societies help spread information about new developments throughout the community. Some conferences include workshops or short courses of value for personnel training. These conferences also provide an opportunity for staff to interact with experts outside the NWS and establish working relationships that could lead to the innovative partnering necessary for meeting the nation's environmental information needs. The many formal and informal conferences arranged by the NWS, such as those for the SOOs, have been particularly effective in improving operations.

EDUCATING USERS OF WEATHER INFORMATION

The NWS should provide educational aids to reach non-NWS participants in the national environmental information system, as well as broader segments of the user community. This diverse community includes television meteorologists, who are a major conduit for disseminating NWS products and services to the general public. It also includes many other sectors where NWS products and services are (and will be) used in increasingly sophisticated ways: state and local emergency management and public safety officials, airline dispatchers and pilots, transportation and construction companies, managers of energy production and distribution, agriculture, and many more. Improving "weather information literacy" across the spectrum of users will contribute significantly to the overall utility of the information disseminated by the NWS.

The most important results of the NWS modernization and restructuring are better observations, forecasts, and warnings, but a by-product is a wealth of new information. New means for broad cost-effective dissemination (for example, sites on the World Wide Web of the Internet) are evolving rapidly. With interactive capabilities, the disseminated information can be accompanied by on-line help and other tools to aid novice users in learning what products mean or what responses may be appropriate. The NWS should continuously assess mechanisms for disseminating weather and related environmental information and suggested ways of using it.

In the future, weather education for special applications, for the average citizen, and for school children will change substantially. Information will include graphical presentations of data in three dimensions displayed against models of local terrain. Advanced local computing capabilities will allow students to run visual simulations to compare models or play "what-if" games. Patterns that are difficult to visualize and assimilate from data or words will become intuitive and readily discernible.

A public education program should explain what information is available from the provider network, why the information is relevant to users, how to interpret a forecast or warning, and how to prepare for severe weather. Means for providing this public education could include:

- access to weather information as part of the kindergarten-to-high-school (K–12) curriculum
- weather awareness weeks in schools and communities
- promotional material (literature, web sites, and public presentations)
- partnerships with the Federal Emergency Management Agency and local emergency preparedness/management agencies to convey information about disaster prevention and mitigation (Box 4-1)
- outreach to the construction industry (for developing and enforcing building standards), insurance companies, and other commercial interests concerned about preventing or mitigating the effects of damaging weather and related phenomena
- outreach through partnerships with transportation and agricultural agencies (federal and state), as well as interested private-sector providers, on ways to access and use weather-related environmental information
- partnerships between providers and outdoor nonprofit organizations to provide weather information for outdoor recreation activities
- partnerships with hospitals, health care institutions and health maintenance organizations, public health agencies (e.g., Centers for Disease Control and Prevention and state public health departments) to disseminate health-related weather information
- special forums on weather-related topics (e.g., tornado watches and heat alerts and the use of probabilistic forecasts)

IMPLICATIONS FOR THE NATIONAL WEATHER SERVICE

The NWS should establish a formal mechanism for periodically assessing and prioritizing its needs for staffing and for education and training. This mechanism should consider trends in science and technology that affect operations and

Box 4-1
National Disaster Education Coalition An Example of Successful Partnering

The central goals of the National Disaster Education Coalition are to raise public awareness of natural disasters and increase the public's ability to prepare for and respond to them. Members of the coalition are the American Red Cross, the Federal Emergency Management Agency's U.S. Fire Administration, the NWS, the National Fire Protection Association, the U.S. Geological Survey, the National Coordinating Council on Emergency Management, and the National Emergency Managers Association. By pooling their expertise, member agencies can provide more accurate information. By combining members' efforts, a broader audience receives a more consistent message. The united voice of several respected agencies has strengthened their common message.

In 1998, the coalition sponsored an exhibit at a U.S. Geological Survey open house in Reston, Virginia. Other activities planned for 1998 include jointly reviewing and updating brochures on natural disasters, identifying information gaps, and producing materials to fill those gaps. For example, publications are being planned on the topics of volcanic eruptions, landslides and mud flows, and wildland fires. The coalition is evaluating the impact of materials produced by members or by the coalition.

The coalition is also developing products for the International Decade for Natural Disaster Reduction, including an "Electronic Field Trip" for children. Another joint project is to create a guidebook for providers of local disaster education. This guidebook will describe how disaster-related information can be produced and disseminated through public-private partnerships.

The coalition is also examining its own working processes to facilitate cooperation and sharing among the member agencies. Coalition members are keeping each other abreast of relevant research and new applications, as well as consulting frequently among themselves when creating or changing materials with the coalition's logo.

education and training activities. Besides polarimetric radar, other examples of emerging technology developments include the retrieval and use of radio occultation soundings, mesoscale modeling and analysis (including three and four dimensional data assimilation approaches), the integration of data from multiple sources, and risk management based on probabilistic information. The NWS should maintain an updated list of the scientific, technological, and societal trends relevant to its mission. NWS assessments of its staffing needs and of the educational and training needs of its staff would benefit from independent advice from outside NOAA and the NWS. The NWS should maintain visible and openly accessible career paths that provide opportunities for personnel to migrate between the NWS, universities, and other providers in the environmental information network.

