WHEN WEATHER MATTERS

Science and Services to Meet Critical Societal Needs

Committee on Progress and Priorities of U.S. Weather Research and Research-to-Operations Activities

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

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Preface

Every 2 or 3 years, the National Research Council's Board on Atmospheric Sciences and Climate (BASC) conducts a Summer Study workshop on a subject selected by BASC as topical and important. The subject of the 2009 BASC Summer Study workshop was "Progress and Priorities of U.S. Weather Research and Research-to-Operations Activities." About 50 experts in various aspects of weather research and operations joined the eight committee members and BASC staff for 2 full days of presentations, discussion, and debate; Appendix E contains the workshop agenda, and Appendix F lists the workshop participants. The workshop provided a foundation of ideas and information for this report. To build upon the information-gathering workshop, the committee held three in-person meetings and several teleconferences and undertook additional study to elaborate on many of the findings and questions from the workshop. This report has been peer-reviewed and contains recommendations that are primarily addressed to the sponsoring federal agencies.[1] However, virtually all of the eight major recommendations are also germane to the academic community and the private sector. In addition to specific research and transitional research-to-operations (R2O) aspects of the recommendations, there are also numerous references to the need to maintain, create, and nourish effective partnerships among the public, private, and academic sectors. This is especially the case with regard to transitioning research findings into operations, but it applies as well to many of the research needs identified in the study. Fully realizing the potential for vastly improved weather knowledge, information, and forecasts requires close collaboration among all three sectors of the weather enterprise in the United States. Our nation has the advantage of having the most sophisticated and well-developed private weather sector in the world, and this will

[1]This study was organized by the National Research Council with funding from the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the National Science Foundation.

aid us in realizing that potential more quickly and effectively. The strength of the domestic private weather sector is in large part a consequence of its interactions with the federal agencies and academia. The committee hopes that this report will provide readers with an even greater appreciation of the value of the interactions and feedbacks among the three sectors.

This report is not a comprehensive assessment of the state of U.S. weather research and the transition of research findings and products into operations but instead is a snapshot of the weather community as gauged by the workshop participants and the study committee. Further, the report does not seek to address important issues uniquely related to climate research nor does it touch on intra- and interagency organizational procedures and practices. Instead, the report puts forth the committee's best judgment on the most pressing high-level, weather-focused research challenges and R2O needs and makes corresponding recommendations. These are made pertaining to a broad set of ongoing or "established" issues that include observations, global nonhydrostatic modeling, data assimilation, probabilistic forecasting, quantitative precipitation and hydrologic forecasting, and predictability. The report also identifies three important, "emerging" issues—very high impact weather, urban meteorology, and renewable energy development—that were not identified (or were largely undervalued) in previous studies.

The committee could not have done its work without the professional and collegial support of the BASC staff throughout. They organized the summer workshop on very short notice, served as reporters and participants in the workshop's small-group discussions, managed the various committee meetings, and took care of the many important details in organizing this report. The committee's sincere thanks and acknowledgment are gratefully extended to Dr. Maggie Walser, Associate Program Officer; Dr. Toby Warden, Program Officer; Dr. Curtis Marshall, Senior Program Officer; Ms. Lauren Brown, Research Assistant; Ms. Rita Gaskins, Administrative Coordinator; and Ms. JaNeise Sturdivant, Program Assistant. The committee also thanks all of the invited experts who gave so freely of their time and participated in the summer workshop (please refer to Appendixes E and F) and extends special appreciation to Dr. Alexander "Sandy" MacDonald, Director, National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Earth Systems Research Laboratory (ESRL), who could not attend the summer workshop but instead made a presentation on ESRL research perspectives at the committee's October 6–7, 2009, meeting in Boulder, Colorado. Last, the committee extends its thanks and appreciation to the experts who reviewed the draft of this report. Their comments were most insightful and extremely helpful.

For my part, this has been a rewarding experience to have worked with and learned from so many who are so obviously devoted to our science and what it can do for humanity.

Walter F. Dabberdt, *Chair*
Committee on Progress and Priorities
of U.S. Weather Research and
Research-to-Operations Activities

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 (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its 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 review of this report:

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Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by **Lee Branscome**, Climatological Consulting Corporation Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary

The goal of weather prediction is to provide information people and organizations can use to reduce weather-related losses and enhance societal benefits, including protection of life and property, public health and safety, and support of economic prosperity and quality of life. In economic terms, the benefit of the investment in public weather forecasts and warnings is substantial: the estimated annualized benefit is about $31.5 billion, compared to the $5.1 billion cost of generating the information (Lazo et al., 2009). Between 1980 and 2009, 96 weather disasters in the United States each caused at least $1 billion in damages, with total losses exceeding $700 billion (NCDC, 2010). Between 1999 and 2008, there were an average of 629 direct weather fatalities per year (NWS, 2010). The annual impacts of adverse weather on the national highway system and roads are staggering: 1.5 million weather-related crashes with 7,400 deaths, more than 700,000 injuries, and $42 billion in economic losses (BTS, 2007). In addition, $4.2 billion is lost each year as a result of weather-related air traffic delays (NOAA, 2010). Weather is also a major factor in the complex set of interactions that determine air quality; more than 60,000 premature deaths each year are attributed to poor air quality (Schwartz and Dockery, 1992).

Better forecasts and warnings are reducing these numbers, but much more can be done. The past 15 years have seen marked progress in observing, understanding, and predicting weather. At the same time, the United States has failed to match or surpass progress in operational numerical weather prediction (NWP) achieved by other nations and failed to realize its prediction potential (UCAR, 2010); as a result, the nation is not mitigating weather impacts to the extent possible.

This report represents a sense of the weather community as guided by the discussions of a Board on Atmospheric Sciences and Climate community workshop held in summer 2009. It is not a comprehensive assessment of the state of U.S. weather research and the transition of research findings and products into operations. Further, the report does not seek to address important issues uniquely related to climate research nor does it touch on intra- and interagency organizational procedures and practices. Instead, the report puts forth the committee's judgment on the most pressing high-level, weather-focused research challenges and research-to-operations (R2O) needs, and makes corresponding recommendations. This report addresses issues including observations, global nonhydrostatic coupled modeling, data assimilation, probabilistic forecasting, and quantitative precipitation and hydrologic forecasting.

The report also identifies three important, emerging issues—predictions of very high impact (VHI) weather, urban meteorology, and renewable energy development—not recognized or emphasized in previous studies. Cutting across all of these challenges is a set of socioeconomic issues, whose importance and emphasis, although increasing, has been undervalued and underemphasized in the past and warrants greater recognition and priority today.

IMPROVE SOCIOECONOMIC RESEARCH AND CAPACITY

Socioeconomic considerations are fundamental in determining how, when, and why weather information is, or is not, used. They are an extremely important component of weather research and R2O (and also transfers from operations to research, O2R). Yet the weather prediction enterprise still lacks interdisciplinary capacity to understand and address socioeconomic issues. Socioeconomic expertise is underutilized in the weather community. There are key gaps in the socioeconomics of weather that, when filled, will substantially benefit the weather community and, more importantly, society at large. The committee identified three priority topics in the socioeconomics of weather information requiring attention: estimating its value, understanding its interpretation and use, and improving communication of information. Until these gaps are filled, the value of the work of the weather community will not be realized in the broader context of advancing weather prediction capabilities for societal benefit. The committee's vision is that by ~2025, a core group of social scientists and meteorologists will form a strong, mutually beneficial partnership in which multiple areas of science work together to ensure weather research and forecasting meet societal needs.

Recommendation: The weather community and social scientists should create partnerships to develop a core interdisciplinary capacity for weather-society research and transitioning research to operations, starting with three priority areas:

- **estimating the societal and economic value of weather information;**
- **understanding the interpretation and use of weather information by various audiences; and**
- **applying this knowledge to improve communication, use, and value.**

To be effective, the partnership between the weather community and social scientists should be two-way and balanced, and should include a variety of social science perspectives. Members of the weather community, including research institutions, universities, individual meteorologists, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation, and other agencies, should pursue multiple mechanisms for building research and R2O capacity in the socioeconomics of weather, including long-term interdisciplinary programs; grant-funded and directed research, R2O, and applications activities; integrated social–physical science testbeds; mission agency programs to develop capacity; and educational initiatives. The required capacity should be developed and utilized through partnerships across agencies, programs, and disciplines, and in concert with academia and the private sector.

CONTINUE PURSUING ESTABLISHED WEATHER RESEARCH AND TRANSITIONAL NEEDS

There are multiple research and transitional goals that have been recognized for some time as important and achievable but have yet to be realized; moreover, all have significant societal benefits and needs for input from social scientists. The committee refers to these as *established* priorities. Four are identified: global nonhydrostatic coupled modeling, quantitative precipitation forecasting, hydrologic prediction, and mesoscale observations.

Predictability and the Need for Global Nonhydrostatic Coupled Models

Global nonhydrostatic NWP models[1] coupled with ocean and land models are essential as the spatial resolution of models continues to increase, especially with grid spacing less than 10 km. High-resolution nonhy-

[1] Nonhydrostatic NWP models are atmospheric models in which the hydrostatic assumption is not made, so that the vertical momentum equation is solved. As model resolution increases, the model grid spacing decreases and the applicability of the hydrostatic assumption similarly decreases.

drostatic models (with grid spacing around 2 km) remove the dependence of the model on convective parameterizations, which has been a major barrier to progress in weather forecasting.

A number of key capabilities remain to be developed for nonhydrostatic coupled models: explicitly resolved convection in global models; advanced assimilation of convective-scale observations that eliminates precipitation spin-up and improves initial conditions; improvements in cloud microphysics and physics of the planetary boundary layer (PBL); atmospheric coupling to ocean and land models; and convective-scale ensemble prediction and post-processing systems.

Observations remain inadequate to optimally run and evaluate most high-resolution models and determine forecast skills at various temporal and spatial scales. Perhaps even more challenging is the need to develop suitable and effective verification and evaluation metrics and methods for determining probabilistic forecast skill at different scales. Improved data assimilation as part of the forecast system is also important for acquiring and maintaining up-to-date observing systems. High-resolution and ensemble forecasts require significant increases beyond the National Centers for Environmental Prediction's current high-performance computing capacity for model predictions but also for data assimilation, post-processing, and visualization of the unprecedented large volumes of data.

There is also a pressing need for basic research to more fully understand the inherent predictability of weather phenomena at different temporal and spatial scales. Because of error growth across all scales, from cumulus convection to mesoscale weather and large-scale circulations, a high-resolution (preferably cloud-resolvable) nonhydrostatic global model is crucial to address error growth and better understand the predictability of global weather systems.

Recommendation: Global nonhydrostatic coupled atmosphere–ocean–land models should be developed to meet the increasing demands for improved weather forecasts with extended timescales from hours to weeks.

These modeling systems should have the capability for different configurations: as a global model with a uniform horizontal resolution; as a global model with two-way interactive finer grids over specific regions; and as a regional model with one-way coupling to various global models. Also required are improved atmospheric, oceanic, and land observations, as well as significantly increased computational resources to support the development and implementation of advanced data assimilation systems such as four-dimensional variational (4DVar), ensemble Kalman filter (EnKF), and hybrid 4DVar and EnKF approaches.

Quantitative Precipitation Forecasting

Quantitative precipitation forecasts (QPFs[2]) are especially important for many societal issues but are much less skillful than forecasts of meteorological state parameters (pressure, temperature, and humidity) and winds (Fritsch and Carbone, 2004). QPF skill, although lagging progress in forecasting other variables, has nonetheless increased steadily but slowly over the past 30 years. Forecasts are more skillful at shorter range and lesser cumulative precipitation amounts, which occur much more frequently than heavy or extreme events. Considerable skill has been achieved in the dynamical prediction of cool-season orographic precipitation, which accounts for much of the skill associated with the winter season. Forecast ability for precipitation associated with extratropical fronts and cyclones is increasingly skillful at synoptic scales.

However, the least skillful predictions occur under weakly forced conditions when local variability and physical factors are more likely to exert influence on precipitation occurrence and amount. General circulation models used for operational weather prediction have not represented convective precipitation systems explicitly but rather have used parameterizations. The limitations of cumulus parameterizations and the subsequent lack of predictive skill (Fritsch and Carbone, 2004) have led to the conclusion that short-range weather prediction applications need to explicitly represent deep moist convection in forecast models.

Predicting the probable location of convective rainfall events is also dependent upon improving initial and boundary conditions in the forecast models. With respect to the lower troposphere, PBL depth and high-resolution vertical profiles of wind and water vapor are necessary, together with surface analyses that are skillful in capturing mesoscale variability on a scale of approximately 10 km or less.

Mesoscale ensemble prediction techniques need to be further exploited with respect to skill in explicit predictions of moist convection and accompanying precipitation. This includes trade-offs between the number of members and their spatial resolution, and issues related to member generation and

[2] QPF refers to forecasts of precipitation that are quantitative (e.g., millimeters of rain, centimeters of snow) rather than qualitative (e.g. light rain, flurries), indicating the type and amount of precipitation that will fall at a given location during a particular time period.

selection. Ensemble predictions hold promise to mitigate and quantify forecast uncertainty, especially with respect to the detailed time and location of specific events for which the intrinsic limits of predictability are uncertain.

> **Recommendation: To improve the skill of quantitative precipitation forecasts, the forecast process of the National Weather Service should explicitly represent deep convection in all weather forecast models and employ increasingly sophisticated probabilistic prediction techniques.**
>
> Global and regional weather forecast models should represent organized deep convection explicitly to the maximum extent possible, even at resolutions somewhat coarser than 5 km, as may be necessary initially, in the case of global models. Explicit representation should markedly improve forecast skill associated with the largest and highest impact precipitation events. The introduction of explicit convection will likely require the refinement of microphysical parameterizations, boundary-layer and surface representations and other model physics, which are, in themselves, formidable challenges.
>
> Probabilistic prediction should be vigorously pursued through research and the development and use of increasingly sophisticated ensemble techniques at all scales. New tools need to be developed for verification of probabilistic, high-resolution ensemble model forecasts, eventually supplanting equitable threat scores.

Hydrologic Prediction

An advanced hydrologic modeling system requires the ability to translate precipitation forecasts into similarly accurate, distributed runoff and streamflow predictions by invoking the physical mechanisms of runoff generation, snow accumulation, surface-groundwater exchanges, river and floodplain routing, river hydraulic routing, and agricultural and other consumptive uses. These elements of an advanced hydrologic prediction system are far from being well observed, far from being well understood, far from being appropriately represented in numerical prediction models, and far from being even rudimentarily verified. Major changes in hydrologic research and infrastructure are needed to meet the pressing societal and economic demands of flood protection and water availability.

In the meteorological and atmospheric sciences community, advances in NWP and climate modeling have been enabled to a large degree by the development of community-supported and -developed models. In the hydrologic community, no equivalent effort exists. Development of a robust hydrologic forecast capacity will require a strategic commitment to a systematic hydrologic prediction framework effort that brings together (1) the collective resources of the hydrologic community in establishing a unified hydrologic observational, research, and modeling agenda; (2) the atmospheric and hydrologic communities in developing, testing, and improving a fully coupled atmospheric–hydrologic prediction system; and (3) the research and operations communities to jointly identify research priorities that fill important gaps in the application of hydrologic products by government agencies and the private sector. A verified distributed model is certain to accelerate both R2O and O2R transitions and serve other user communities.

Recommendation: Improving hydrologic forecast skill should be made a national priority. Building on lessons learned, a community-based coupled atmospheric–hydrologic modeling framework should be supported to accelerate fundamental understanding of water cycle dynamics; deliver accurate predictions of floods, droughts, and water availability at local and regional scales; and provide a much needed benchmark for measuring progress.

To successfully translate the investment in improved weather and climate forecasts into improved hydrologic forecasts at local and regional scales, and meet the pressing societal, economic, and environmental demands of water availability (floods, droughts, and adequate water supply for people, agriculture, and ecosystems), an accelerated hydrologic research and R2O strategy is needed. Fundamental research is required on the physical representation of water cycle dynamics from the atmosphere to the subsurface, probabilistic prediction and uncertainty estimation, assimilation of multisensor observations, and model verification over a range of scales. Integral to this research are integrated observatories (from the atmosphere to the land and to the subsurface) across multiple scales and hydrologic regimes.

Mesoscale Observational Needs

Improved observing capabilities at the mesoscale[3] are an explicit aspect of every weather priority identified in this study, including socioeconomic

[3] The *Glossary of Meteorology* (Glickman, 2000) defines mesoscale as "Pertaining to atmospheric phenomena having horizontal scales ranging from a few to several hundred kilometers, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones, and topographically generated weather systems such as mountain waves and sea and land breezes."

priorities such as reduction in vulnerability for dense coastal populations, and improvements in forecasts at the scale of flash floods and routinely disruptive local weather. Observations at the mesoscale are increasingly important to establishing initial conditions for global models as resolution improves. These include observations that either resolve mesoscale atmospheric structure or uniquely enable mesoscale NWP. The emphasis on mesoscale observations is motivated by the scale and phenomenology associated with disruptive weather; the necessity to understand it, detect it, and warn of the potential consequences; and improved capacity to specifically predict or otherwise anticipate it at very short to short ranges (0 to 48 hours).