A proactive outreach program of education and dissemination of information to users of NWS products will contribute to the more effective use and understanding of weather information. It will also establish a broad constituency that understands and appreciates the role of the NWS in the environmental information network. By keeping in mind the range of educational needs and opportunities, the NWS can take the lead or actively participate in outreach areas, as appropriate.

5

Road Map for the Future

`The Vision.` *In 2025, weather and environmental information will be used routinely in making individual, business, and governmental decisions. This information will flow through an expanding network of providers in the private sector and in government at the federal, state, and local levels. It will be provided to users as products and services that address particular needs (such as air quality or traffic congestion reports and forecasts, as well as weather reports).*

The NWS will be responsible for the basic infrastructure to support state-of-the-art weather information services and will be the leading provider of weather and climate data for the environmental information network. To fulfill its mission, the NWS will assimilate data from more diverse and technically advanced observing systems into sophisticated analysis and modeling tools. The NWS will work in partnership with the research community and a greatly expanded provider community to provide timely information based on the latest scientific understanding of weather phenomena.

In the year 2025, weather products and services will be vastly improved and substantially more useful to society. Advanced technology will be a vital part of every step of the observation, forecast, and delivery process, guided by the dynamic and dramatic positive reinforcement between progress in science and confirmation of new scientific understanding through improved predictive power. Advances associated with the NWS modernization are already fostering a revolution in the value of environmental data. In the emerging information economy, the value of this environmental information (observations, forecasts, and the knowledge of how to apply these data) will draw resources of human talent and capital investment to innovations at every step in the process: from observing systems to computing capability and modeling techniques, to articulation of specialized applications fed by massive flows of timely data.

Based on the information in the preceding chapters, the panel has developed the following recommendations on how the NWS can participate in and foster improvements in weather and environmental services. The recommendations appear under four headings: realizing potential benefits to the nation; applying enabling science and technologies; merging weather information services into environmental information services; and meeting organizational challenges.

REALIZING BENEFITS TO THE NATION

The formal NWS modernization and restructuring has provided the foundation for the NWS to become a dynamic, bold, responsive weather service that can lead the way in realizing enormous benefits to the nation. To meet the challenges that lie ahead, the NWS must evolve in response to a rapidly changing environment. It must support and exploit advances in science and technology, while working through a variety of public and private partnerships to provide broad weather and environmental information services.

Recommendation 1. The National Oceanic and Atmospheric Administration and the National Weather Service should more aggressively support and capitalize on advances in science and technology to increase the value of weather and related environmental information to society.

APPLYING ENABLING SCIENCE AND TECHNOLOGIES

Ongoing research and development are necessary to provide the scientific foundation for improving operational observations and predictions and the resulting user-oriented forecast products. The principles embodied in the USWRP (U.S. Weather Research Program) are well suited to guide scientific research in directions that are likely to reap benefits for users of weather and climate information. One of the foremost of these principles is that the program's research agenda should be shaped by a careful assessment of the most important weather-related needs of society. Moreover, the USWRP has established mechanisms for a continuing dialogue among users of weather information, providers of weather information, and the research and development community. In addition, several other national and international research programs are highly relevant to weather service operations. These include the World Weather Research Program, which is closely coordinated with the USWRP, and the U.S. Global Change Research Program and the World Climate Research Program, which address important aspects of climate and the environment that are integral to the NWS's role in environmental prediction. The NWS should expand its participation in and support of these programs.

Traditionally, NWS research and development activities have been undertaken in the national centers. In the modernized weather service, the SOO (science and operations officer) and DOH (development and operations hydrologist) positions at field offices provide an opportunity to extend research and development activities to the field offices. These individuals can initiate and conduct applications-oriented research and development at the local level, in concert with local universities and the broader research community.

Recommendation 2. The National Weather Service should be an active partner and participant in national and international research enterprises in weather, hydrology, climate, and environmental sciences.

Advances in scientific understanding and technologies will provide abundant opportunities for the NWS to make incremental improvements in its products and services. An evolutionary approach to upgrading its operational systems, rather than episodic radical overhauls separated by years of little improvement, will enable the NWS to avoid obsolescence, minimize risk, and implement new ideas and technologies on an ongoing basis. An evolutionary approach will also eliminate the organizational trauma associated with episodic overhauls.

The rapid development, testing, and implementation of new algorithms and techniques will require sound science and proficient engineering. Skilled scientists at NWS field offices (represented in the current personnel structure by the SOOs and DOHs) working with universities, research institutions, and the private sector could help develop and incorporate advances into NWS operations efficiently and effectively.