A national mesoscale observing network is needed for a wide variety of stakeholders inclusive of basic and applied researchers, intermediate users associated with weather–climate information providers, and a wide variety of end users at all levels of government and numerous commercial sectors. Satellite observations are expected to assume a primary role at altitudes above the continental PBL.

There is a pressing need for research and development leading to improved mesoscale data assimilation techniques in operational forecast systems. Improved analyses require better knowledge of systematic errors in observations, especially because mesoscale data are often sparse or patchy, and relatively poorly documented compared to those from standard synoptic observations. The structure and variability of the lower troposphere is not well known because vertical profiles of water vapor, temperature, and winds are not systematically observed at the mesoscale (Schlatter et al., 2005). The sensitivity to these observation gaps is not well understood but is likely substantial in urban (Dabberdt et al., 2000) and coastal (Droegemeier et al., 2000) regions where population density is high and in mountainous regions, which are a proximate cause for major forecast errors downstream (Smith et al., 1997). The relative absence of high-resolution PBL profiles impedes progress in skillful predictions at the mesoscale over both land and coastal waters. Mesoscale predictability is dependent, to some considerable degree, on mesoscale initial conditions. This is especially true with respect to specific predictions of deep moist convection and attendant heavy rainfall and severe weather (Fritsch and Carbone, 2004).

Mesoscale observations need to be a focus of testbeds intended to develop and introduce new paradigms in environmental observation. This is particularly important and urgent with respect to fully integrating methods in nowcasting with dynamical prediction in the 0- to 6-hour range, thereby improving performance in severe weather, hydrologic forecasts, and routinely disruptive weather.

Recommendation: Federal agencies and their partners should deploy a national network of profiling devices for mesoscale weather and chemical weather prediction purposes. Such devices should incorporate capabilities that extend from the subsurface to 2–3 km above the surface level. The entire system of observations in support of mesoscale predictions should be coordinated, developed, and evaluated through test-bed mechanisms.

As a high infrastructure priority, optical and radio-frequency profilers should be deployed nationally at approximately 400 sites to continually monitor lower tropospheric meteorological conditions. To meet national needs in support of chemical weather forecasts, a core set of atmospheric pollutant composition profiles should be obtained at approximately 200 urban and rural sites. To meet national needs for representative land–atmosphere latent and sensible heat flux data, a national, real-time network of soil moisture and temperature profile measurements should be made to a nominal depth of 2 m and deployed nationwide at approximately 3,000 sites.

Federal agencies, together with state, private-sector, and nongovernmental organizations, should employ mesoscale testbeds for applied research and development to evaluate and integrate national mesoscale observing systems, networks thereof, and attendant data assimilation systems as part of a national 3D network of networks.

INCREASE ATTENTION TO EMERGING WEATHER RESEARCH AND TRANSITIONAL NEEDS

Several research and R2O needs have come to be recognized over the past 5 to 10 years as increasingly important, yet remain in the early stages of understanding or implementation. These are denoted as *emerging* weather research and transitional needs, in contrast to established needs. Three high-priority emerging needs are identified: VHI weather, urban meteorology, and renewable energy development.

Very High Impact Weather

VHI weather is defined here as weather that endangers public health and safety or causes significant economic impacts, including

1. severe and disruptive weather hazards that change rapidly on the timescale of minutes to hours or a few days, and

2. persistent weather hazards that occur on longer timescales of days to weeks or even years (e.g., drought).

Advancing the understanding, monitoring, and prediction of VHI phenomena and impacts requires improving the accuracy and timeliness of observations, forecasts, and warnings in order to develop an efficient response system that helps minimize and mitigate hazardous weather impacts.

A new paradigm for the coming decades is the expansion in emphasis from weather prediction alone to the prediction of weather *and* related impacts. This expansion necessitates development of new modeling and observational tools, innovative forecast guidance products, and methods of information and warning dissemination. This shift also demands full integration of the physical and socioeconomic sciences.

One major challenge for such an expansion is to exploit ensemble modeling more fully to produce quantitative probabilistic forecasts of atmospheric quantities with estimates of uncertainty, and for these to then be used to generate probabilistic forecasts of the impacts and risks of pending VHI weather situations, thereby enabling improved decision making. Teams of physical scientists, social scientists, and professionals from user groups will need to work together to define the needed observations and impact parameters.

Recommendation: The federal agencies and their state and local government partners, along with private-sector partners, should place high priority on providing not only improved weather forecasts but also explicit impact forecasts. An effective integrated weather impacts prediction system should utilize high-quality and high-resolution meteorological analysis and forecast information as part of coupled prediction systems for VHI weather situations.

This will require

- fundamental research in both the physical and social sciences to improve understanding and prediction of VHI weather phenomena, and the provision of warnings and risk assessments in support of decision making;
- development of impact parameters and representations for multiple applications (e.g., morbidity, electric grid vulnerability, storm surge and flood inundation areas);
- research to determine and obtain critical and timely observations;
- end-to-end participation by multiple sectors and disciplines (including modelers, observationalists, forecasters, social scientists, and

end users) to jointly design and implement impact-forecasting systems; and

- multidisciplinary undergraduate and graduate programs that can address the emerging field of VHI weather–impacts prediction, risk assessment and management, and communication through fully integrated research, education, and training for the new generation of scientists, forecasters, emergency managers, and decision makers.

Urban Meteorology

Urbanization of the world's population has given rise to more than 450 cities around the world with populations in excess of 1 million and more than 25 so-called megacities with populations over 10 million (Brinkhoff, 2010). The United States today has a total resident population of more than 308,500,000,[4] with 81 percent residing in cities and suburbs as of mid-2005 (UN, 2008).

Urban meteorology is the study of the physics, dynamics, and chemistry of the interactions of Earth's atmosphere and the urban built environment, and the provision of meteorological services to the populations and institutions of metropolitan areas. Although the details of such services are dependent on the location and the synoptic climatology of each city, there are common themes, such as enhancing quality of life and responding to emergencies. Experience elsewhere (e.g., Shanghai, Helsinki) shows urban meteorological support is a key part of an integrated or multihazard warning system that considers the full range of environmental challenges and provides a unified response from municipal leaders.

A national initiative to enhance urban meteorological services is a high-priority need for a wide variety of stakeholders, including the general public, commerce and industry, and all levels of government. Some of the activities of such an initiative include conducting basic research and development; prototyping and other R2O activities to enable very short- and short-range predictions; supporting and improving productivity and efficiency in commercial and industrial sectors; and urban planning for long-term sustainability.

Urban testbeds are an effective means for developing, testing, and fostering the necessary basic and applied meteorological and socioeconomic research, and transitioning research findings to operations. An extended, multiyear period of continuous effort, punctuated with intensive observing and forecasting periods, is envisioned.

Recommendation: The federal government, led by the National Oceanic and Atmospheric Administration, in concert with multiple public

[4]See http://www.census.gov/main/www/popclock.html.

and private partners, should identify the resources needed to provide meteorological services that focus on where people live, beginning with a high-priority urban meteorology initiative to create infrastructure, products, and services tailored to the special needs of cities.

Although NOAA should be the lead agency in such an initiative, its success will require effective partnerships with other federal, state, and local government agencies, academia, and the private sector, as well as with all sectors of the user community, both public and private. Under the leadership of NOAA, a consortium of national and local partners should establish a small number of urban testbeds for the purpose of determining urban user needs for tailored meteorological information and then developing, testing, and evaluating various observing, modeling, and communication strategies for providing those end users with an effective suite of societally relevant and cost-effective products and services to meet those needs. The goal of such testbeds would be to conduct or foster the necessary basic and applied research and then transition the research findings together with the practical lessons learned into operations, and to extend these capabilities, appropriately scaled, to cities across the nation.

Renewable Energy Development

The production of energy from renewable sources—hydro, biomass, geothermal, municipal waste, wind, and solar—is an integral part of the challenge to reduce reliance on fossil fuels, achieve a meaningful measure of energy independence, and minimize anthropogenic climate change. Electricity generation from renewable resources represents a small yet rapidly growing fraction that is projected to produce 14 percent of total domestic generation in 2030. However, there are significant weather dependencies and uncertainties that challenge the use of renewable energies—especially wind and solar—in a production and distribution system that must provide stable and reliable electric power where and when it is needed.

There are a host of weather-related research and operational challenges that will need to be met to provide reliable and predictable wind power. These challenges pertain to wind turbine design and operation, wind energy exploration, wind plant siting and design, wind integration, and the effects of a changing climate. Like so many other weather research and R2O priorities, those pertaining to wind energy involve both observations and modeling and include

- **Exploration:** Assessing the wind energy resource requires observations to quantify the distribution of wind speed as a function of location, time, and height.
- **Wind turbine design:** Because of their large span, wind turbines are exposed to variable atmospheric stresses, which place demands on their design that require detailed knowledge of mean and turbulent flow conditions.
- **Wind plant architecture:** The design of wind parks and their power generating efficiency heavily depend on wake interactions and interferences among neighboring turbines, and the effects of local topography.
- **Operations:** Wind forecasts on the 6- to 48-hour timescale are important for projecting wind energy production, but wind park operations are also susceptible to "wind ramp" events—abrupt, major changes in wind speed. Managing wind power integration on the 30-minute to 6-hour timescale requires accurate very short range NWP and nowcasts.

The current state of mesoscale observations is inadequate to support the high-resolution modeling needs of the wind energy industry. Meteorological observations—primarily wind and turbulence, but also temperature—are required to aid in wind park assessment, siting, and design and to assess the performance of individual wind turbines. Because of the significant vertical extent of large wind turbines and the effects of wind shear and turbulence, it is essential to have detailed wind structure information up to heights of ~0.5 km above ground level.

A hierarchy of models, each simulating a cascade of spatial scales, is required to address various wind-dependent aspects of wind turbine and wind park design and operation, including computational fluid dynamics models; very high resolution atmospheric (including large-eddy simulation) models; high-resolution mesoscale models, and nowcasting methods.

Solar energy systems produce electricity, directly or indirectly, from ambient sunlight. Like wind, the availability of solar power is also highly variable in space and time. Developers of large solar plants and utilities using distributed photovoltaic systems have common needs for reliable observations of solar radiation, historical and real-time databases, and accurate forecasts on a variety of scales.

Existing historical, national databases are based on in situ measurements from a few tens of surface-based radiometers together with satellite cloud imagery and analytical interpolation algorithms. However, the accuracy of the hourly estimates of surface solar irradiance from satellite imagery is inadequate (only ±20 percent), and the spatial database resolution of ≥10 km does not meet many users' needs for 1-km data.

Utility operators require historical data and solar resource forecasts on several timescales: ≤3 hours for "dispatching" to enable a steady power supply to the grid; 24 to 72 hours for system operations planning; and seasonal to interannual forecasting for economic analyses and system planning. There is currently no existing operational solar forecasting capability that meets user needs. These needs include highly resolved (15 minutes and sometimes less) short-range forecasts that, in turn, require more site-specific in situ downwelling solar and infrared radiation measurements, improved satellite estimates, better extrapolation methods, and reliable, operational solar forecasting not available today.

Improved observations, simulations, and predictions of wind and turbulence, and solar radiation, are needed with high spatial and temporal resolution and accuracy to optimally locate, design, and operate wind and solar energy facilities. These efforts will require a focused, high-priority national research and R2O program that is carefully and closely integrated with the mesoscale observing and predicting initiatives and socioeconomic actions recommended throughout this report. To be successful, these efforts will require effective collaborations and partnerships among power system designers, operators, grid managers, observationalists, researchers, forecasters, and modelers.

Recommendation: The effective design and operation of wind and solar renewable energy production facilities requires the development, evaluation, and implementation of improved and new atmospheric observing and modeling capabilities, and the decision support systems they enable. The federal agencies should prioritize and enhance their development and support of the relevant observing and modeling methods, and facilitate their transfer to the private sector for implementation.

CONCLUSION

An active dialogue is needed among stakeholders representing a wide range of disciplines and organizations. One approach that has been effective in the past is for the federal agencies to initiate and lead such a dialogue through a community "weather summit" that brings the parties together to identify priorities and define specific actions to establish a cohesive approach to the planning of weather research and R2O.

As our nation's weather challenges have changed, so must our scientific research and operational priorities change. The various socioeconomic, established, and emerging issues identified in this report require increased attention. This involves undertaking the needed research and transferring the important research results into operations. The community also needs to establish and nurture effective partnerships among government, academia, and industry. As such, this report and its recommendations are relevant to all parties in the weather enterprise: agency decision makers, policy makers, research scientists, private-sector applications specialists, teachers, public and private user groups and organizations, and the general public.

1

Introduction

Does weather matter? Weather is an integral part of daily life (Figure 1.1). Weather has enormous impact on the economy, public health, and safety in the United States and worldwide. Although the benefit of public weather forecasts and warnings cannot be fully measured in economic terms alone, a recent survey has nevertheless estimated its annualized value at about $31.5 billion, compared to a $5.1 billion cost to generate the information (Lazo et al., 2009).

The goal of weather prediction is to provide information that people and organizations—including public officials, government agencies, businesses, and private citizens—can use to reduce weather-related losses and enhance benefits. Weather and weather forecasts matter for a wide range of societal[1] goals, most notably protection of life and property, public health and safety, and support of economic prosperity and quality of life in conjunction with many issues, such as water resource management, sustainable energy development and food production, and transportation.

Weather-related disasters result in significant loss of life and property and disruption to communities and businesses. Between 1980 and 2009 there were 96 disasters in the United States that each caused at least a billion dollars in damage due to very high impact weather events along with total losses exceeding $700 billion (NCDC, 2010; Figure 1.2). On average for the period 1999 to 2008, there were 629 directly caused weather fatalities (NWS, 2010; Figure 1.3), but averages do not tell the whole story. In 1995, there were 1,362 direct weather fatalities, of which more than half were caused by a severe heat wave in Chicago. The most disastrous weather year in the last half century in the United States was 2005, due in large part to

[1]Economic considerations are a type of societal consideration; thus, in the remainder of this report, the term "societal" includes "economic." The "social sciences" are an assembly of scientific disciplines that address social and economic issues; see the introductory paragraphs of Chapter 2 for a more detailed discussion.

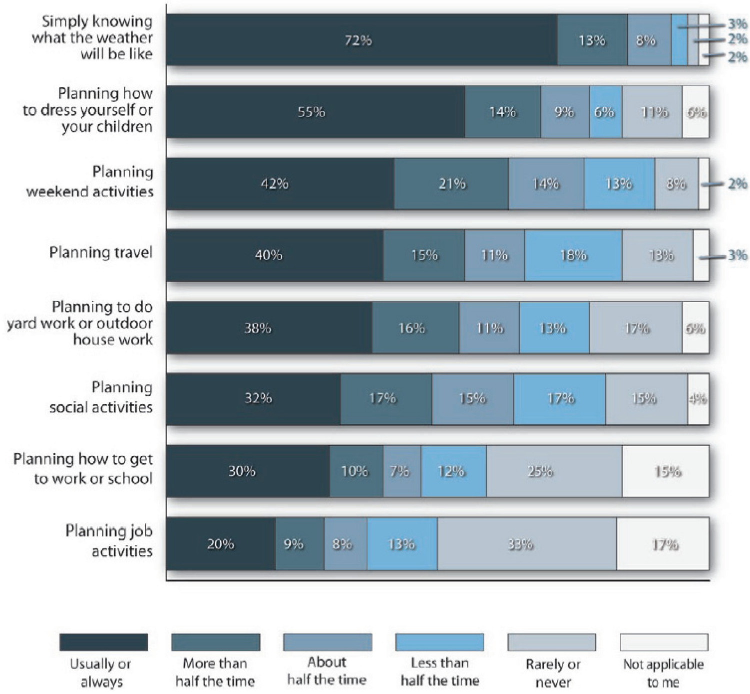

FIGURE 1.1 This figure shows weather forecasts are integral to the daily life of the U.S. public as well as to U.S. economic activity and public safety. It illustrates the frequent use of weather forecasts for different types of decisions by members of the U.S. public, based on results from a survey of 1,465 respondents. The survey question asked "On average, year round, how often do you use weather forecasts for the activities listed below?" As the figure illustrates, weather forecasts are used frequently by many members of the U.S. public for a variety of activities. SOURCE: Lazo et al. (2009).

the destruction and death resulting from Hurricane Katrina; in all, 2005 had nearly 1,500 direct weather fatalities and more than $100 billion in property and crop damages. The annual impacts of adverse weather on the national highway system and roads are staggering: 7,400 weather-related deaths; 1.5 million weather-related crashes; more than 700,000 weather-related injuries; $42 billion in economic loss; and nearly 1 billion hours per year of weather-related delays (BTS, 2007). In addition, $4.2 billion is lost each year as a result of air traffic delays attributed to weather (NOAA, 2010). For comparison, the average economic loss from the effects of airborne volcanic

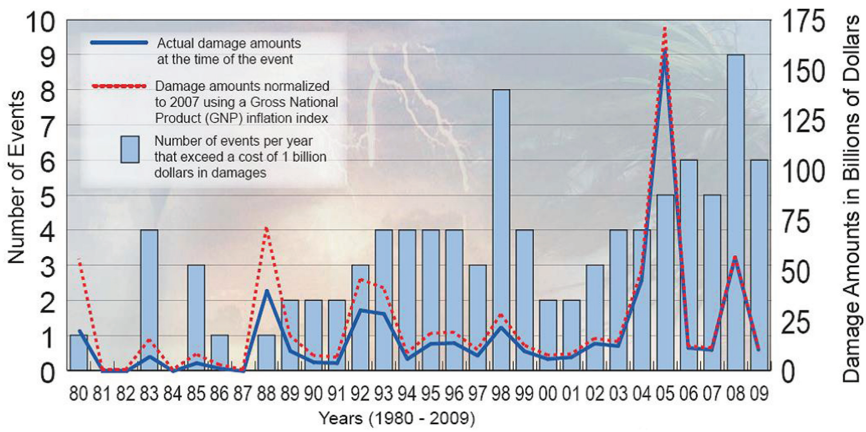

FIGURE 1.2 Number and magnitude of U.S. weather disasters that exceeded $1 billion for the 30-year period 1980 to 2009. Although the dashed red curve accounts for inflation-adjusted damages, it does not account for the effects of increasing social vulnerability, increasing coastal populations, and expensive coastal development (e.g., Pielke et al., 2008). SOURCE: NCDC (2010).

ash on U.S. air transportation is about $70 million per year[2] (Kite-Powell, 2001). Weather is also a major factor in the complex set of interactions that determine air quality, and more than 60,000 premature deaths each year are attributed to poor air quality (Schwartz and Dockery, 1992). Better forecasts and warnings are reducing these numbers, but much more can be done.