Recommendation 3. The National Weather Service should commit to and plan for ongoing and timely incorporation of scientific and technical advances in the operational weather observation, analysis, and prediction system. To implement its commitment, the National Weather Service should take the following steps:

- Develop technologies, in cooperation with universities and the public and private sectors, that enhance systems for observing weather phenomena and for assimilating and analyzing resulting data.
- Evaluate, on a quantitative basis, alternative technologies and approaches for the development, testing, and deployment of a cost-effective system of synergistic observing instruments and platforms, incorporating the principle that integrated measurements taken by multiple sources using diverse techniques can provide a better estimate of a physical quantity than any one instrument alone.
- Test and evaluate new forecasting concepts and systems expeditiously, through rapid prototyping at the appropriate centers or selected forecast offices.
- Maintain a research staff of sufficient size and expertise at the national centers to develop new forecast techniques and products that further their broad national missions.
- Work with the National Oceanic and Atmospheric Administration to strengthen National Weather Service interactions with the National Environmental Satellite, Data, and Information Service and the Environmental Research Laboratories, ensuring that their combined activities are coherent, systematic, and mutually supportive.
- Work with the academic community on a continuous basis to improve numerical weather prediction models.
- Maintain a strong scientific capability at the field offices to conduct application-oriented research and development at the local level (for example, through the science and operations officers and development and operations hydrologists).
- Provide appropriate computing capabilities at field offices to ensure that new technologies can be tested and applied.

Numerical modeling of the coupled atmosphere-ocean-land system will be the core of weather and climate prediction. Improving forecasts requires the ability to assimilate a broad array of initializing data at higher resolution and accuracy into models that better represent the underlying physical processes. Running these complex models and testing their results quickly enough to provide timely forecasts will require increased computational power. To realize the potential benefits of timely, more reliable forecasts at higher resolution, the NWS will need the most advanced and powerful supercomputing capability available. As the diversity, density, and coverage of observations increase, and as more realistic models at higher resolutions are developed, any shortfall in computational power will increasingly restrict the ability of NWS centers to realize the potential benefits of available observing and forecasting technologies.

Recommendation 4. Congress and the administration should provide the resources needed by the National Weather Service to regain and maintain the state-of-the-art supercomputing capability required to support the advanced analysis and modeling systems that are fundamental to the nation's weather and climate forecast systems.

MERGING WEATHER INFORMATION SERVICES INTO ENVIRONMENTAL INFORMATION SERVICES

The increasing accuracy and specificity of weather, climate, and hydrologic information will create opportunities for broader environmental information services. NWS forecast and warning services will be an essential component of the information on weather, climate, hydrology, space weather, air quality, and other environmental factors used by the expanded provider network to serve a variety of economic and other societal needs. The information services and products provided by this network will be directed toward specific users, distributed through broadly based environmental information dissemination services, and evaluated on how well they meet user needs.

Recommendation 5. The National Weather Service should collaborate with a variety of partner-providers to integrate weather and related information into comprehensive environmental information services.

ORGANIZATIONAL ISSUES

Now that the formal modernization program is almost complete, the NWS has established a strategic planning exercise to estimate its future needs. This exercise must become an ongoing process that seeks the views, opinions, and assistance of the broad external community of scientists and technologists, secondary weather service providers, and representatives of end-user groups.

Meeting changes in user needs and upgrading technology and processes to improve efficiencies and effectiveness will require stable long-term funding that is adequate to implement long-range plans based on validated requirements. The current NWS/NOAA budgeting process has only a two-year planning horizon. The obscurity of the current budget structure creates difficulties in understanding the level of resources committed to specific functional areas. Irregular or inadequate support is disruptive and expensive in both human and financial terms; it limits the quality and extent of services and denies potential benefits to the user community.

Recommendation 6. The National Weather Service should perform strategic long-range planning for orderly development of the infrastructure and technology that support the services for its constituents. Congress, the Office of Management and Budget, the U.S. Department of Commerce, and the National Oceanic and Atmospheric Administration should provide stable and adequate funding to the National Weather Service consistent with its needs and plans.

The diverse and rapidly evolving user community, advancing technology, and changing relationships among members of the weather community will require a parallel evolution in the organizational structures of NOAA and the relationships among its components, including NWS, the National Environmental Satellite, Data, and Information Service, and the Office of Oceanic and Atmospheric Research. This evolution will need to occur at all levels of organization, including the field offices and national centers. The organizational structure must be sufficiently flexible to exploit new ideas, respond to changing user roles, and manage change.

Recommendation 7. The National Weather Service should routinely examine and anticipate the needs of primary customers and ultimate users. In the context of changing requirements, the National Oceanic and Atmospheric Administration should periodically adapt its organizational structure and operating processes to foster effective relationships among the National Weather Service, the National Environmental Satellite, Data, and Information Service, and the Office of Oceanic and Atmospheric Research.

The atmosphere and oceans transcend national boundaries. Realizing the predictive capabilities envisioned in this report will require higher-quality, higher-resolution global observations. The creation of a global database of unprecedented quality, coverage, reliability, and breadth will require unprecedented cooperation by major data-gathering nations. The NWS has historically supported a global observing network that provides data freely and openly to all countries.

Recommendation 8. The National Weather Service should maintain and strengthen its leadership role in seeking international cooperation for the free and open exchange of weather and climate data for the benefit of users in all nations.

The adaptation of emerging science and technology to the evolving needs of the NWS will require a scientific staff that is informed on the latest understanding of weather, hydrology, and climate phenomena and is experienced in applying this knowledge. The heavy investment in technology for NWS operations will require a technical support staff that is expert in the operation,

BOX 5-1
Criteria for Selecting Science and Technology Initiatives

General criteria should be applied to *all* initiatives and new or significantly improved programs and systems. The specific criteria apply to the acquisition of new observing systems, computing facilities, the development of new products, and education and training programs.

General Criteria
1. Does the initiative support the mission of the NWS?
2. What are the benefits of the initiative to the NWS and to society?
3. Are the benefits worth the cost?
4. Are the scientific, technical, and political risks acceptable?
5. Will the initiative build partnerships with the academic community, the private sector, and the international community?
6. Have disinterested individuals (e.g., from outside the NWS or implementing organizations) with broad expertise and viewpoints reviewed the initiative?

Observing Systems
1. Will the new system add value to the analysis, forecasting and warning process (i.e., produce better forecasts)?
2. Will the new system reduce data gaps?
3. Will the new system strengthen the overall observational system through synergism with existing or future systems?
4. Will the new system effectively replace older or more expensive systems?
5. Will the new system reduce the risk of failure of older systems?

Computer Facilities
1. Will the new computer facilities permit more efficient handling of observations or the operation of more accurate and useful forecast models with higher resolution for significant weather?
2. Will the new computer facilities more effectively assimilate and analyze existing and future data sets, thereby improving forecasts and forecast products?
3. Will the new computer facilities support improved climate forecasts of use to NWS customers?

New NWS Products
1. Is there an existing need or demand for the product?
2. Is it likely that a new need or market will be created that will provide a useful service to society?

Education and Training
1. Will the activity contribute to a better-educated, better-trained workforce?
2. Will the activity contribute to better forecasts, warnings, and other services?
3. Will the activity contribute to the long-term professional growth and versatility of the NWS workforce?

maintenance, and upgrading of this technology. The NWS staff must be technically sophisticated, trained in the behavioral tools of teamwork and consensus building, and adept at monitoring and improving their performance.

Recommendation 9. The National Weather Service should provide for the ongoing professional development of a knowledgeable, flexible workforce through continuing education and training, taking advantage of appropriate university resources.

For NWS customers to apply NWS products and services effectively, the primary customers in the environmental information provider network and the ultimate consumers (organizations and individuals) must appreciate the role of the NWS in enabling and fostering the provider network. Well informed partner-providers and users will support the NWS in obtaining the resources to advance the vision of improved weather services described in Part I of this report.

Recommendation 10. The National Weather Service should participate with other public institutions, professional societies, and the private sector in educating the general public and specialized users about the causes and consequences of weather-related environmental phenomena; the utility and limitations of environmental observations, forecasts, and warnings; and the roles of the National Weather Service and its partners in providing this information.

SETTING PRIORITIES FOR SCIENCE AND TECHNOLOGY INITIATIVES

The panel has emphasized the importance of upgrading NWS facilities and services on a continual rather than episodic basis. This evolutionary upgrading will require the NWS to stay abreast of *all possible* new opportunities, while making decisions about which ones to pursue. As part of its task, the panel was asked to suggest criteria for setting priorities among proposed science and technology initiatives. In Box 5-1, the panel suggests both general and area-specific criteria based on the recommendations in this chapter and information in the report.

The panel realizes that all opportunities and initiatives carry some risk. The criteria assume that the initiative being evaluated will be technically successful. However, new initiatives must not only be feasible from a scientific and technical point of view, they must also contribute to the NWS mission, meet societal needs, and be cost-effective.

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Acronyms

4DVAR	four-dimensional variational data assimilation
ACARS	Aircraft Communications Addressing and Reporting System
ACE	Advanced Composition Explorer (satellite)
ACOG	Atlanta Committee for the Olympic Games
AIRS	advanced infrared sounder
AMSU	advanced microwave sounding unit
ARINC	Aeronautical Radio, Inc.
ASCI	Accelerated Strategic Computing Initiative
ASM	atmosphere-system model (an NWP model that combines the atmosphere, oceans, land, and sea ice)
ASOS	Automated Surface Observing System
ASTER	advanced spaceborne thermal emission and reflection radiometer
AWIPS	Advanced Weather Interactive Processing System
CERES	Clouds and Earth's Radiant Energy System
COMET	Cooperative Program for Operational Meteorology, Education and Training
CSM	climate system model
DOH	development and operations hydrologist
ECMWF	European Centre for Medium-Range Weather Forecasts
EOS	Earth Observing System (a NASA satellite system)
EWIS	economic weather impacts scale
GOES	geostationary operational environmental satellite
GPS	global positioning system
GPS/MET	global positioning system and meteorological (satellite)
HF	high frequency (radio band in the electromagnetic spectrum)
HWIS	human weather impacts scale
ITWS	Integrated Terminal Weather System
LEO	low Earth orbiting
LM	lightning mapper
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NEXRAD	Next-Generation [weather] Radar (Weather Service Radar [WSR] 88D)
NOAA	National Oceanic and Atmospheric Administration (U.S. Department of Commerce)
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NSCAT	NASA ocean wind scatterometer
NWP	numerical weather prediction
NWS	National Weather Service (National Oceanic and Atmospheric Administration, U.S Department of Commerce)
QPF	quantitative precipitation forecast
SOO	science and operations officer
SPARCLE	Space Readiness Coherent Lidar Experiment
TRMM	Tropical Rainfall Measuring Mission (satellite)
USWRP	U.S. Weather Research Program
UTC	coordinated universal time (ZULU)
WFO	weather forecast office
WTWS	Wind Shear and Turbulence Warning System