HISTORICAL DEVELOPMENTS IN U.S. WEATHER RESEARCH

The past 15 years have seen marked progress in understanding weather processes and the ability to observe and predict the weather. At the same time, the United States has failed to match or surpass progress in operational numerical weather prediction achieved by some other nations and failed

[2]This average does not include the recent Eyjafjallajökull eruption. The U.S. State Department reported on April 20, 2010, that "The economic ramifications caused by the activity of Iceland's Eyjafjallajökull volcano are mounting, with airlines reporting losses on the scale of $200 million per day following the shutdown of many European airports, and a wider impact moving across the globe as trade goods transported by air have been unable to reach their markets." Source: http://www.america.gov/st/business-english/2010/April/20100420163812esnamfuak6.422061e-02.html.

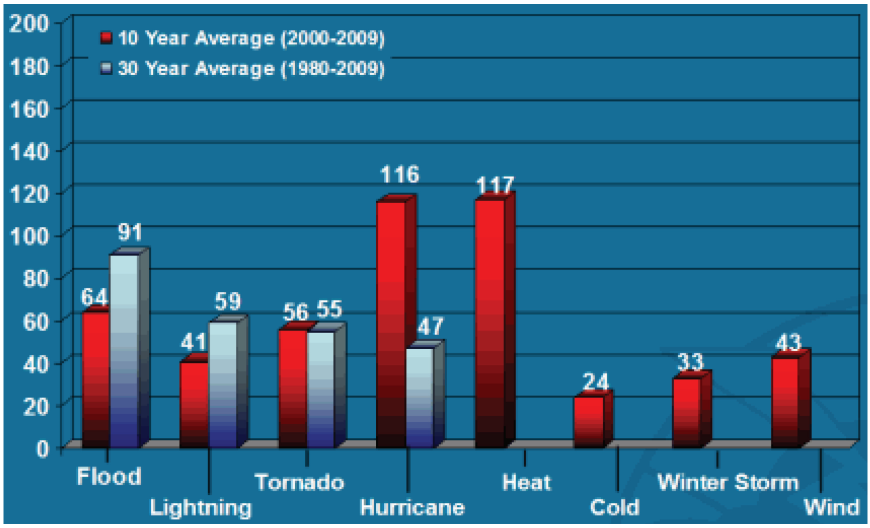

FIGURE 1.3 10- and 30-year average number of fatalities directly attributable to weather in the United States, not including weather-caused traffic deaths. There are not 30 years of data available for heat-, cold-, winter storm-, or wind-related deaths; therefore only 10-year averages are shown for these events. SOURCE: NWS (2010).

to realize the prediction potential we believe is achievable.[3] In addition, there has also not been a commensurate focus on the social sciences and their role in problem identification, analysis, and response. As a result, the United States is not mitigating weather impacts—death, injury, disruption, and property and economic losses—to the extent possible.

During the 1990s, federal agencies supported a number of weather research and research-to-operations (R2O) planning activities. For example, the U.S. Weather Research Program (USWRP) began as a multiagency research program whose purpose was to identify key gaps in the understanding and simulation of all types of severe weather and their societal impacts in order to accelerate the rate at which weather forecasts were improved. The USWRP was overseen by a scientific steering committee that convened 11

[3]An in-depth review of the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) National Centers for Environmental Prediction (NCEP) organized by the University Corporation for Atmospheric Research at the request of NCEP was under way at the time of the 2009 BASC Summer Study workshop. The review report was recently completed and is available online at http://www.vsp.ucar.edu/events/NCEP_reviews_2009.html.

Prospectus Development Teams (PDTs) and several community workshops, whose purpose was to identify research opportunities for improving the scientific understanding of severe weather and its operational forecasting. These PDTs and workshops were the starting point for a number of efforts including field campaigns and testbeds that are operating today. (Table 1.1 includes reports of the PDTs and USWRP workshops as well as the numerous National Research Council [NRC] reports that have addressed weather research.)

MOTIVATION FOR THE CURRENT STUDY

Every few years, BASC works with its core agency sponsors (the National Aeronautics and Space Administration [NASA], NOAA, and the National Science Foundation [NSF]) to design a Summer Study that serves as an opportunity for scientists, industry, and the agencies to exchange information and views about a contemporary issue. A major component of these studies is a summer workshop designed to facilitate candid discussion on a topic identified by BASC members as timely and important. Given the importance of weather to a wide variety of stakeholders and societal goals, and the Board's consensus that U.S. weather research is not currently realizing its full potential, the 2009 BASC Summer Study workshop focused on weather research and the transitioning of research results into operations (R2O).

The 2009 BASC Summer Study workshop examined the progress, priorities, and future directions of weather research and R2O activities in the United States (Appendix D). The workshop was designed to give the committee input and feedback from a diverse set of about 50 weather professionals and stakeholders from academia, the private sector, and government (Appendix E). In organizing the 2009 BASC Summer Study workshop, the committee drew upon the broad range of issues identified in publications that summarized the findings of the various USWRP PDTs and workshops together with numerous reports prepared by the NRC (Table 1.1 lists all of the reports that were considered). The committee used this information to establish broad themes for each of the five different working groups that convened at the 2009 BASC Summer Study workshop (see Appendix E for the workshop agenda); the five workshop themes were (1) socioeconomic impacts; (2) observations/data assimilation/model development; (3) very high impact weather; (4) quantitative precipitation and hydrologic predictions; and (5) the unique challenges of topography and urbanization. The

TABLE 1.1 Representative List of Publications Since 1995 That Provide Recommendations for Weather Research and Research-To-Operations.

Year	Type	Reference	Title
1995	NEXRAD Panel	NRC, 1995a	Aviation Weather Services: A Call for Federal Leadership and Action
1995	NRC Report	NRC, 1995b	Toward a New National Weather Service: Assessment of NEXRAD Coverage and Associated Weather Services
1995	USWRP PDT-1	Emanuel et al., 1995	Report of the First Prospectus Development Team of the U.S. Weather Research Program to NOAA and the NSF
1996	USWRP PDT-2	Dabberdt and Schlatter, 1996	Research Opportunities from Emerging Atmospheric Observing and Modeling Capabilities
1996	USWRP PDT-3	Rotunno and Pietrafesa, 1996	Coastal Meteorology and Oceanography
1997	USWRP PDT-4	Smith et al., 1997	Local and Remote Effects of Mountains on Weather: Research Needs and Opportunities
1997	USWRP PDT-6	Pielke et al., 1997	Societal Aspects of Weather
1997	USWRP PDT-7	Emanuel et al., 1997	Observations in Aid of Weather Prediction for North America
1997	USWRP Workshop	USWRP, 1997a	Workshop on the Social and Economic Impacts of Weather
1997	USWRP Workshop	USWRP, 1997b	Hurricane Landfall Workshop
1997	USWRP Workshop	USWRP, 1997c	Workshop on Data Assimilation
1998	NRC Report	NRC, 1998a	The Atmospheric Sciences: Entering the 21st Century
1998	NRC Report	NRC, 1998b	The Meteorological Buoy and Coastal Marine Automated Network for the United States
1998	USWRP PDT-5	Marks and Shay, 1998	Landfalling Tropical Cyclones: Forecast Problems and Associated Research Opportunities
1998	USWRP PDT-8	Fritsch et al., 1998	Quantitative Precipitation Forecasting
2000	NRC Report	NRC, 2000a	Assessment of the Current Status of the U.S. Weather Research Program
2000	NRC Report	NRC, 2000b	From Research to Operations: Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death
2000	USWRP PDT-9	Droegemeier et al., 2000	Hydrological Aspects of Weather Prediction and Flood Warnings
2000	USWRP PDT-10	Dabberdt et al., 2000	Forecast Issues in the Urban Zone
2000	USWRP Workshop	USWRP, 2000	Workshop on the Weather Research Needs of the Private Sector
2002	NRC Report	NRC, 2002	Weather Radar Technology Beyond NEXRAD
2002	USWRP Workshop	USWRP, 2002	Warm Season QPF Workshop
2003	NRC Report	NRC, 2003a	Critical Issues in Weather Modification Research

Year	Type	Reference	Title
2003	NRC Report	NRC, 2003b	Fair Weather: Effective Partnerships in Weather and Climate Services
2003	NRC Report	NRC, 2003c	Tracking and Predicting Atmospheric Dispersion of Hazardous Material Releases: Implications for Homeland Security
2003	NRC Report	NRC, 2003d	Weather Forecasting Accuracy for FAA Traffic Flow Management: A Workshop Report
2003	USWRP Workshop	USWRP, 2003a	Workshop on Design and Development of Multifunctional Mesoscale Observing Networks in Support of Integrated Forecasting Systems
2003	USWRP Workshop	USWRP, 2003b	Air Quality Forecasting Workshop
2004	NRC Report	NRC, 2004	Where the Weather Meets the Road: A Research Agenda for Improving Road Weather Services
2004	USWRP PDT-11	Dabberdt et al., 2004	Meteorological Research Needs for Improved Air Quality Forecasting
2005	NRC Report	NRC, 2005a	Flash Flood Forecasting Over Complex Terrain: With an Assessment of the Sulphur Mountain NEXRAD in Southern California
2005	NRC Report	NRC, 2005b	Improving the Scientific Foundation for Atmosphere-Land-Ocean Simulations
2006	NRC Report	NRC, 2006a	Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts
2006	NRC Report	NRC, 2006b	Toward a New Advanced Hydrologic Prediction Service
2007	NRC Report	NRC, 2007a	Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond
2007	NRC Report	NRC, 2007b	Environmental Data Management at NOAA: Archiving, Stewardship, and Access
2007	NRC Report	NRC, 2007c	Strategic Guidance for the National Science Foundation's Support of the Atmospheric Sciences: An Interim Report
2008	NRC Report	NRC, 2008a	Evaluation of the Multifunction Phased Array Radar Planning Process
2008	NRC Report	NRC, 2008b	Satellite Observations to Benefit Science and Society: Recommended Missions for the Next Decade
2009	NRC Report	NRC, 2009b	Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks

five working groups then identified research and transitional problems, challenges, needs, and opportunities in eight overlapping areas that frame the organization of this report:

- socioeconomics,
- observations,
- weather modeling and predictability,
- hydrologic modeling,
- quantitative precipitation estimation and forecasting,
- impacts forecasting,
- urban weather, and
- renewable energy siting and production.

The contents of this report are based on both the 2009 BASC Summer Study workshop and its working group deliberations, as well as the expertise and judgment of the committee members and their discussions at subsequent meetings.

Achievements and Challenges

In assessing the state of U.S. weather research and operations, the rate of progress, and the need for advancing research and transitioning results into operations, it is helpful to identify a baseline or reference point. The committee examined progress over the past 15 or so years because that is an interval long enough to assess achievement yet short enough to gauge the recent rate of progress. It also is a period when numerous reviews and assessments were undertaken.

One study in particular, *The Atmospheric Sciences Entering the Twenty-First Century* (NRC, 1998b), stands out for its breadth and depth. The report identified two imperatives and three major research recommendations. The imperatives were seen as critical and they constituted that study's two highest priority recommendations. Both imperatives pertained to the state of observations, and the need for (1) optimizing and integrating existing observation capabilities, and (2) developing new observation capabilities. It is not surprising, then, that the present study also identified a similarly widespread need for improved observations throughout the set of recommendations. This need was further articulated in the decadal survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (NRC, 2007a) that brought critical attention to the deterioration of U.S. satellite observing capabilities.

The major research recommendations of the *21st Century* report were both diverse in their scope and insightful in their relevance. The report called for

1. resolution of interactions at atmospheric boundaries and among different scales of flow;
2. extension of a disciplined forecast process to new areas such as climate, chemistry, air quality, and space weather; and
3. initiation of studies of emerging areas, including climate, weather and health, water resources, and rapidly increasing emissions to the atmosphere.

Since the mid-1990s and the release of the *21st Century* report, the United States has achieved an impressive array of advances both in weather research and in transitioning many research results into operations. Among those important achievements, the following are several notable examples:

- Completing full implementation in 1997 of the NWS Modernization Program (e.g., NRC, 1999) that had begun in the 1980s, highlighted by its capstone project—deployment of 166 WSR-88D NEXRAD Doppler radars, and subsequently initiating a program in 2009 to field test the feasibility of upgrading these radars with dual-polarization capability for hydrometeor classification and improved quantitative precipitation estimation
- Doubling tornado warning lead times from 6 minutes in the early 1990s to about 13 minutes in the current decade, while almost tripling flash flood warning times from 17 to 45 minutes over the same interval. Unfortunately, the annual average number of tornado deaths for the 6-year period 2000 to 2005 was 44, which is unchanged from the corresponding average for 1990 to 1995.
- Decreasing the 72-hour mean hurricane track forecast error for the Atlantic Basin from approximately 480 km (1991–1995) to approximately 280 km (2003–2008), and decreasing the corresponding 24-hour mean error from approximately 150 km to approximately 110 km
- Developing more sophisticated research ensemble and probabilistic research predictions, and advanced research data assimilation systems
- Implementing a number of infrastructure programs to facilitate testing research products and their transition to operations, such as the Joint Center for Satellite Data Assimilation, the Developmental Testbed Center, and numerous testbeds (e.g., hurricane and hydrologic testbeds)
- Implementing in 2004 a limited-area operational 24-hour prediction product for near-surface 1- and 8-hour ozone concentrations, and a

corresponding CONUS (contiguous United States) capability that went operational in 2007

- Establishing in 1994, the nation's first comprehensive statewide surface mesonet in Oklahoma, which has since built out to include 120 stations. Today there are about 70 disparate federal, state, local, and private mesonets throughout the country comprising more than 27,500 surface stations.[4]

Although the list of accomplishments is important and encouraging, there are numerous areas where much more needs to be done to better observe and understand weather processes, more accurately and reliably predict weather and weather impacts, and mitigate the negative and often disastrous human, economic, and physical consequences of weather (Figure 1.4). Examples of current challenges include the following:

- NEXRAD, the U.S. weather radar network, is unable to observe three-quarters of the planetary boundary layer, where people live and much weather is spawned.
- Today, forecasts provide predictions of weather variables, but predictions of weather impacts would also be valuable.
- Forecasts of wind and solar irradiance for alternative (or renewable) energy production and management are in their infancy and are woefully inadequate.
- Improved observational capabilities for soil moisture and profiling the lower atmosphere are lacking yet widely and urgently needed.
- U.S. satellite capabilities are deteriorating.
- Hydrologic forecasts are needed to better predict flooding, save lives and property, and manage water resources.
- Hurricane intensity forecasts still have alarmingly low skill, as does the quantitative prediction of warm-season precipitation; both are major challenges in weather and impacts prediction.

Charge and Approach

The committee was charged (Appendix D) with using the information and insight from the 2009 BASC Summer Study workshop and previously published works to address questions about U.S. weather research and R2O activities: What has and has not been achieved? What may no longer be rel-

[4] See http://madis.noaa.gov/mesonet_providers.html.

FIGURE 1.4 The Great Galveston Hurricane of September 8, 1900 destroyed the city and killed more than 8,000 people (top). More than a century later on August 29, 2005, Hurricane Katrina made landfall on the Louisiana coast, inundating the city of New Orleans and neighboring areas (bottom). Despite a nearly perfect 48-hour track forecast, Katrina caused more than 1,000 direct weather fatalities and more than $81 billion in property and crop damages. SOURCE: NOAA (2007) and iStock Photo.

evant? What current issues were not previously anticipated? And what could be done in the short term to reinvigorate agency and interagency planning for weather research and R2O activities in the United States? It is important to note that this study does not critique earlier USWRP or NRC documents, nor does it formally review current agency planning documents.

This report represents a sense of the weather community as discussed by the workshop participants and the committee; it is not a comprehensive, in-depth assessment of the state of U.S. weather research and the transition of research findings and products into operations. Further, the report does not seek to address important issues uniquely related to climate research nor does it touch on intra- and interagency organizational procedures and practices. Instead, the report puts forth the committee's judgment on the most pressing high-level, weather-focused research challenges and R2O needs, and makes corresponding recommendations.

Organization of the Report

This report covers three broad areas—socioeconomics, established needs, and emerging needs. Chapter 2 focuses on the pressing and pervasive need for socioeconomic research and applications in virtually all topical areas. Socioeconomic considerations are presented first to avoid the too-often stereotyping that has occurred in the past when social science has been considered only in hindsight rather than as a primary element of the problem and the solution. Socioeconomic considerations provide much of the motivation for research and R2O activities in nonhydrostatic modeling, quantitative precipitation forecasting and hydrologic prediction, and mesoscale observations. Such considerations are also an integral part of very high impact weather, urban meteorology, and renewable energy production. Socioeconomic needs also motivate and support a growing emphasis on understanding the linkages between climate and weather through a spectrum of spatial and temporal scales. Thus, socioeconomic considerations are woven throughout the meteorological community's activities and its priorities.

Chapter 3 covers four topical areas that have been addressed in previous studies but that continue to require considerable attention, albeit with increased priority, resources, and a sense of urgency. These are labeled *established* needs for weather research and the transition of research results into operations. Four established needs are identified. All are in various stages of development but none have been resolved despite having been identified as pressing in numerous previous studies. The four established needs and issues include global nonhydrostatic coupled modeling, quantitative precipitation estimation and forecasting, hydrologic prediction, and mesoscale observations.

Chapter 4 addresses several research and R2O needs that have come to be recognized in the United States over the past 5 to 10 years as increasingly important, but that are only in the early stages of understanding or implementation. These are labeled *emerging* weather research and transitional needs, in contrast to the established needs discussed in Chapter 3. Three high-priority emerging needs were identified in the 2009 BASC Summer Study workshop and subsequent committee discussions; they are very high impact weather, urban meteorology, and renewable energy production. The reader may wonder why very high impact weather is included here as an emerging need rather than in the preceding chapter as one of several established needs. The answer lies in the emphasis on forecasting weather impacts in conjunction with the traditional focus on forecasting weather per se. Urban meteorology had been recognized in the United States in the 1960s as an important topic, and much seminal urban meteorological research was conducted until the early 1980s when it was abruptly deemphasized. A reemphasis on the meteorology of the urban zone and its societal import began again in the 1990s and continues today. Lastly, the meteorological challenges associated with the special needs of the renewable energy industry have come into sharp focus over the past 5 or so years. In all three emerging areas, much remains to be done.

Virtually all research and transitional needs have both established and emerging aspects, and so many of the established challenges and needs cited in Chapter 3 are closely coupled to the emerging needs discussed in Chapter 4, and vice versa. A few research and R2O needs, such as hurricane track and intensity forecasting and air quality prediction, are conspicuous by their absence as named sections in the report. However, they are included in the discussions within several of the other sections (e.g., global nonhydrostatic coupled modeling, urban meteorology, and very high impact weather, to name but three).

Finally, Chapter 5 provides a few summary comments while the appendixes provide references, definitions of acronyms and abbreviations, biographical sketches of the committee members, and details of the 2009 BASC Summer Study workshop that served as the backbone of the study.

THE CHALLENGE

It is crucial that the weather enterprise address these established and emerging issues and the research needed to develop the capacity to deal with them, and transfer important research results into operations. We need to start by recognizing that as the world and the United States' challenges have changed, the scientific research priorities and operational priorities need to change as well. As such, this report and its recommendations are relevant to all parties in the weather enterprise: agency decision makers, policy makers, research scientists, private-sector applications specialists, teachers, public and private user groups and organizations, and the general public. In particular, this report is intended to inform NASA, NOAA, and NSF program managers and policy makers of the many priorities that need to be addressed in guiding the future of U.S. weather research and operations.

2

Socioeconomic Research and Capacity

Understanding and addressing socioeconomic aspects of weather prediction is critical for the weather community to reach its goals and for society to fully benefit from advances in weather prediction. To date, the weather prediction community and society are still far from achieving the full potential that comes from integrating social sciences expertise with weather research and research to operations (R2O).

As discussed in the introduction, weather and weather information affect a wide range of socioeconomic sectors and decisions. Socioeconomic considerations are fundamental in determining how, when, and why the weather information produced by research and R2O activities is, or is not, used. Thus, socioeconomics is an extremely important component of weather research and the transfer of research results to operations (and also the transfer of operations knowledge and experience back to research—O2R). Yet the weather prediction enterprise still lacks interdisciplinary capacity to understand and address socioeconomic issues. As a result, socioeconomic expertise is underutilized in the weather community, and the potential value of socioeconomic considerations in planning and executing weather activities has not been fully achieved. In the same way that there are major gaps in weather research and R2O, there are also gaps in research and R2O in socioeconomics of weather that, when filled, will substantially benefit the weather community and, more importantly, society at large. Unless and until these gaps are filled, the value of the work of the weather community will not be fully realized in the broader context of advancing weather prediction capabilities for societal benefit.

The importance of integrating socioeconomic considerations into weather research and R2O emerged as a strong theme at the 2009 Board on Atmospheric Sciences and Climate (BASC) Summer Study workshop. Socioeconomic themes have been discussed by other groups examining major issues in meteorology, including previous NRC committees (e.g., NRC, 1998b, 2006a), the National Oceanic and Atmospheric Administration (NOAA) Science Advisory Board (NSAB, 2003, 2009), the World Meteorological Organization (Rogers et al., 2007), the international THORPEX[1] program (Morss et al., 2008b; Shapiro and Thorpe, 2004), and USWRP PDT reports (Emanuel et al., 1995; Pielke et al., 1997). Yet the 2009 BASC Summer Study workshop represented the first time that socioeconomic issues have been discussed as a core priority in weather prediction research and R2O at the level of an NRC committee and workshop. Integration of socioeconomic considerations was viewed by workshop participants from a variety of disciplines and backgrounds as important in general for meeting weather community and societal needs, and more specifically to address the established and emerging weather research and R2O needs that are identified in Chapters 3 and 4 of this report. Achieving this integration requires incorporating knowledge and tools from the social sciences.

The social sciences are an assembly of scientific disciplines that address social and economic issues with rigorous theory and methods. These disciplines each have specific knowledge, approaches, and expertise that can contribute substantively to the goal of understanding society's weather-related needs and providing usable weather information to stakeholders, including public officials, industry, and members of the public. Social science disciplines that can benefit weather research and R2O include economics, human geography, political science, public policy, communication, anthropology, sociology, and psychology. Interdisciplinary fields that integrate social and physical sciences, such as environmental science, risk communication, and natural hazards, can also make important contributions to producing usable weather information.

Although this chapter focuses mostly on information related to weather forecasts, current and historical weather information also have significant societal value. Examples include the use of wind data for siting wind energy facilities and information about past hazardous weather events for public- and private-sector management of future hazardous weather risks. The priorities and mechanisms discussed below are also applicable to benefit the use and value of these types of weather information.

RECENT TRENDS

Societal needs have a long history of being considered in weather prediction, and during the past 15 years, socioeconomic issues in weather predic-

[1]THORPEX originally was denoted as "The Observing System Research and Predictability Experiment," but that terminology is no longer used.

tion have been discussed in a number of different venues. For example, the U.S. Weather Research Program (USWRP) sponsored a Prospectus Development Team (PDT–6) focused on socioeconomic aspects of weather prediction and related priorities. The PDT–6 report (Pielke et al., 1997) discussed the benefits of integrating societal-aspects research into weather prediction efforts and found that despite the recognized importance of societal aspects of weather, this area has received too little attention for too long. Priorities identified in the PDT–6 report included integrating users into all aspects of weather prediction efforts, and not just at the "end of the line." The NRC *21st Century* report (1998b) identified societal considerations as important, and it included them in Imperative 1 (Optimize and Integrate Observation Capabilities) and Leadership and Management Recommendation 3 (Assess Benefits and Costs). However, the NRC *21st Century* report did not identify socioeconomic research or R2O as specific priorities.

Some progress has been made toward the goals identified by PDT–6. Societal aspects of weather are receiving greater attention within the weather prediction community. They are often a topic of significant discussion at community meetings, such as the 2009 BASC Summer Study workshop and recent American Meteorological Society (AMS) Summer Community meetings.[2] The AMS Symposium on Policy and Socio-Economic Research, which has been held annually since 2006, has been growing rapidly, and in recognition of the increasing interest in this area, in 2009 the AMS launched a new journal *Weather, Climate, and Society*. User needs are being incorporated into some weather prediction efforts earlier in the research and development process; examples include the discussions of emerging needs in Chapter 4 of this report and the National Science Foundation (NSF) Collaborative Adaptive Sensing of the Atmosphere (CASA) Engineering Research Center (Box 2.1). The weather prediction community now often includes the input of at least one social or interdisciplinary scientist in important discussions. For example, in recent years, NRC committees addressing societally relevant issues in meteorology have typically included social scientists and interdisciplinary experts. This represents significant progress over the past decade.

However, societal considerations do not yet have a full voice, and social sciences are not yet recognized as full and equal partners in most weather research and R2O efforts. The social sciences include multiple areas of relevant expertise and methodological approaches; one or two individuals can provide only a subset of the social science perspectives that can be useful

[2] See http://www.ametsoc.org/boardpges/cwce/docs/BEC/index.html.

BOX 2.1
Examples of Successes in Integrated Work on Socioeconomics of Weather

Over the years, a variety of research and R2O efforts have addressed socioeconomic aspects of weather. Six examples of current programs that do so by integrating social sciences and meteorology are provided here. Each has a different focus and strategy. These programs demonstrate how such integrated programs can enhance weather community efforts and help society benefit from meteorological advances.

The **Collaborative Adaptive Sensing of the Atmosphere (CASA)**[1] center is an interdisciplinary effort aimed at developing dense networks of small radars to "revolutioniz[e] our ability to observe, understand, predict and respond to hazardous weather events." Funded as an NSF Engineering Research Center since 2003, CASA is a partnership among governmental, industrial, and academic entities. The center has included social science and end-user components since its inception. Recent integrated CASA successes include studies of emergency management decision making, public response to severe weather, and user-defined adaptive radar scanning strategies (e.g., Bass et al., 2009; McLaughlin et al., 2009; Philips et al., 2007; Rodriguez et al., 2010) and a demonstration of CASA's end-to-end approach during the May 13, 2009 tornado event (Philips et al., 2009).

The **Communicating Hurricane Information (CHI)**[2] program is a joint NOAA–NSF solicitation "focusing on advancing fundamental understanding of the communication of hurricane outlooks, forecasts, watches, and warnings both to decision makers (i.e., emergency managers, elected officials) and to the general public." As of 2009, five programs were being funded with total funding of approximately $2 million. This program illustrates how agencies can partner to support integrated weather–society work that simultaneously advances fundamental understanding and addresses mission agency needs. It also illustrates how well-designed research initiatives can entrain social scientists with a variety of expertise into addressing weather forecasting issues.

The **University of Washington Probability Forecast (PROBCAST)**[3] project is a "prototype and test bed for exploring the best approaches for communicating high-resolution uncertainty information to a large and varied user community" (Mass et al., 2009). This research and applications effort, which integrates work in meteorology, statistics, and psychology, developed over approximately 10 years with funding from NSF and the Department of Defense (DOD). Recent PROBCAST successes include research studies examining how people interpret and use probabilistic information (Joslyn et al., 2009) and the PROBCAST Web-based portal that disseminates weather forecast uncertainty information.

The **Collaborative Program on the Societal Impacts and Economic Benefits of Weather Information (SIP)**[4] was founded in 2004 to "improve societal gains from weather forecasting by infusing social science research, methods, and capabilities into the Weather Enterprise." SIP is hosted at NCAR in Boulder, Colorado, with support from NOAA (through the U.S. Weather Research Program) and NSF, as well as from research grants. Recent SIP successes include results from a nationwide survey examining the public's sources, perceptions, and uses of and values for, weather forecast information, including forecast uncertainty (Lazo et al., 2009, Morss et al., 2008a, 2010), a working group and workshop (Gladwin et al., 2007) that helped initiate the NOAA–NSF CHI program solicitation (see above); and the WAS*IS program (see below).

The **Social Science Woven into Meteorology (SSWIM)**[5] program "promotes collaborative research and partnerships between the social sciences and the physical sciences to enhance societal relevance and to reduce the human risk from atmospheric and related hazards." SSWIM was founded in 2008 at the National Weather Center in Norman, Oklahoma, and is supported by NOAA and the University of Oklahoma. Recent SSWIM successes include cohosting 2008 and 2009 workshops[6] with NOAA's Hazardous Weather Testbed and Global Systems Division to improve the development of new hazardous weather warning products.

Weather and Society*Integrated Studies (WAS*IS)[7] is a "grassroots movement that is changing the weather enterprise by integrating social science into meteorological research and practice in comprehensive and sustained ways." The WAS*IS program focuses primarily on empowering early career participants to address integrated weather–society issues by introducing social science methods and concepts and building community through workshops (Demuth et al., 2007). The movement aims to help change from what WAS to what IS the future of integrated weather studies not by generating explicit research products, but by building exposure, commitment, and capacity.

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[1] See http://www.casa.umass.edu/.
[2] See http://www.nsf.gov/pubs/2008/nsf08551/nsf08551.htm.
[3] See http://probcast.washington.edu/.
[4] See http://www.sip.ucar.edu.
[5] See http://www.sswim.org.
[6] See http://ewp.nssl.noaa.gov/wasis2008/ and http://www.weather.gov/warningworkshop/.
[7] See http://www.sip.ucar.edu/wasis.

to weather prediction. Moreover, social scientists are still often treated as consultants on projects, brought in once the activity is well under way. Social scientists can contribute not only to demonstrating or helping realize socioeconomic value once a meteorological effort is nearly complete; they can make perhaps even more important contributions to problem identification and research design. Further, progress toward addressing the societal and interdisciplinary priority areas identified more than a decade ago in the NRC (1998b) report has been minimal (Morss et al., 2008b). These areas are of major importance for the weather community in providing cost-effective services for society, but there has been limited motivation or support to pursue them. Although NOAA has made some progress in incorporating social sciences in some areas, social sciences capabilities within NOAA are inadequate and are far from being sufficiently utilized to meet NOAA's and the nation's needs (NSAB, 2009; Figure 2.1). Programs to train meteorologists and social scientists to understand and apply each other's perspectives are also lacking.

Thus, despite previous discussions and efforts, limited progress has been made in bridging the gap between weather prediction and the social sciences. Yet interest in doing so continues to grow. To build on the current momentum and discuss socioeconomics as a high-level priority for the weather prediction community, the 2009 BASC Summer Study workshop included socioeconomic impacts as one of five focal topics. The goal of the socioeconomic discussions was to entrain multiple perspectives at an NRC-sponsored community-level workshop to identify key steps for advancing weather–society research and R2O. Previous related efforts were briefly discussed, but opinions on successes, failures, and the reasons underlying them differed. The bulk of the discussions focused on how to most productively move forward.

Discussions of socioeconomic issues at the 2009 BASC Summer Study workshop received the critical input of physical, social, and interdisciplinary scientists and managers engaged in a variety of weather–society research and R2O activities. The workshop included three presentations on progress and priorities in socioeconomics of weather, followed by a discussion among all workshop participants. An interdisciplinary socioeconomic working group then met to discuss weather–society research and R2O priorities in greater detail, and discussions among the group continued after the workshop. Socioeconomic considerations were also discussed in conjunction with other workshop focal topics, especially the emerging applications (Chapter 4). The concepts and priorities presented here represent a synthesis of discussions at the workshop and those of the study committee.