Glossary

Algorithm. A component of a computer program (or set of programs) designed to solve a certain kind of problem. *WSR-88D* radars (*NEXRAD*) employ algorithms to analyze radar data and automatically determine storm motion, probability of hail, accumulated rainfall, and several other parameters.

Chemical weather. The state of the atmosphere as described by its chemical composition especially variable trace constituents such as ozone, oxides of nitrogen, carbon monoxide, etc.

Climate. The qualitative and/or quantitative characterization of the weather at a particular place or region, or over an entire planet, for a specified period of years, by the statistics (e.g. averages, maxima and minima, probabilities of occurrence) of weather elements such as temperature, humidity, precipitation, and wind velocity. Changes in the statistics of weather elements over a series of specified climate-measuring periods provide a measure of the trends in climate.

Corona. The pearly outer envelope of the Sun observed during solar eclipses or with the coronagraph. At sunspot minimum, the corona has large extensions along the Sun's equator, with short brush-like tufts near the poles. At sunspot maximum, the equatorial extensions are much smaller, and the corona is more regular in shape.

Cyclone. An atmospheric cyclonic circulation, a closed circulation. A cyclone's direction of rotation (counterclockwise in the Northern Hemisphere) is opposite to the rotation of an anticyclone. Modern meteorology restricts the use of *cyclone* to the so-called synoptic-scale circulations (typically 1000-3000 km).

Cyclonic. Having a sense of rotation about the local vertical the same as that of the Earth's rotation; that is, as viewed from above, counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

Data assimilation. Process of using observations to correct or adjust model predictions wherever and whenever the observations are available.

Distributed modeling. In hydrology, the correlation of many observations and estimates of rainfall over space and time with information on topography, soil types, and soil saturation to determine how much rain is likely to be running off a region into a river and forecast where flooding will occur within a basin.

Dropsonde (also called `parachute radiosonde`**).** A radiosonde dropped by parachute from an aircraft for the purpose of obtaining soundings of the atmosphere below.

Ensemble forecasting. A number of independent computer model integrations with initial conditions slightly perturbed to represent uncertainty in the analysis. Ensemble forecasting has three main objectives: (1) to improve a single forecast by averaging forecasts over the ensemble; (2) to estimate the reliability, or conversely the uncertainty, of a forecast; and (3) to provide a basis for probabilistic forecasts by assigning probability values to possible flow evolutions.

Flops. Floating point operations per second, a measure of the speed of a processor.

Fuzzy logic. In meteorology, an objective decision-making process that quantitatively deals with uncertainty and imprecision in observation and forecasting algorithms.

Geostationary satellite. A satellite that orbits the Earth at the same rate that the Earth rotates, thus remaining over a fixed place above the equator.

Gigaflops. A unit of computer speed equal to 10^9 floating point operations per second (flops).

Hybrid forecasting. The use of a mix of advanced forecasting techniques to forecast weather.

Hydrograph. A graphical representation of stage or discharge at a point on a stream as a function of time. The most common type, the observed hydrograph, represents river gauge readings plotted at the time of observation. Other types of hydrographs are derived statistically from observed data and include distribution graphs and unit hydrographs.

Microscale. The smallest scale of atmospheric motions, typically from millimeters to a few meters.

Mesoscale. Size scale referring to weather systems smaller than *synoptic-scale* systems but larger than *storm-scale* systems. Horizontal dimensions generally range from around 50 miles to several hundred miles.

Nowcast. A short-term weather forecast, generally for six hours or less.

Occultation. The gradual emergence or disappearance of the electromagnetic waves emitted from a celestial body or spacecraft behind another celestial body; for example, an eclipse of a star or planet by the moon as seen from the Earth, or the eclipse of a GPS satellite by Earth as observed from an orbiting GPS radio receiver.

Polarization. The state of electromagnetic radiation when transverse vibrations are regular, e.g., all in one plane, in a circle, an ellipse, or some other definite curve. Radiation may become polarized because of the nature of its emitting source, as is the case with many types of radar antennas, or because of processes to which it is subjected after leaving its source, like the scattering of solar radiation as it passes through the Earth's atmosphere.

Predictability. The quality or state of being predictable or expected on the basis of observation, experience, or scientific reason.

Probabilistic forecasting. Determining the probability of occurrence of different weather events.

Probability. The chance that a prescribed event will occur, represented as a fraction between zero and one. The probability of an impossible event is zero, and of an inevitable event is one. Probability is estimated empirically by relative frequency, that is, the number of times a particular event occurs divided by the total count of all events in the class.