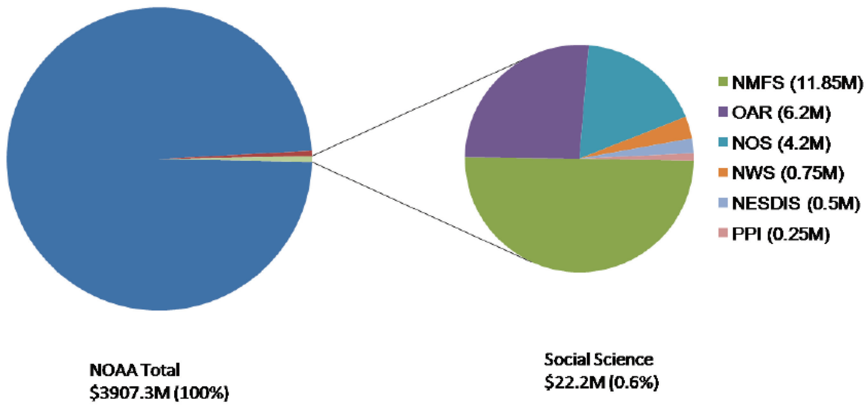

FIGURE 2.1 NOAA invests a relatively small amount in social science related to weather. FY 2008 social science budget as a proportion of total NOAA budget and as distributed across line offices (NWS = National Weather Service; OAR = Oceanic and Atmospheric Research; NESDIS = National Environmental Satellite Data and Information Service; PPI = Office of Program Planning and Integration; NMFS = National Marine Fisheries Service; NOS = National Ocean Service). Most of NOAA's OAR investment in social science in FY 2008 was in climate and other nonweather areas; the total FY 2008 social science budget for the Weather and Water mission goal within NOAA was $0.75M. SOURCE: NSAB (2009).

PRIORITY WEATHER–SOCIETY TOPICS

During the workshop and subsequent meetings of the study committee, meteorologists and social scientists jointly identified three initial priority topics for weather research and R2O activities in the socioeconomics of weather information: estimating value; understanding the interpretation and use of information; and improving communication of information. The first focuses primarily on economic value, although other societal values (such as environmental health or human well-being) may be considered. The second and third focus primarily on other, noneconomic social science perspectives, although economic perspectives and tools can be applied as well to address user needs and communications.

For each topic, sample research and R2O questions are briefly mentioned. Note that although the questions are not discussed in detail, substantial complexity underlies them. Addressing each area will require bringing theoretical and methodological tools from the social sciences together with input from meteorology researchers, meteorology practitioners, and forecast users.

Estimating Value

Reliable estimates of the economic value of weather impacts and forecasts are key to demonstrating the importance of weather prediction programs and to making cost-benefit decisions among different options for allocating weather prediction resources. Estimating the value of forecasts often requires understanding their use (the second priority area). Valuation can also provide insight into the use of forecasts, and thus help improve forecast communication and use. Economists employ multiple approaches and tools for valuing weather impacts and forecasts, such as econometric modeling, decision analysis, and nonmarket valuation. Each has particular strengths and weaknesses and is best suited for different applications. Thus, to build a holistic picture of the value of weather impacts and forecasts to different societal sectors and society as a whole, a core weather-economics expertise needs to be entrained and applied to estimate value from complementary perspectives. Weather and weather forecasts also have significant societal and cultural value that can be examined using perspectives from other, noneconomic, social science disciplines, including public policy, sociology, and anthropology.

Examples of interdisciplinary research and R2O questions in this area include the following:

- What are the impacts of current weather forecasts on different sectors of the U.S. economy (such as transportation and energy), and what would be the value of forecast improvements?
- How do weather and weather forecasts interact with socioeconomic infrastructure and systems (such as the transportation system or electric power grid) to influence weather impacts and forecast value?
- How do the benefits of improving forecasts of the timing and location of hurricane landfall compare with the benefits of improving forecasts of hurricane intensity at landfall?
- What are the costs and benefits to different sectors and groups of longer lead times for tornado warnings?
- What are the cost-benefit trade-offs among different improvements to observational networks and among investments in different components of weather prediction systems (e.g., increased resolution, improved data assimilation, improved physics, ensemble size)?

Understanding User Needs, Interpretation, and Use of Information

A key component of the provision of more beneficial weather forecasts is understanding how people interpret forecast information and use it for their needs. This includes individuals and organizations in the private and public sectors. Forecast and warning information is interpreted through the lens of individuals' and organizations' risk perceptions, experience, needs, beliefs, capabilities, and so on. Further, forecasts are only one of many factors that affect weather-related decisions; cultural, political, economic, and other considerations are also important, as well as interactions with systems such air transportation systems, power grids, and communication networks. Thus, understanding user needs and value requires understanding how people interpret forecasts and how forecasts influence people's behavior in different contexts. A variety of social science and related theories, from disciplines such as communication, sociology, psychology, and human geography, can be used to understand forecast interpretation and use, employing approaches such as in-depth interviews, focus groups, surveys, and decision experiments. The resulting knowledge can be applied to improve forecast communication, use, and value, and is key to providing societally beneficial impact forecasts as discussed in Chapter 4. To develop holistic understanding that is both deep and broad, work in this area will need to include in-depth studies of cases and specific contexts as well as studies that span populations, economic sectors, regions, and meteorological phenomena.

Examples of questions in this area include the following:

- What makes various populations more or less vulnerable to severe weather events, and how can improved weather information help mitigate those vulnerabilities?
- How do people (individually and within organizations) interpret severe weather warnings, and what motivates people to respond?
- When and how do the biases and framing effects that have been identified in other risk communication contexts affect interpretations and use of weather forecasts?
- What are people's mental models of risks from hazardous weather events such as hurricanes and floods? How do those mental models promote or limit interpretation and use of information about weather risks and decisions about protective actions?
- How do people interpret and use forecast information that communicates uncertainty in different ways, and in what circumstances can uncertainty information help individuals and organizations make better decisions?
- What are the weather forecast information needs of air transportation providers and users related to the Next Generation Air Transportation System

or NextGen,[3] and what do those needs mean for development of forecasts for NextGen and design of the NextGen system?

- What impact variables are most important to different individuals and organizations in advance of various types of very high impact weather events, for use in their decisions (see Chapter 4)?

Improving Communication of Information

For forecast and warning information to be used effectively, it needs to be received and understood. People receive forecast information from different sources, ranging from media broadcasters, to the Internet and social networking sites, to friends and family. Thus, effective development and dissemination of weather forecasts requires an understanding of how different communication modes influence interpretation and use of weather forecast information, and how different communication channels and modes interact. Understanding barriers to effective communication and to motivating effective risk-reducing behavior is also important. Given the uncertainty inherent in weather forecasting, it is particularly important to address communication of forecast uncertainty to users ranging from businesses to emergency managers to the general public. Work in this area includes more traditional research approaches such as interviews and surveys as well as stakeholder-oriented and participatory approaches that can aid transition of concepts from research to operations.

Examples of questions include the following:

- How do people integrate weather forecast information gathered from different sources to form risk perceptions and resolve perceived information conflicts?
- How do people make decisions to seek new information as a weather situation and its forecasts evolve?
- How is new forecast information integrated with experience, earlier information, and other considerations to update or confirm risk perceptions and decisions?
- What roles do social networks play in disseminating forecast information, and how are new media technologies changing how weather information is communicated to different populations?
- How will a transition from a “warn-on-detection” to “warn-on-forecast” paradigm within the NWS affect severe weather warning communication and use for various audiences?

[3] See http://www.faa.gov/about/initiatives/nextgen/.

- How can the answers to the above questions be applied to develop mechanisms to more effectively communicate weather information and forecasts—particularly those containing uncertainty information—in ways that account for different interpretation by different user groups and promote beneficial behavior?

In all of these priority areas, a sustained, interdisciplinary effort is needed to develop core knowledge that can be applied to address current community needs for weather information, as well as to address new research questions and weather R2O needs as they arise. As in meteorology, quantitative and qualitative approaches can be combined to develop more complete understanding. Relevant social science and interdisciplinary expertise is best entrained from the beginning of studies, to ensure that the work incorporates relevant social science theory and knowledge developed in other contexts and avoids reinventing existing findings. To be most effective, this work would need to link with progress in allied domains that examine risk communication and decisions under risk and uncertainty, such as healthcare and nonweather hazards. Such cross-fertilization would also help attract more leading social scientists to devoting effort to weather prediction issues.

In some situations, addressing these priority areas will involve applying existing social science theories and methods to weather information contexts. Doing so will not only improve knowledge about socioeconomics of weather; it will often also generate interdisciplinary theoretical and methodological advances. In other situations, application to weather contexts will require development of new or substantially improved theories and methods. Thus, work in these priority areas will involve a mix of application and enhancement of existing tools with fundamental new developments. Because meteorologists and researchers from different social science fields can have different ways of learning and knowing, creating successful collaborations and outcomes will require acknowledging and respecting these different backgrounds and approaches.

The findings from this work would not only help the weather community improve the use and value of existing weather information, they would also help the community identify information gaps. In this way, socioeconomic research has the added advantage of identifying groundbreaking new areas for meteorological research and R2O activities. Examples are provided in the discussions in Chapter 4 on very high impact weather, urban meteorology, and renewable energy production.

Commitment to addressing the socioeconomics of weather has another advantage: helping agencies and the weather community at large make policy and investment decisions. Weather research and R2O activities inevitably involve choices among priorities for investing resources, and different groups' societal and economic priorities will invariably differ. For example, a 5-day forecast indicating that a coastal tourism area may need to be evacuated to save lives because of an approaching hurricane may conflict with local businesses' desire to retain customers and employees and with the area's long-term economic prosperity if an evacuation turns out to be unnecessary. Investments in research and R2O activities to improve 10-day weather forecasts may mean fewer resources for improving 0- to 24-hour forecasts. Similarly, investments in probabilistic forecasts with larger numbers of ensemble members could result (at least in the near term) in lower resolution forecasts. Decisions about such trade-offs can be informed by an understanding of societal needs for forecasts. Socioeconomic considerations are also important for decisions about designing forecast dissemination and decision support systems of the future, such as new NWS products and NextGen. Thus, weather–society capacity and knowledge can help agencies and political and business leaders make such decisions within a broader policy framework (e.g., Morss, 2005; Morss et al., 2005).

INTEGRATING THE SOCIAL SCIENCES AND WEATHER: A PATH FORWARD

One approach to categorizing interdisciplinary "sociometeorology" research and R2O activities is to consider a combination of "cutting-edge" and "off-the-shelf" (readily available) knowledge in the different disciplines. The most innovative and riskiest research will combine cutting-edge social science with cutting-edge meteorology, advancing science and knowledge in both fields. For some research and R2O questions, cutting-edge social science will most appropriately be applied with off-the-shelf meteorology, or vice versa. Each of these types of work is needed and has value for advancing interdisciplinary knowledge and weather community goals. From an integrated perspective, work that applies off-the-shelf meteorology in a new way to address cutting-edge societal needs has potential to be just as groundbreaking as other types of work. As a result, it is important for fundamental, applied, and use-inspired activities to be supported in career development and by funding agencies.

Building programs that develop and conduct research and R2O activities in these different ways requires two-way partnerships among meteorologists and social scientists, where different perspectives and interests are discussed and incorporated. Depending on the program, different areas of expertise and methodological approaches from the social sciences will be needed. There are different approaches that can be taken to build interdisciplinary capacity and expertise. No single approach alone will suffice, but a combination of complementary approaches is required. Summarized below are some opportunities for building interdisciplinary capacity that could be considered (along with a few current examples). Pursued together, programs of this type can develop the required interdisciplinary capacity and knowledge and also apply it to meet weather community, agency, and societal needs.

- **Long-term programs to establish and maintain expertise and resources for integrating social sciences and weather prediction:** Current examples include the National Center for Atmospheric Research's (NCAR's) Societal Impacts Program (SIP) and the Oklahoma National Weather Center's Social Science Woven Into Meteorology (SSWIM) program (Box 2.1). A significant feature of both programs is their colocation with (and integration of social scientists into) a major meteorological entity. This colocation and integration is important because it facilitates engaging social science to advance weather–society knowledge and applications.
- **Grant-funded research to address priority fundamental and R2O issues at the weather–society interface:** Currently, few research and R2O activities focused on weather–society issues are funded by the federal agencies. This is in contrast to the climate arena, where a variety of programs fund socioeconomic and policy research. One current example of this type of effort in the weather arena is the NOAA/NSF-funded Communicating Hurricane Information (CHI) program (Box 2.1), in which NOAA and NSF, in conjunction with an interdisciplinary group of experts, identified key social science issues related to the hurricane forecast and warning system and then issued a call for proposals. Such grant programs are one of the most effective mechanisms for addressing priority interdisciplinary issues that involve more basic research or for which the most fruitful approaches and expertise are not apparent; in other words, where PI-driven creativity and innovation can make key contributions. They are also a strong mechanism for building interdisciplinary teams and entraining new social science and interdisciplinary expertise to address weather prediction issues.
- **Directed research to quickly address priority applied issues at the weather–society interface:** When the specific questions are well-defined, concrete results are needed in a few months or years, and the methodologies to produce those results are known and well developed, the most appropriate mechanism can often be directed research efforts such as targeted short-term grants, contracts, or consultant studies (e.g., Centrec, 2003; Lazo

and Chestnut, 2002). Such studies generally involve off-the-shelf social science combined with off-the-shelf meteorology. As socioeconomic capacity is developed within the weather prediction community, more studies may fall into this category.

- **Collaborative social science–physical science or –engineering ("end-to-end-to-end") testbeds that integrate social science into the development of new meteorological technologies and products:** A current example is the NSF CASA Engineering Research Center (Box 2.1), which has incorporated social science as an equal partner in multiple aspects of its work. The long-term programs described above may also include efforts of this type. Such efforts combine new weather technologies and products, users and their socioeconomic considerations, and social science expertise. In doing so, they provide a focusing mechanism for integrating social sciences into meteorology in ways that meet users' and meteorologists' needs.
- **Agency programs to develop internal and external capacity to address specific weather–society needs related to the missions of NOAA/NWS and other agencies:** Developing internal agency capacity will require hiring social and interdisciplinary scientists as well as social science training of existing agency personnel. External capacity familiar with agency needs can be developed through mechanisms such as programs for interdisciplinary university faculty, postdoctoral researchers, and graduate students to work in residence at specific agencies (similar to the American Association for the Advancement of Science's Science & Technology Policy Fellowship program,[4] but focused on weather-society work). Such programs are needed to develop R2O applications of social sciences and to allow agencies to effectively use input from social science efforts. An important aspect of such programs is engaging a diversity of social science disciplines, since different disciplines (and subdisciplines) bring different perspectives relevant to addressing agency missions.
- **Educational initiatives to train the next generation of meteorology researchers, forecasters, and practitioners in integrated weather–society thinking:** A small group of meteorologists who understand socioeconomic issues is developing, and the community of interdisciplinary weather–society researchers is growing. However, these individuals have been trained largely through their own initiative to pursue interdisciplinary education and through small efforts such as the WAS*IS (Weather and Society*Integrated Studies) program (Box 2.1). This group is also well below the critical mass required to meet weather community needs. Thus, educational initiatives

[4]See: http://fellowships.aaas.org/

are needed to train meteorology students, forecasters, and practicing meteorologists in societal aspects of weather. Interdisciplinary undergraduate and graduate programs are also needed for meteorologists and social scientists interested in weather–society careers. Such initiatives can be developed by universities, NOAA/NWS, and other organizations, and fostered by community-wide institutions such as AMS.

Several current examples of such programs are provided in Box 2.1. These programs are complementary, and each fills a unique niche. Their successes include interdisciplinary research projects and results, forecast programs and products that integrate end-user needs, and researchers and forecasters knowledgeable in the integration of meteorology and social sciences. Although such programs demonstrate substantial progress in integrated weather–society work, it will take time for these efforts to demonstrate large-scale benefits to the weather community and society. Further, they are far from sufficient in filling the weather community's needs in this area, and funding for many of the programs is currently limited or uncertain in the future. This highlights the need for long-term, sustainable funding for such programs. To further this collaborative work, the weather community can build on examples in areas such as the multiple U.S. centers focusing on natural hazards research and reduction, the National Marine Fisheries Service and other natural resources management programs, and NOAA's Regional Integrated Sciences and Assessments program to address climate issues important to regional decision makers.

Agency coordination is important for facilitating efforts to address socioeconomic aspects of weather, but many of the ideas and much of the implementation effort will need to come from within the weather research and R2O community and from allied social scientists. Given the interdisciplinary nature of this area, specific ideas and partnerships will need to be developed through in-depth discussion among meteorologists and social scientists from various disciplines. Periodic workshops that bring social scientists and meteorologists together to discuss priority research and R2O topics in socioeconomic aspects of weather prediction will aid in integrating these fields. AMS and long-term programs such as NCAR's SIP and the Oklahoma National Weather Center's SSWIM program are already coordinating such discussions, and they can continue to facilitate workshops on a variety of topics. Because limited time was available at the 2009 BASC Summer Study workshop to discuss socioeconomic programs and issues, workshop participants noted the potential value of a future community workshop for social and interdisciplinary scientists to discuss priorities and strategies for weather–society research and R2O in depth. Mission agencies, such as NOAA, can organize workshops focused on addressing specific social science needs for transitioning R2O.

Vision

The committee's vision is that by ~2025 a core group of social scientists and meteorologists will have formed a strong, mutually beneficial partnership in which multiple areas of science work together to ensure that weather research and forecasting meet societal needs. The knowledge and expertise needed to address critical problems at the weather–society interface efficiently and reliably will be readily available, and it will be applied regularly to address research questions of interest to both social scientists and meteorologists and to enhance weather R2O and operations. Where societal considerations are integral to meteorological projects and programs, social scientists with appropriate expertise will be engaged from the onset of planning, so that the social sciences can most effectively contribute to program goals and outcomes. Sufficient support will be available to incorporate relevant social science perspectives from various disciplines into traditionally physical science–oriented programs, and to provide opportunities for sustained, mutually beneficial social science–meteorology partnerships. This includes institutional and funding support from government agencies (including NOAA, NSF, NASA, and others) as well as community support from other agencies, universities, research institutions, AMS, and other members of the weather enterprise.

Progress is being made, as illustrated by the activities in Box 2.1 and the growing number of people interested in integrated weather–society issues, but current activities and capacity are still below critical mass, and years will be needed for the benefits of these efforts to be broadly realized. After decades of discussing the importance of socioeconomic considerations, the vision is that the weather prediction community will finally have the capacity to understand and act on them. The benefits will be realized through integrated, interdisciplinary research, R2O, and operational work in very high impact weather, urban meteorology, renewable energy production, and other, long-standing issues (e.g., transportation) at the weather–society interface. Socioeconomics will be infused into weather research and forecasting in these areas; and in discussions of weather community priorities, socioeconomic perspectives will be integrated into findings and recommendations. This will result in meteorological researchers and forecast providers, social scientists, and forecast users working together to generate weather science and services that effectively meet critical societal needs.

Recommendation: The weather community and social scientists should create partnerships to develop a core interdisciplinary capacity for weather–society research and transitioning research to operations, starting with three priority areas:

- **estimating the societal and economic value of weather information;**
- **understanding the interpretation and use of weather information by various audiences;**
- **and applying this knowledge to improve communication, use, and value.**

To be effective, the partnership between the weather community and social scientists should be two-way and balanced, and should include a variety of social science perspectives. Members of the weather community, including research institutions, universities, individual meteorologists, NOAA, NSF, and other agencies, should pursue multiple mechanisms for building research and R2O capacity in the socioeconomics of weather, including long-term interdisciplinary programs; grant-funded and directed research, R2O, and applications activities; integrated social science–physical science testbeds; mission agency programs to develop capacity; and educational initiatives. The required capacity should be developed and utilized through partnerships across agencies, programs, and disciplines, and in concert with academia and the private sector.

3

Established Weather Research and Transitional Needs

There are multiple research and research-to-operations (R2O) issues that have been recognized for some time as important and achievable but that have yet to be completed or implemented in practice. The committee refers to these as *established* needs for weather research and the transition of research results into operations—in contrast to the emerging needs discussed in Chapter 4. Four established priority needs are identified, and all are in various stages of development, but none have yet been resolved despite having been identified as pressing in numerous previous studies (see Table 1.1). They include global nonhydrostatic coupled modeling, quantitative precipitation forecasting, hydrologic prediction, and mesoscale observations. The reader may question why hurricane intensity forecasting is not included here as an established need. The answer lies in the unavoidable reality that virtually all research and transitional needs have both established and emerging aspects, and so the hurricane intensity challenge is embedded within the following section on predictability and coupled modeling and it is also embedded in the following chapter dealing with emerging needs.

UNDERSTANDING PREDICTABILITY AND GLOBAL NONHYDROSTATIC COUPLED MODELING

The United States continues to maintain world leadership in weather and climate research as indicated, for example, by the worldwide use of weather[1] and climate[2] research models developed in the United States and the leadership positions held by U.S. scientists in international programs. The nation has also made substantial investments in the development of global satellite, in situ, and remote sensing observing systems. In spite of

[1]Weather Research and Forecasting (WRF) model; see http://www.wrf-model.org.
[2]Community Climate System Model (CCSM); see http://www.ccsm.ucar.edu.

these accomplishments, the United States is not the world leader in global numerical weather prediction (NWP). Figure 3.1 indicates that the United States has made steady progress in global weather forecasting performance, but so have other countries.

Within the United States, however, the performance of the NOAA/NWS National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) is superior to the Navy Operational Global Atmospheric Prediction System (NOGAPS) operated by the Fleet Numerical Meteorology and Oceanography Center (FNMOC). In particular, the gap in model performance between NCEP and the European Centre for Medium-Range Weather Forecasts (ECMWF) has not narrowed in the past 15 years. The primary reason is the slow and sometimes ineffective transfer of achievements in the external research community to operational centers in the United States (R2O). Another reason is the lack of investment and progress in assimilating observations in advanced weather prediction models, which is also related to the slow R2O process in data assimilation. In addition, NCEP's high-performance computing (HPC) capacity, despite recent upgrades, lags behind the capacities of many other major prediction centers around the world.[3] The complexities associated with using a hydrostatic global model (GFS) and a variety of regional (nonhydrostatic and hydrostatic) models[4] makes it very challenging to maintain and improve these prediction models and associated data assimilation schemes, particularly at the underresourced NCEP. As a consequence, the United States is not fully realizing the potential benefits of its substantial investments in observing systems.

Progress and Remaining Needs

As the horizontal grid spacing of models continues to decrease, especially to less than 10 km, hydrostatic models are no longer appropriate, and it is essential that global nonhydrostatic NWP models (Box 3.1) be coupled with ocean and land models. In fact, Japan's global Non–hydrostatic Icosahedral Atmospheric Model (NICAM), which runs on the Earth Simulator[5] computer, has reached horizontal grid spacing of 3.5 km (Satoh et al., 2008), which results in a spatial resolution 10 times greater (and an areal

[3]These and other findings have been discussed in the recently completed external review of NCEP, the "2009 Community Review of National Centers for Environmental Prediction," that was managed by the University Corporation for Atmospheric Research (UCAR). The executive summary of the NCEP review is included as Appendix B of this report.

[4]The NCEP website describes the models operated by NCEP; see http://www.emc.ncep.noaa.gov/.

[5]See http://www.jamstec.go.jp/esc/index.en.html.

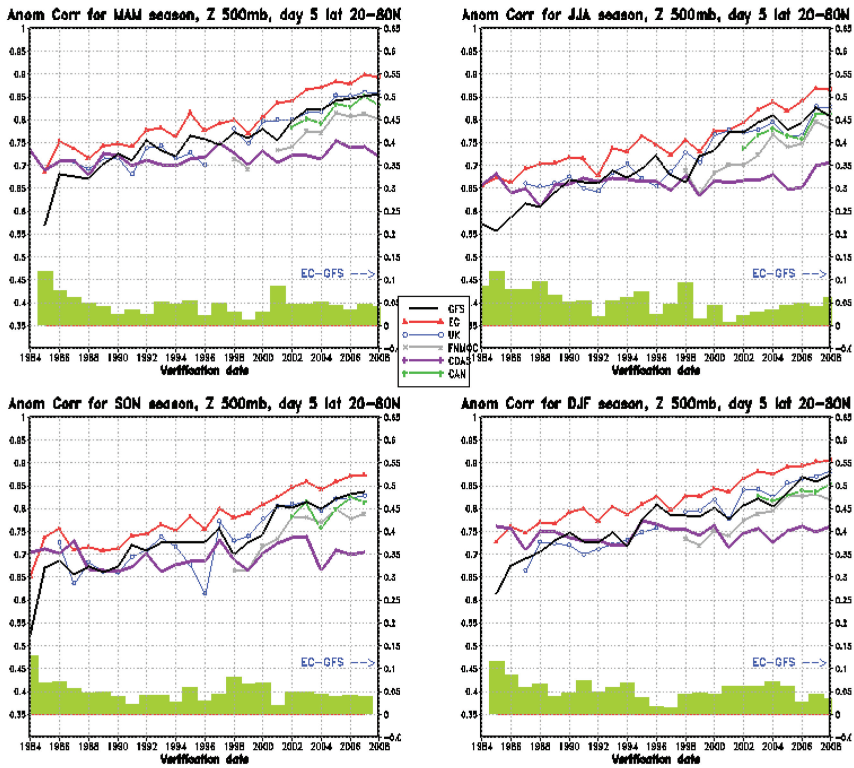

FIGURE 3.1 The United States and other countries have made steady progress in global weather forecasting performance. Time series of seasonal mean anomaly correlations of 5-day forecasts of 500-hPa heights for different forecast models (Global Forecast System [GFS], ECMWF (EC in legend), UK Meteorological Office [UKMO], Fleet Numerical Meteorology and Oceanography Center [FNMOC], the frozen Coordinated Data Analysis System [CDAS], and Canadian Meteorological Centre [CMC] model) from 1985 to 2008. Seasons are 3-month non-overlapping averages, Mar–Apr–May, etc. for the Northern Hemisphere. The green shaded bars at the bottom are differences between ECMWF and GFS performance. SOURCE: NCEP. Available at http://www.emc.ncep.noaa.gov/gmb/STATS/html/seasons.html.

resolution 100 times greater) than the 35-km grid spacing of the hydrostatic GFS model at NCEP's Environmental Modeling Center (EMC).[6] ECMWF has also upgraded its operational forecasts to 16-km grid spacing since January 2010.

Now is an optimal time to invest in this area because of many achievements that have been made in the past decade, such as progress in global

[6]See http://www.emc.ncep.noaa.gov/gmb/STATS/html/model_changes.html.

BOX 3.1
Modeling Terminology

Convective parameterizations: When an atmospheric model's grid spacing is too coarse relative to the scales of convective clouds, convective processes cannot be resolved by the model and hence are represented in terms of the grid-scale model variables. This is a necessary simplification that cannot be avoided unless the model grid spacing is small enough to explicitly resolve these convective clouds.

High-resolution nonhydrostatic atmospheric models: Nonhydrostatic atmospheric models are models in which the hydrostatic approximation (that the vertical pressure gradient and buoyancy force are in equilibrium) is not made, so that the vertical velocity equation (arising from applying Newton's second law to atmospheric motion) is solved. This allows nonhydrostatic models to be used successfully for horizontal scales of the order of 100 m. "High resolution" has different meanings for global, regional, and local models and its meaning also changes with time (or with the increase of computing power over time). At present, "high resolution" usually refers to a few kilometers in horizontal grid spacing in global models and around 1 km for regional models.

Icosahedral grid: This is a geodesic grid formed by arcs of great circles on the spherical Earth. It consists of 20 equilateral triangular faces expanded onto a sphere and further subdivided into smaller triangles. It provides near-uniform coverage over the globe while allowing recursive refinement of grid spacing.

Incompatible lateral boundary conditions: Lateral boundary conditions refer to the conditions at the horizontal boundaries of regional atmospheric–ocean–land models that are necessary for running these models and are provided from the output of global models or reanalyses. Incompatible conditions can arise from differences in the regional and global models in the model physics (e.g., cloud microphysics), dynamics (e.g., atmospheric waves), or configuration (e.g., topography), and can have a significant and negative impact on regional modeling.

Predictability and predictive skill: Predictability refers to the extent to which future states of a system may be predicted based on knowledge of current and past states of the system. Because knowledge of the system's past and current state is generally imperfect (as are the models that utilize this knowledge to produce predictions), predictability is inherently limited. Even with arbitrarily accurate models and observations, there may still be limits to the predictability of a physical system due to chaos. In contrast, predictive skill refers to the statistical evaluation of the accuracy of predictions based on various formulations (or skill scores). Predictability provides the upper limit in the time for skillful predictions.

Quantitative Precipitation Estimation (QPE): QPE refers to the estimation of precipitation amounts or rates based on remote sensing data from radar, satellites, or lightning detection systems, and also estimates from in situ gauges that may or may not provide spatially representative data.

Quantitative Precipitation Forecasting (QPF): QPF refers to forecasts of precipitation that are quantitative (e.g., millimeters of rain, centimeters of snow) rather than qualitative (e.g., light rain, flurries), indicating the type and amount of precipitation that will fall at a given location during a particular time period.

Testbeds: A testbed is a platform for rigorous testing of scientific theories, numerical models or model components, and new technologies. Testbeds in weather forecasting allow for the testing of new ideas in a live environment similar to that in weather forecasting, and hence accelerate the transition from research to operations.

nonhydrostatic research modeling, progress in data assimilation (including the assimilation of WSR-88D radar reflectivity and radial velocity data over the continental United States), and increased high-performance computing capacity.

A recent achievement is the establishment of various testbeds (e.g., the multiagency, distributed Developmental Testbed Center; and the virtual National Oceanic and Atmospheric Administration [NOAA] Hydrometeorological Testbed [HMT]), which will be helpful for the R2O transition as venues to test new observing and forecast capabilities. The National Aeronautics and Space Administration (NASA)/NOAA/Department of Defense (DOD) Joint Center for Satellite Data Assimilation (JCSDA) has also been established with the goal of accelerating the use of global satellite data in operational forecasting. However, extramural funding to support operationally oriented research at these testbeds is very limited (Mass, 2006).

In addition to the requirement for better weather forecasting models and more efficient and effective data assimilation methods, there is a pressing need for basic research to better understand the inherent predictability of weather phenomena at different temporal and spatial scales, which is also relevant to social scientists whose research and questions often have elements of scale (see Chapter 2). There is also a major emerging weather research question concerning how weather may change in a changing climate. These and similar issues have been raised in various previous studies (e.g., PDT–1 [Emanuel et al., 1995]; PDT–2 [Dabberdt and Schlatter, 1996]; PDT–7 [Emanuel et al., 1997]; NRC, 1998b), but little progress has been achieved. Although the relationship between changes in climate and weather is important both scientifically and practically, it is outside the scope of the present study and this report.

It is now widely recognized that physical processes at the atmosphere–ocean–land interface play a significant role in weather forecasting, such as the impact of atmosphere–wave–ocean coupling on hurricane forecasting (Chen et al., 2007) and land–atmosphere coupling on near-surface air temperature, humidity, turbulent fluxes, convection initiation, and precipitation. The role of biological (e.g., vegetation greenness and leaf area index) and chemical (e.g., trace gases, aerosols) processes in weather and air pollution forecasting has also received increased attention.

Unified Modeling Frameworks and Coupled Modeling

Many global weather forecasting models, such as those at NCEP and ECMWF, are hydrostatic because their grid spacings are generally greater than 10 km or so. In contrast, many regional weather research and forecast models (e.g., WRF) are nonhydrostatic. Of particular note are high-resolution nonhydrostatic models (those with grid spacing around 2 km), which would remove the dependence of the model on convective parameterizations, a major barrier for progress in weather forecasting. Global nonhydrostatic NWP models would provide a unified framework for global and regional modeling, and consequently help form a more seamless transition between weather and climate predictions; the importance of a unified framework was recently advocated by the World Climate Research Program in its new strategic plan (WCRP, 2009). The UK Meteorological Office[7] has adopted this approach with positive results (Figure 3.1). Such a unified nonhydrostatic modeling system with different configurations (e.g., as a global model with a uniform horizontal resolution, as a global model with two-way interactive finer meshes at specific regions, or as a regional model) has also been developed in the United States (Walko and Avissar, 2008). The nonhydrostatic WRF model has been widely used (there are thousands of registered domestic and international users from public agencies, academia, and the private sector) as a regional model for research and weather forecasting (e.g., NCEP); WRF can also be configured as a global model. However, with a latitude-longitude grid in the global WRF, a polar filter is still required, and a better alternative grid may be the icosahedral grid (see Box 3.1). This development of a unified framework would facilitate and increase the interaction among several communities that have traditionally been segregated—the weather and climate communities, and the regional and global modeling communities. A common model framework would also reduce costs through improved efficiencies and enhanced collaborations in the development of various model physical parameterizations.

High-resolution global nonhydrostatic models have the potential to improve regional modeling because many regional weather prediction and data assimilation problems are essentially global problems; better global models can also reduce the effects of incompatible lateral boundary conditions for the regional models through the use of consistent model physics and two-way nesting. The ability to run both global and regional models in two-way nested mode will also create many new research opportunities (e.g., to study changes in weather in a changing climate and the potential upscaling effects on global circulations).