Radiation. 1. Electromagnetic energy being propagated through free space by virtue of joint variations in the electric and magnetic fields in space. 2. Energy propagated through any medium by virtue of the wave motion of that medium, as in the propagation of sound waves through the atmosphere or ocean waves along the water surface.

Radiance. The flux density of radiant energy per unit solid angle and per unit projected area of radiating surface.

Radio occultation. As applied in GPS meteorology, a technique whereby radio signals propagating from a GPS satellite to a LEO satellite are refracted by the Earth's atmosphere during about a 60 second period before the signal is occulted by the Earth, providing a refractivity profile of the atmosphere. From these measurements, temperature, pressure, and water vapor distributions can be determined.

Radio occultation technique. The use of GPS transmitter radio path delay profiles through the Earth's atmosphere to infer the thermodynamic structure of the atmosphere.

Radiosonde. A balloon-borne instrument for the simultaneous measurement and transmission of meteorological data.

Rawinsonde. Method of upper-air observation consisting of an evaluation of the wind speed and direction, temperature, pressure, and relative humidity aloft by means of a balloon-borne radiosonde tracked by a radar or radio direction-finder.

Soil moisture accounting. A hydrologic model used by the NWS that produces a river forecast based on calibrated six-hour historical rain gauge measurements combined with six-hour rainfall measurements and estimation of precipitation and run-off over a basin.

Sounding. 1. In geophysics, any penetration of the natural environment for scientific observation. 2. In meteorology, same as upper-air observation. However, a common connotation is that of a single complete rawinsonde observation.

Space weather. Conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and endanger human life or health. Adverse conditions in the space environment can disrupt satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socioeconomic losses.

Synoptic. In general, pertaining to or affording an overall view. In meteorology, this term has become somewhat specialized in referring to the use of meteorological data obtained simultaneously over a wide area for the purpose of presenting a comprehensive and nearly instantaneous picture of the state of the atmosphere.

Thermodynamics. In general, the relationships between heat and other properties (such as temperature, pressure, density, etc.).

Upper air. In synoptic meteorology and in weather observing, that portion of the atmosphere above the shallow layer of air closest to the Earth. No distinct lower limit is set, but the term is usually applied to levels above 1 kilometer from the surface.

Water vapor (also called `aqueous vapor, moisture`**).** Water substance in vapor form; one of the most important constituents of the atmosphere.

Weather. The state of the atmosphere near the ground as described by the temperature, pressure, humidity, wind speed and direction, cloud cover, visibility, cloud type, and the type and rate of precipitation.

Biographical Sketches of Panel Members and Advisors

PANEL MEMBERS

William E. Gordon (chair) is a member of the National Academy of Sciences and the National Academy of Engineering. His professional career has been devoted to designing and developing radio communication systems (e.g., tropospheric forward scatter) and powerful radars (e.g., incoherent scatter) for studying the Earth's atmosphere. During his military service and at the University of Texas, he studied the effects of atmospheric refraction on radars; he received a Ph.D. in electrical engineering from Cornell for work on radiowave propagation. He is known as "the father of the Arecibo Observatory" for his work, with others, in conceiving that facility and directing its design, construction, and early operations. He served as professor, dean of science and engineering, and provost at Rice University, where he is a distinguished professor emeritus. Dr. Gordon is also a member of the Japan National Academy of Engineering and a fellow of the American Association for the Advancement of Science, the American Geophysical Union, and the Institute of Electrical and Electronics Engineers. He received the van der Pol Medal from the International Union of Radio Science (URSI), the Arctowski Medal from the National Academy of Sciences, the Centennial Medal from the IEEE, and honorary medals from the Soviet Academy of Sciences and the Bulgarian Academy of Sciences.

Richard A. Anthes is president of the University Corporation for Atmospheric Research (UCAR), a nonprofit consortium that manages the National Center for Atmospheric Research (NCAR) and collaborates with many international meteorological institutions. Dr. Anthes received his B.S., M.S., and Ph.D. degrees from the University of Wisconsin-Madison. He has been a research scientist at the National Oceanic and Atmospheric Administration (NOAA), a professor of meteorology at Pennsylvania State University, and director of NCAR. Dr. Anthes, a fellow of the American Meteorological Society (AMS), was awarded the Meisinger and Charney awards of the AMS for his research on the theory and modeling of tropical cyclones and mesoscale meteorology. In addition to publishing more than 90 peer-reviewed articles and books, he has been a member or chair of more than 30 national committees for the National Aeronautics and Space Administration (NASA), NOAA, AMS, the National Science Foundation, and the National Research Council.

David Atlas is a distinguished visiting scientist at the NASA Goddard Space Flight Center, where he was formerly the director of the Laboratory for Atmospheric Sciences. He received his B.S. from New York University and his M.S. and D.Sc. from the Massachusetts Institute of Technology (MIT). He has been the chief of the Weather Radar Branch, Air Force Cambridge Research Laboratories, a professor at the University of Chicago, and a program director at NCAR. In addition to serving as president of the AMS, he received the Rossby, Meisinger, Abbe, and Remote Sensing awards of that society for his work in radio science and meteorology. He has also received awards from the American Institute of Aeronautics and Astronautics, the Royal Meteorological Society, and NASA. He was president of the Inter-Union Commission on Radio Meteorology of the URSI and the International Union of Geophysics and Geodesy.