A number of key capabilities remain to be developed for coupled nonhydrostatic models; they include sufficiently high spatial and temporal resolutions that enable convection and high-impact weather to be explic-

[7] See www.metoffice.gov.uk/science/creating/daysahead/nwp/um.html.

itly resolved (avoiding the limitations of cumulus parameterizations) in global models; assimilation of convective-scale observations using advanced methods that eliminate precipitation spin-up and improve initial conditions in general; improvements in cloud microphysics, physics of the planetary boundary layer (PBL), and interface physics related to the atmospheric coupling to ocean and land processes; and design and development of convective-scale ensemble prediction and post-processing systems for improved and readily interpretable probabilistic forecasts.

Various numerical methods—spectral, finite-difference, and finite-volume—have been used in global hydrostatic weather forecasting models. For global high-resolution nonhydrostatic models, further evaluation of these methods and development of new methods are still needed. New grid cell structures (rather than the traditional latitude-longitude grids) are needed, especially for the treatment at the poles (e.g., Walko and Avissar, 2008). A promising combination might be the finite-volume method with icosahedral grid cells (e.g., Heikes and Randall, 1995). In particular, a new global weather forecasting model with icosahedral horizontal grid, isentropic-sigma hybrid vertical coordinate, and finite-volume horizontal transport (called "FIM") has been developed at the NOAA Earth Systems Research Laboratory (ESRL).[8] The hydrostatic version of FIM is available, but the nonhydrostatic version remains to be developed.

Observations are still inadequate to optimally run and evaluate most high-resolution models and determine forecast skills at various scales. (A detailed discussion of the opportunities and needs for mesoscale observations is provided in the last section in this chapter.) Perhaps even more challenging is the development of suitable and effective verification and evaluation metrics and methods for determining probabilistic forecast skills at different scales.

High-resolution and ensemble forecasts require high performance computing (HPC) capability for model predictions but also for data assimilation, post-processing, and visualization of the unprecedented large volumes of data. HPC facilities are currently available at some Department of Energy (DOE) and NASA centers, as well as at NSF-sponsored centers, which are usually used for research and climate simulations. It would be beneficial to have an HPC center that is dedicated to the support of weather forecasting and research in the academic and related research community to facilitate R2O activities. HPC facilities are also suboptimal within NOAA for operational weather forecasting. A substantial increase in computing capacity

[8] See http://fim.noaa.gov.

dedicated to the operational and research communities for the high-resolution weather modeling enterprise is required (see Appendix B). The recent NOAA partnership with the DOE Oak Ridge National Laboratory on HPC support (with a focus on climate research and prediction) will help alleviate the HPC demand at NCEP. Also crucial is development of improved software to increase the computational efficiency and scalability of the forecast models as well as post-processing and visualization, particularly at petascale (10^{15}) HPC (e.g., NRC, 2008c).

Data Assimilation and Observations

Data assimilation as part of the forecast system is also important for acquiring and maintaining observing systems that provide the optimal cost-benefit ratio to different user groups and their applications. Data denial experiments can selectively withhold data from one (or more) system(s) and assess the degradation in forecast skill. Data assimilation can be used to determine the optimal mix of current and future in situ and remotely sensed measurements, and also for adaptive or targeted observations (e.g., Langland, 2005). It is also beneficial to understand the impacts of observing systems on model performance and the resulting forecast accuracy (e.g., Gelaro and Zhu, 2009; Rabier et al., 2008). With aging satellites in space and insufficient satellites in the NASA and NOAA pipelines to replace or enhance them, observing system simulation experiments can also help support detailed cost-benefit analyses.

Besides the satellite and radiosonde data that are widely used in global operational NWP, the assimilation of data from radar and other sources is also crucial, particularly for regional forecasting. Preliminary work done at the University of Oklahoma (Xue et al., 2009) indicates that a high-resolution regional model initialized using global model output has relatively large initial errors in precipitation forecasting but these errors do not further increase with time in the first few hours. On the other hand, their results also indicate that regional precipitation forecasting with radar data assimilation has smaller initial errors but they increase rapidly with time in the first few hours, as expected from our understanding of atmospheric predictability.

For data assimilation in high-resolution, cloud-resolving, and coupled air–sea–land models, it is particularly important to address the inconsistency in model physics and observations. For instance, the cloud droplet size distribution assumed in models may not be the same as that assumed in satellite-retrieved cloud properties. Although significant progress has been made in data assimilation using the individual model component of the atmosphere, ocean, or land, progress is lacking with the fully coupled system. There is also a lack of coherent observations across the atmosphere–ocean–land interface for data assimilation in the fully coupled models.

It is important to critically compare different advanced data assimilation methods, (e.g., the ensemble Kalman filter [EnKF] and 4-dimensional variational [4DVar] analysis) with those methods currently used by some operational models such as 3-dimensional variational (3DVar) approaches. For instance, the Navy's FNMOC recently initiated operational use of the Naval Research Laboratory's 4DVar data assimilation system to replace the 3DVar in NOGAPS. Preliminary impact tests (Xu and Baker, 2009) indicate that equivalent 5-day forecast skill with the 4DVar system is extended about 9 hours in the Southern Hemisphere and 4 hours in the Northern Hemisphere, and tropical cyclone 5-day track forecast errors are reduced. Similarly, the experiments at the NOAA ESRL (MacDonald, 2009) indicate that the EnKF improves global weather forecasts compared with the 3DVar system. A community consensus is emerging that the future of data assimilation may belong to a hybrid EnKF-4DVar system (e.g., Zhang et al., 2009); the pace in testing and implementing such a hybrid system needs to be accelerated at NCEP.

Model advances—such as improved grid resolution, model physics, and data assimilation—also improve the performance of short-range, 0- to 12-hour forecasts. These forecasts are of high societal relevance for many applications, such as forecasting severe weather (warning the public and protecting lives and property), wind speed/direction changes (improving the use of wind-generated power), solar radiation (for solar power generation), visibility (for surface and aviation transport), and air pollution (for public health). Such forecasts also demand and stimulate the development of new observing technologies and measurements, such as the high-performance, low-cost, polarimetric X-band radar networks being developed within the Collaborative Adaptive Sensing of the Atmosphere (CASA) program (McLaughlin et al., 2007, 2009).

Observational data with high temporal and spatial resolution are crucial to the understanding of atmospheric processes, providing data for assimilation in models, and evaluating and improving those models. This requires the synergistic combination of data from diverse sources. Rawinsonde, radar, satellite, and aircraft data as well as data from other sources all play complementary roles in weather research and forecasting.

Rawinsonde coverage needs to be maintained and enhanced because of its value for weather forecasting and evaluation of satellite data. Geostationary satellites provide excellent temporal coverage, but new technologies are still required to add passive microwave sensors that can penetrate through clouds. Polar orbiting satellites provide global coverage with better spatial resolution, but active microwave, infrared, radio frequency, and optical sensors are still needed to provide data on the three-dimensional structure of the atmosphere. Soundings of refractive index (as a function of atmospheric temperature and the partial pressures of dry air and water vapor) from global positioning system (GPS) satellites have also proved very useful for weather forecasting. NEXRAD (WSR 88-D) radars provide excellent precipitation detection above the PBL over relatively flat surfaces, but their spatial coverage—especially over the western United States—is far from complete, and some radars are not optimally sited for weather research and forecasting. The increase in the number of radar sites and technological upgrades (e.g., the planned dual-polarization capability) are very much needed. The massive numbers of surface networks need to be effectively used in data assimilation. Similarly, methods to make good use of the large numbers of automated meteorological reports from commercial aircraft need to be developed (Moninger et al., 2003). More detailed discussion on mesoscale observations are provided in the last section of this chapter.

Finally, a national capacity needs to be developed for optimizing the transitioning of environmental observations from research to operations. Such a capacity is still lacking at present (NRC, 2009b). A rational five-step procedure for configuring an optimal observing system for weather prediction was proposed a decade ago by a prospectus development team, PDT–7 (Emanuel et al., 1997) and remains relevant today. Briefly summarized, the procedure involves identifying specific forecast problems; using contemporary modeling techniques; estimating the incremental forecast improvements; estimating the overall cost (to the nation, rather than to specific federal agencies); and using standard cost-benefit analyses to determine the optimal deployment.

Recommendation: Global nonhydrostatic, coupled atmosphere–ocean–land models should be developed to meet the increasing demands for improved weather forecasts with extended timescales from hours to weeks.

These modeling systems should have the capability for different configurations: as a global model with a uniform horizontal resolution; as a global model with two-way interactive finer grids over specific regions; and as a regional model with one-way coupling to various global models. Also required are improved atmospheric, oceanic, and land observations, as well as significantly increased computational resources to support the development and implementation of advanced data assimilation systems such as 4DVar, EnKF, and hybrid 4DVar–EnKF approaches.

Predictability

Intrinsic predictability of the atmosphere–ocean–land system is a fundamental research issue. Even though predictability has been studied for the past half century and was a major theme in the Stormscale Operational and Research Meteorology (STORM) documents in the 1980s (e.g., NCAR, 1984), not much is known today about the inherent limits to predictability of various weather phenomena at different spatial and temporal scales. Because of the error growth across all scales, from cumulus convection to mesoscale weather and large-scale circulations, a high-resolution (preferably cloud-resolvable) nonhydrostatic global model is crucial to address such error growth and better understand the predictability of weather systems. Although predictability is obviously important to operational forecasting, increased emphasis on basic science (such as the limits of predictability) would be beneficial to the greater weather community.

Another fundamental question of predictability is error growth across various scales. This issue is particularly important as higher-resolution nonhydrostatic global models are developed. For instance, how up-scaling error growth from convective scales affects the larger scale circulation is poorly understood in both regional and global models. Some recent modeling experiments indicate that increasing model resolution may not improve forecasting skill for the first few days but may improve forecasts for days 3 through 5 (MacDonald, 2009).

Actual predictive skill may likely be dependent on the specific phenomenon (e.g., mesoscale convective systems [MCSs] versus tornadoes). It is difficult to assess predictive skill, because the lack of skill can result from problems arising from data and data assimilation deficiencies, errors in numerical representation, intrinsic predictability limitations, and forecast verification methodology. Retrospective forecasts have been found to be helpful in better understanding forecast errors and improving global forecast skills (Hamill et al., 2006). To address both intrinsic predictability and predictive skill, global nonhydrostatic modeling can be helpful. If such models are used operationally and if they become user-friendly and available to the research community, researchers will be able to assist in diagnosing the sources of errors by rerunning modeling cases with large (and small) forecast errors and carefully analyzing the results. In short, it is difficult to address and understand intrinsic predictability in the current operational prediction environment.

To address prediction skill, there is the need to understand the causes of poor forecasts (or forecast outliers), identify sources of error (e.g., in model physics, observations, or methods), and identify solutions that may improve prediction skill. The research community can contribute significantly to an understanding of these issues by using operational models (O2R) in their research and transferring research results back to the operational centers (R2O). Further discussion of the importance of O2R is provided in Box 3.2.

Societal Benefits

Improvements in weather forecasting brought about by better models will help increase U.S. economic efficiency and productivity; improve management of air, land, rail, and ship transportation systems including NextGen and the Federal Highway Administration's IntelliDriveSM Initiative;[9] improve renewable energy siting and production; and enhance other weather-sensitive applications where better forecasts lead to increased safety, cost avoidance, and improved performance. Participation of social scientists and the socioeconomic community is required to address the societal impacts and quantify the benefits, improve the focus of weather research, and realize the importance of weather forecasting in general. Their participation is also crucial to address the value of new and improved weather information products from high-resolution nonhydrostatic regional and global models. These issues are discussed in more detail in Chapter 2 (Socioeconomic Research and Capacity) and Chapter 4 (Emerging Weather Research and Transitional Needs).

QUANTITATIVE PRECIPITATION ESTIMATION AND FORECASTING

The Challenge

QPFs (Box 3.1) are much less skillful than forecasts of meteorological state variables (pressure, temperature, and humidity) and winds (Fritsch and Carbone, 2004). Precipitation, while often forced by large-scale dynamical conditions, is also heavily influenced by regional mesoscale circulations, microscale processes within cloud systems, and localized forcings near

[9]See http://www.intellidriveusa.org/.

BOX 3.2
Importance of Operations to Research (O2R)

Although R2O is usually emphasized, O2R is also important. Routine forecasts and verifications at operational centers provide outstanding questions in weather research. If the research community can present ideas to directly address these questions, operational centers will have a strong motivation to accelerate the transition of these ideas to operation, because these ideas might facilitate solving operational weather forecasting problems. Furthermore, few, if any, individual groups have the capability to routinely run ensembles of weather forecasting models as large as those at operational centers.

To make O2R efficient, the operational centers and the research community need to work more closely. One way to achieve this would be for the NWS and its NCEP/EMC to make the operational models more user-friendly and available to the research community (beyond what NCEP/EMC has already done to make ensemble model outputs available to researchers). In particular, the operational models need to be well documented so that graduate students can easily run these models and understand the model physics and dynamics. The research community, in turn, could use those ensemble outputs to better analyze, understand, and improve the poor forecast cases, address research questions related to weather forecasting, and also use the operational models in their research. The TIGGE project (THORPEX Interactive Grand Global Ensemble; Bougeault et al., 2010) illustrates good progress in this area. TIGGE has made available for the first time the ensemble forecasts from multiple operational centers in a consistent format. As useful as these datasets are, even the TIGGE archive does not contain the full arrays of model fields.

It is necessary to place more emphasis on providing the full, high-resolution data stream of observations and forecasts to the entire community in a timely fashion, as originally suggested by Mass (2006). Currently, NCEP cannot distribute all of the data it produces from its modeling system, significantly filtering the output in both three-dimensional space and time before distribution. This limits the ability of users to capitalize on the full value of these forecasts. This limitation will only grow worse as the resolution and duration of forecasts increase and as ensemble systems proliferate. As a way to alleviate this issue, modeling centers could consider becoming "open" centers, inviting value-adding applications access to the full and direct model output within the centers. Such an open approach would likely also catalyze more intellectual exchanges between members of the weather enterprises.

the planetary surface. A casual glance at typical precipitation patterns associated with individual events reveals substantial mesoscale variability in all seasons. This variability challenges both the forecast process and the adequacy of precipitation observations, which enable hydrologic prediction and precipitation forecast verification.

QPE Status and Progress

Operational QPE (Box 3.1) over U.S. territory is currently achieved through contributions from traditional gauge observations and the national network of Doppler radars (mainly WSR-88D). Space-based infrared and microwave data are employed over oceanic regions.

Gauge measurements are relatively accurate but lack representativeness in patchy convective precipitation, thereby leading to analysis errors, even for relatively dense mesoscale surface networks. Radar estimates are inclusive of nearly all rainfall where there is coverage; however, these are prone to well-known biases and uncertainty in application of the reflectivity–rainfall rate transformation function (e.g., Wilson and Brandes, 1979). The operational implementation of polarimetric WSR-88D capabilities promises a marked improvement in QPE over U.S. land areas and adjacent coastal waters. This will include precipitation phase, characteristic hydrometeor size range, and hydrometeor type discrimination, in addition to reduced uncertainty in cumulative amounts. These improvements will greatly benefit those hydrologic predictions that are based solely on observations. Remaining uncertainties are associated with network density, which could be satisfied through a combination of mesoscale surface networks that might reasonably include gauges and inexpensive, gap-filling high-frequency radars (as exemplified by the NSF CASA project; McLaughlin et al., 2007, 2009).

Merged infrared and microwave satellite products can also be helpful in mesoscale rainfall estimation (e.g., Joyce et al., 2004) where rain gauge and radar information is unavailable, though temporal resolution is a limiting factor in the utility of such products for short-range forecast applications. Convective rainfall can also be estimated from measurements of cloud-to-ground lightning activity, albeit with substantial uncertainty, as recently described by Pessi and Businger (2009) for the North Pacific Ocean.

QPF Progress and Seasonal Verification Performance

The skill in quantitative precipitation forecasts, while lagging progress in forecasting other variables, has increased steadily over the past 30 years as measured by equitable threat scores[10] (e.g., Figure 3.2). Forecasts are more skillful at shorter range and lesser cumulative precipitation amounts, which

[10]The Equitable Threat Score is a statistical skill score commonly used in the verification of quantitative precipitation forecasts. The score increases and forecasts are rewarded when both forecast and observed amounts greater than a given threshold are collocated (see http://www.meted.ucar.edu/satmet/goeschan/glossary.htm).