Robert F. Brammer is currently a vice president and technical director at TASC, where he heads several inter-organizational technology programs for independent research and development, university research, and new business activities. He led the development of TASC's Computing Technology Center, where research is conducted on digital mapping, precision guidance, remote sensing, nondestructive testing, photo-sensor realistic scene generation, and computational fluid dynamics. The center also evaluates advanced computing architectures for the government and industry. In addition to a decade of work on Trident submarine programs at TASC, Dr. Brammer initiated programs to develop ground stations for meteorological satellites, which led to TASC's acquisition of WSI Corporation. TASC/WSI is the largest private-sector provider of value-added meteorological and oceanographic information services. Prior to joining TASC, Dr. Brammer worked on real-time software and ground-station engineering for Apollo and Skylab at NASA Goddard Space Flight Center. He also did research on adaptive control, coherent communications, and precise time transfer. Dr. Brammer received his B.S. degree from the University of Michigan and his M.A. and Ph.D. degrees in mathematics from the University of Maryland. He is a member of a number of professional and honorary societies.

Kenneth C. Crawford is a professor of meteorology at the University of Oklahoma, director of the Oklahoma Climatological Survey, and the state climatologist. He came to the university after 28 years with the National Weather Service (NWS), where he was a research meteorologist at the National Severe Storms Laboratory, an operational meteorologist, and a senior field manager. Professor Crawford is director of the Oklahoma Mesonet, a statewide network of 115 automated observing and transmitting stations, and the senior administrative official for the OK-FIRST project to improve the dissemination of weather information to local public safety officials. Dr. Crawford is a fellow of the AMS and has made numerous international presentations. He earned his B.S. from the University of Texas at Austin, his M.S. from Florida State University, and his Ph.D. from the University of Oklahoma.

George J. Gleghorn retired from TRW Space and Technology Group as vice president and chief engineer. During 37 years at TRW, he contributed to numerous "firsts" in space flight, including Pioneer I, the first NASA spacecraft; Pioneer 5, which reported the first data from interplanetary space; Intelsat III, the first satellite to broadcast live television worldwide; the Orbiting Geophysical Observatory; and NASA's tracking and data relay satellite. He also contributed to Pioneers 6, 10, and 11 and the development of the Atlas, Thor, and Titan ballistic missiles. Earlier, he worked at Hughes Aircraft and the Jet Propulsion Laboratory (JPL) and served in Korea as a naval officer. Dr Gleghorn holds a B.S. from the University of Colorado and a Ph.D. in electrical engineering and mathematics from the California Institute of Technology. He is a fellow of the American Institute of Aeronautics and Astronautics and a member of the National Academy of Engineering and the NASA Aerospace Safety Advisory Panel. He recently chaired two studies for the National Research Council on orbital debris and its potential effects on the International Space Station and has participated in design and readiness reviews for NASA spacecraft.

David S. Johnson worked for 26 years on the U.S. operational meteorological satellite program and the cooperative international network of meteorological satellites and ground stations. He retired from NOAA as the assistant administrator for satellites. After retirement, he consulted on remote sensing satellite systems and served for eight years as a study director at the National Research Council for the post-Challenger evaluation of NASA's risk management and as first director of the National Weather Service Modernization Committee. Mr. Johnson received A.B. and M.S. degrees in meteorology from the University of California, Los Angeles. He is a fellow of the AMS, American Geophysical Union, and American Astronautical Society and an associate fellow of the American Institute of Aeronautics and Astronautics. He was president of the AMS in 1974 and has received numerous awards from government agencies and professional societies.

Veronica F. Nieva is a social and organizational psychologist whose research has focused on evaluating the effectiveness of procedural, organizational, and technological interventions in public-sector organizations, military institutions, and private industry. Her consulting and research are aimed at understanding, measuring, and improving human resource and organizational functioning. She has also studied the work behaviors of women in relation to gender issues in the workplace at Westat. Dr. Nieva is a vice president and director of the Organizational and Management Research Group at Westat. Previously, she worked at The Urban Institute, the Advanced Research Resources Organization, and the Institute for Social Research (University of Michigan). She has taught at the Ateneo de Manila University in the Philippines and the University of Michigan. Dr. Nieva holds an M.A. and Ph.D. in organizational psychology from the University of Michigan and an M.A. in social psychology from the Ateneo de Manila University. She has published two major books and numerous articles and technical reports.

Dorothy C. Perkins is deputy associate director of flight projects for Earth Observing System (EOS) Information Systems at NASA Goddard Space Flight Center where she is in charge of implementing the EOS Data and Information System, which includes the ground systems for spacecraft control and the processing, archiving, and distribution of scientific data from the NASA Earth Sciences Enterprise missions. She previously served as deputy director of applied engineering and technology at Goddard, mission services manager for the NASA Space Operations Management Office, chief of the Mission Operations and Systems Development Division at Goddard, and manager of information system technology programs at Goddard.

Robert J. Serafin worked at Hazeltine Research Corporation, where he designed and developed high-resolution radar systems, and then at Illinois Institute of Technology (IIT) and IIT Research Institute. He joined NCAR as manager of the Field Observing Facility, and, in 1980, he became director of the Atmospheric Technology Division. Since

1989, he has been director of NCAR. Dr. Serafin has published more than 50 technical and scientific papers, holds three patents, and founded the *Journal of Atmospheric and Oceanic Technology*. He received B.S., M.S., and Ph.D. degrees in electrical engineering from Notre Dame University, Northwestern University, and IIT, respectively. He has served on several National Research Council studies, and was chair of the National Weather Service Modernization Committee. He is a member of the National Academy of Engineering and a fellow of the AMS and the IEEE.

Paul L. Smith is professor emeritus at the South Dakota School of Mines and Technology. Dr. Smith received a B.S. in physics and an M.S. and Ph.D. in electrical engineering from the Carnegie Institute of Technology, where he subsequently was on the faculty. He worked at Midwest Research Institute before moving to the Institute of Atmospheric Sciences, where he served as director from 1981 to 1996. His major research interests are radar meteorology, cloud physics, and weather modification. Dr. Smith has held numerous other posts, including an postdoctoral fellow at the National Science Foundation; visiting professor in meteorology at McGill University; chief scientist at Air Weather Service Headquarters, Scott Air Force Base; visiting scientist at the Alberta Research Council; Fulbright Lecturer in radar meteorology at the University of Helsinki; and member of the executive committee of the International Commission on Clouds and Precipitation. He has twice chaired the AMS Committee on Radar Meteorology and is currently on the NEXRAD Technical Advisory Committee.

Arthur I. Zygielbaum is the director of research and development, as well as the assistant director, of Nebraska Educational Telecommunications, which is associated with the University of Nebraska, Lincoln. He took these posts in 1998, after 30 years at the JPL, where his positions included manager of Science Information Systems, deputy manager of the Information Systems Division, and co-principal investigator for the Consortium for the Application of Space Data to Education. At JPL, Mr. Zygielbaum developed systems for spacecraft navigation, measurement of solar charged particle densities, and tests of general relativity theory. He also created JPL's Minority Science and Engineering Initiatives Program. Mr. Zygielbaum holds a B.S. in physics from the University of California, Los Angeles, and an M.S. in electrical engineering from the University of Southern California. He holds several patents, has received numerous NASA awards, and served on the National Weather Service Modernization Committee.

ADVISORS

William D. Bonner, senior research associate at NCAR, spent 20 years with the NWS as director of the eastern region, deputy director of the NWS, and director of the National Meteorological Center. His Ph.D. in geophysical sciences (meteorology) is from the University of Chicago. He has taught at the University of California, Los Angeles, and the University of Maryland. For his NWS service, he received two Senior Executive Service awards (presidential rank) and the Department of Commerce Gold Medal. An AMS fellow and past president, Dr. Bonner served twice on the AMS Council.

Dara Entekhabi, an assistant professor in hydroclimatology and hydrometeorology at MIT, holds two M.A. degrees, in statistical climatology and stochastic hydrology, from Clark University and a Ph.D. in civil engineering (global hydrology and climate modeling) from MIT. He is a member and fellow of the American Geophysical Union, a member of the AMS, and a member of the National Weather Service Modernization Committee.

Charles L. Hosler is a fellow and past president of the AMS and a member of the National Academy of Engineering. From 1947 to 1991, he was on the faculty of Pennsylvania State University, where he was professor and head of the Department of Meteorology, dean of the College of Earth and Mineral Sciences, senior vice president for research, dean of the graduate school, acting executive vice president, and provost. He was chairman of the board and acting president for UCAR and has served on the National Advisory Committee for Oceans and Atmosphere, the National Science Board, and the World Meteorological Organization's panel of experts on education and training. For the National Research Council, Dr. Hosler chaired the Board on Atmospheric Sciences and Climate and the National Weather Service Modernization Committee, as well as serving on many other panels and committees. He currently chairs the board of the Penn State Research Foundation. He has an M.S. and Ph.D. from Pennsylvania State University.

Albert J. Kaehn, Jr., retired from the U.S. Air Force with the rank of brigadier general after commanding the Air Weather Service. Prior to that post, he served as commander of the Third Weather Wing at Offutt Air Force Base; as the assistant for environmental sciences in the Office of the Undersecretary, Defense Research and Engineering; and in various other command and staff positions in the Air Weather Service. He received an M.A. in mathematics from the State University of New York and a B.S. in meteorology from Pennsylvania State University. He is a fellow and past president of the AMS and has served on its executive and governing councils. For his Air Force service, he received, among other honors, the Air Force Distinguished Service Medal, the Legion of Merit, and a Bronze Star. After retiring, General Kaehn worked for Global Weather Dynamics, Inc., and Harris Corporation; he is currently a consultant on organization, management, system development, and business development. He has chaired several committees for the National Research Council.