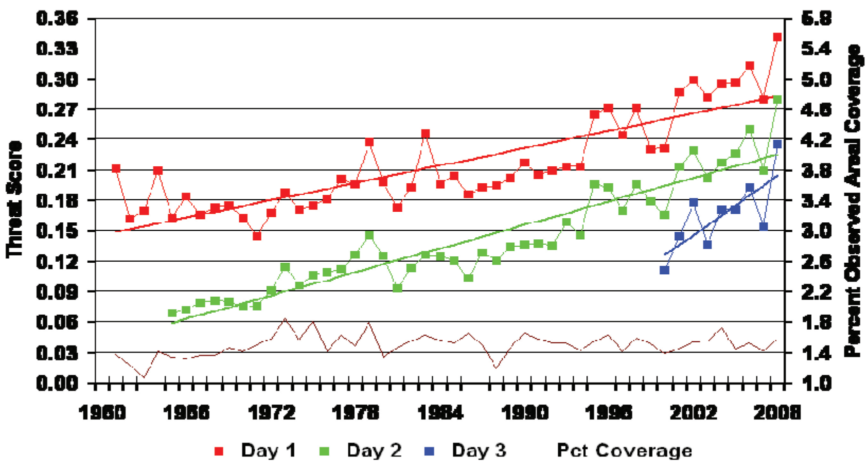

FIGURE 3.2 The skill in quantitative precipitation forecasts, as measured by equitable threat scores, has increased steadily over the past 30 years. This figure shows skill in the equitable threat score from 1961 to 2009 in precipitation predictions by the NOAA NWS NCEP Hydrometeorological Prediction Center for 1.00 inch of precpitation at 24 (red), 48 (green) and 72 (blue) hours. Percent areal coverage refers to the fraction of total forecast area to the area that actually received 1.00 inch or more of precipitation in the forecast period. SOURCE: NOAA NWS NCEP Hydrometeorological Prediction Center. Available at http://www.hpc.ncep.noaa.gov/html/hpcverif.shtml.

occur much more frequently than heavy or extreme events. Nevertheless, progress has been steady with rapidly increasing skill in Day 3 forecasts over the past 10 years as evidenced in Figure 3.2. The seasonal variation in predictive skill is marked by relatively high skill in winter and extremely low skill in summer (Figure 3.3). Although a number of factors come into play for this seasonal cycle, low skill in summer is related to weak forcing at larger scales of motion together with decreased stability and moist convection as the principal precipitation process.

Progress in QPF for Cool-Season Orographic Precipitation

Considerable skill has been achieved in the dynamical prediction of cool season orographic precipitation accounting for much of the skill associated with the winter season (Figure 3.3). By traditional verification methods, such as the equitable threat score, the skill in prediction of cool season orographic precipitation greatly exceeds all other circumstances, including strongly forced precipitation from fronts and cyclones over relatively flat

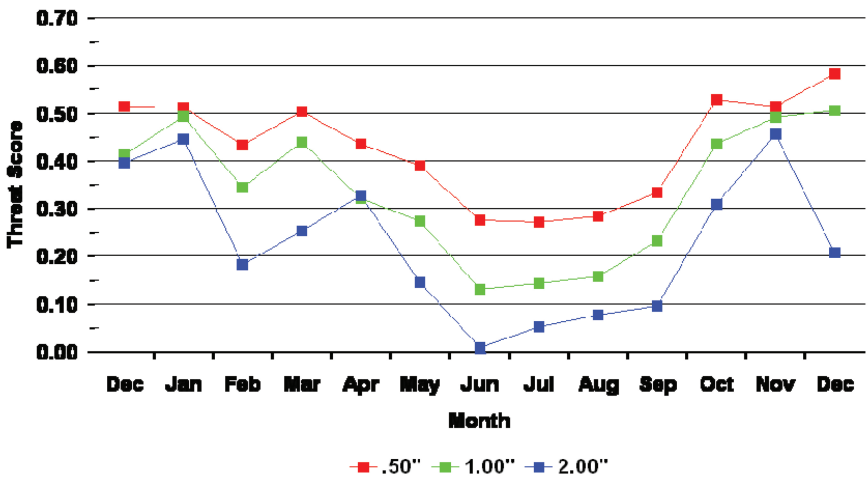

FIGURE 3.3 There is seasonal variation in predictive skill, with relatively high skill in winter and low skill in summer. Monthly skill in the equitable threat score from December 2008 to December 2009 in precipitation predictions by the NOAA NWS NCEP Hydrometeorological Prediction Center for 0.5 (red), 1.0 (green), and 2.0 (blue) inches of precipitation at 24 hours. SOURCE: NOAA NWS NCEP Hydrometeorological Prediction Center. Available at http://www.hpc.ncep.noaa.gov/html/hpcverif.shtml.

land. For example, recent results (Ikeda et al., 2010) from research simulations of snowfall over the central and southern Rockies produce water content equivalents that are highly consistent with in situ SNOTEL observations on an event basis, and often within 2 to 5 percent of cumulative snowfall for seasonal integrations. This skill in orographic precipitation prediction is a consequence of accurate prediction of upstream synoptic scale winds, the prevalence of relatively stable flow regimes, and the mechanical lifting imposed by complex terrain. While the uncertainties and biases are non-negligible, the current status is one that is mainly in need of refinement in the representation of microphysical processes and improved treatment of gravity waves and turbulence.

Progress in QPF for Fronts and Cyclones

Forecast ability for precipitation associated with extratropical fronts and cyclones is increasingly skillful at synoptic scales as cyclone track predictions become more accurate and uncertainty in the intensity of developing storm systems is reduced. This broad category of precipitation events contributes to the skill associated with all non-summer seasons (Figure 3.3). Ensemble prediction techniques for cyclone track and positions of fronts are contributing to this increased skill, especially at medium and extended ranges. Within synoptic-scale regions of baroclinic instability, the amount and phase of precipitation often exhibits considerable variability at the mesoscale, which contributes to reduced forecast skill scores at moderate-to-high cumulative precipitation amounts (Figure 3.3). In such regions, intense snow and rain bands, embedded convection, or squall lines may prevail. This is especially problematic in winter storms where local differences in snowfall amounts and location of the rain/snow line have enormous societal impacts. The limitations to the skill in these predictions are often related to errors in initial and boundary conditions, and deficiencies in parameterizations, both microphysical and dynamical. The former are related to gaps in observations (as discussed under the Mesoscale Observational Needs section at the end of this chapter) together with shortcomings in the data assimilation schemes, both of which are viable candidates for improvement.

The predictions of precipitation from hurricanes and weaker tropical cyclones upon landfall suffer from similar deficiencies. A greater fraction of precipitation is of convective origin in rain bands, and there is a particularly strong dependence of the skill of precipitation forecasts on the precision of forecasts for the cyclone track and its speed of motion. Satellite and airborne adaptive observations at sea (e.g., flight-level wind and state parameter measurements, dropwindsonde soundings, and stepped-frequency microwave radiometer measurements of sea state) are playing an increasingly important role in improving dynamical forecasts of tropical cyclone precipitation following landfall.

Weakly Forced Warm Season: A Principal Focus for Research and R2O Activities

Although the aforementioned deficiencies associated with precipitation forecasts are both important and worthy of further research and forecast system refinements, the least skillful predictions occur under weakly forced conditions when local variability and local physical factors are more likely to exert influence on precipitation occurrence and amount. This is evident in Figure 3.3 where equitable threat scores typically hover between 0.1 and 0.2 for 1 inch of precipitation at the Day 1 range. Historically, much of this precipitation had been characterized as “air mass” convection, occurring pseudo-randomly near the time of maximum diurnal heating in a conditionally unstable atmosphere. Research has since revealed systematic patterns and lower-boundary forcing that emerge in the absence of strong synoptic-scale forcing. An underlying theme is the capacity of convection to self-organize and to scale upward into larger mesoscale convective systems under a fairly wide range of summertime conditions. For example, the foci for triggering convection include shallow thermodynamic or kinematic boundaries. These can be remnants of antecedent convection; the result of natural land surface heterogeneity; or diurnal cycles of mesoscale transport and moisture convergence (e.g., Bonner, 1968; Tuttle and Davis, 2006; Wilson and Schreiber, 1986).

Somewhat larger scale diurnal forcing includes whole cordilleras, such as the Rockies and the Appalachians, and secondary mesoscale convective systems spawned by primary sea breeze convection. Such conditions are most common in mid-summer when convective precipitation is at its maximum and the skill of precipitation prediction is at a deep annual minimum, as exhibited in Figure 3.3 and discussed by Fritsch and Carbone (2004). A substantial fraction of these events is very highly organized in the form of MCSs and sequences thereof, which can remain active for 6 to 60 hours and travel 300 to 2,500 km (e.g., Carbone et al., 2002; Laing and Fritsch, 1997, 2000; Maddox, 1983). Such episodes of diurnally triggered rainfall propagate across North America in a wavelike manner on a daily basis; are most frequent between the Rockies and the Appalachians; and account for approximately 50 percent of summertime rainfall in that region (Carbone and Tuttle, 2008). Such systems are the product of a persistent seasonal circumstance—strong thermal forcing over elevated terrain combined with westerly shear in a conditionally unstable atmosphere. Related forcings include the Great Plains low-level jet and the (Rocky) Mountain–(Great) Plains solenoidal circulation. The heaviest precipitation often occurs in corridors (Tuttle and Davis, 2006), where a region of westerly shear (mainly poleward) intersects a region (mainly equatorward) of convective available potential energy associated with relatively shallow moisture convergence. Owing to the regularity of this diurnal cycle and the coherent regeneration of convective systems, predictability at ranges of 6 to 24 hours, although intrinsic to this convective regime, has not yet been fully captured by operational forecast models.

Improving the Skill of Precipitation Predictions

General circulation models that have been used for operational weather prediction have not represented convective precipitation systems explicitly. That is to say, convective clouds and storms are smaller than the computational grid scale and therefore can be implicit by means of a parameterization (a switch of sorts) that redistributes heat, water substance, and momentum in the model as if convection had occurred in appropriate places and at the appropriate times.

Convective parameterizations have been developed for more than 30 years. Until recently, success had been limited, for the most part, to relatively simple cumulus clouds behaving in a manner similar to rising plumes of buoyant air. Such plumes deposit heat aloft and mix horizontal momentum downward, toward the surface. Whereas such representations of convective rainfall are useful in limited applications, organized deep convective systems are far more complicated and usually act in a dissimilar manner, thus sowing the seeds for faulty NWPs, both regionally in the short term and globally for long-range forecasts. Despite decades of effort, no traditional parameterization scheme has succeeded in systematically reproducing the organized convective rainfall events that are both common and of high impact in the United States and elsewhere globally (Fritsch and Carbone, 2004). A comprehensive review of convective parameterization, including "super-parameterization" techniques, is given by Randall et al. (2003) vis à vis long-term climate research and prediction requirements, for which parameterization will continue to be required in the foreseeable future.

Because of increased computational capacity, limited-area mesoscale models (e.g., Chen et al., 2007; Davis et al., 2003; Liu et al., 2006; Trier et al., 2008), when run at high resolutions with a grid spacing less than 5 km, routinely produce events similar to nature because the models can represent large convective systems without the aid of parameterizations, though specific predictions of individual storms may still have large spatial and temporal errors. At least one global numerical model, the NICAM developed and run on the Earth Simulator in Japan, has successfully demonstrated reproduction of realistic convective events, owing to a high-resolution global model with a grid spacing of 3.5 km (Satoh et al. 2008).

The limitations of cumulus parameterizations and the subsequent lack of predictive skill lead to the conclusion that short-range weather prediction applications need to represent deep moist convection explicitly in forecast models. This is mainly a matter of having sufficient computational capacity, which is commercially available today. Although models with explicit convection are necessary to produce a spectrum of events similar to the observed climatology, this step alone is insufficient for skillful predictions of convective rainfall. Predicting the probable location of such events is dependent upon improving initial and boundary conditions in the forecast models. With respect to the lower troposphere, atmospheric boundary layer depth and high-resolution vertical profiles of wind and water vapor are necessary, together with surface analyses that are skillful in capturing mesoscale variability on a scale of approximately 10 km or less. In addition, it is necessary to characterize land surface conditions so as to properly model the corresponding fluxes of latent and sensible heat fluxes as well as the soil heat flux; the latter being highly dependent on the vertical profiles of soil moisture and soil temperature.

To enable very short- (≤12 hours) and short-range (≤48 hours) summertime predictions, it is therefore necessary to have robust analyses of mesoscale conditions in the lower troposphere and at the land surface. Summertime QPF prediction depends heavily on the three-dimensional structure of water vapor, land surface conditions, and profiles of both soil moisture and temperature (Fritsch and Carbone, 2004).

In addition to employing explicit convection in forecast models and having representative mesoscale initial conditions, mesoscale ensemble prediction techniques could be further exploited with respect to skill in explicit predictions of moist convection and accompanying precipitation. Ensemble predictions hold promise to mitigate and quantify forecast uncertainty, especially with respect to the detailed time and location of specific events for which the intrinsic limits of predictability are uncertain. To realize this promise requires an improved understanding of the ensemble spread and optimum number of ensemble members that are needed, the representativeness of the resulting spread in predictions, and the benefits to be gained (or lost) from higher resolution and fewer ensemble members in a computationally limited environment. The current state of knowledge concerning such trade-offs (and other trade-offs related to data assimilation) is insufficient to provide objective guidance.

Ensemble prediction techniques and related hybrid probabilistic forecast approaches could be pursued as an integral part of the solution toward increased skill in and the utility of warm-season precipitation predictions. For example, at very short range (<6 hours), rule-based, nondynamical forecasting (often referred to as nowcasting[11]) has an important role to play. Extrapolation, neural networks, fuzzy logic, and similar methodologies have demonstrated skill, especially during the "spin-up" period for complex dynamical models. These nondynamical forecast products are part of the in-

[11]Nowcasting usually refers to a 0- to 2-hour forecast of the weather to be expected within the interval 0 to 2 hours from the time of forecast. An experienced forecaster can often use current radar, satellite, and surface observations to identify small-scale weather features, and then estimate their motion and behavior to make an accurate nowcast. In addition, there are sophisticated, objective nowcasting algorithms that use recent trends in the observations to predict weather conditions out to 1 or 2 hours.

formation available to advanced data assimilation systems, thus constituting a blend of nowcasting and dynamical prediction. Such information could be further researched and transitioned, as appropriate, to operations as an integral part of the dynamical forecast process.

Hydrologic Prediction Implications

Precipitation estimation and prediction are intimately related to hydrologic prediction, serving as part of the information necessary to define hydrologic initial and boundary conditions. The amount of rainfall over large areas, although helpful, is insufficient, because hydrologic prediction can be highly sensitive to small-scale variability in precipitation spatial distribution; the probability density function of precipitation rate; subsequent melt rate in the case of ice-phase precipitation; and surface losses such as evaporation of liquid water and sublimation of snow and ice. Several of these factors argue for precipitation verification methods that better inform the hydrologic user of estimated and forecast data than does the equitable threat score. Such methods are widely considered to be "object oriented," including specific location, shape, rate, and translation information in addition to cumulative amount (Davis et al., 2006a, b). Both improved observations, such as with polarimetric radar, and catchment- and convection-resolving models are necessary to achieve this level of sophistication.

Recommendation: To improve the skill of quantitative precipitation forecasts, the forecast process of the National Weather Service should explicitly represent deep convection in all weather forecast models and employ increasingly sophisticated probabilistic prediction techniques.

Global and regional weather forecast models should represent organized deep convection explicitly to the maximum extent possible, even at resolutions somewhat coarser than 5 km, as may be necessary initially, in the case of global models. Explicit representation should markedly improve forecast skill associated with the largest and highest impact precipitation events. The introduction of explicit convection will likely require the refinement of microphysical parameterizations, boundary-layer and surface representations, and other model physics, which are, in themselves, formidable challenges.

Probabilistic prediction should be vigorously pursued through research, and the development and use of increasingly sophisticated ensemble techniques at all scales. New tools need to be developed for verification of probabilistic, high-resolution ensemble model forecasts, eventually supplanting equitable threat scores.

HYDROLOGIC PREDICTION

Despite the fact that the skill of precipitation forecasts has significantly improved over the past decade—especially for cool-season events, as discussed in the preceding section—the skill in hydrologic forecasts has not kept pace. Of all the weather-related hazards in the United States, floods are one of the most devastating; they claim hundreds of lives and cause billions of dollars in damage each year (EASPE, Inc., 2002; NOAA, 2001). From 1970 to 2000, 3,829 deaths were attributed to floods, with an annual average of 128 deaths. Three 10-year cycles show a trend of reduced deaths: 1971 to 1980, 175 average deaths per year; 1981 to 1990, 112 deaths; and 1991 to 2000, 91 deaths (EASPE, Inc., 2002). The average annual flood damages for 1981 to 1990 were $3.2 billion, and for 1991 to 2000, $5.4 billion, which includes the 1993 record-setting floods of the Mississippi River ($18.4 billion in damages; USACE, 2000). Improving the accuracy and lead time of flood forcasts and ensuring timely mitigation plans would reduce weather-related losses and provide other societal benefits such as increased public health and safety.

The 2009 BASC Summer Study workshop participants emphasized the need for our nation to develop an adequate research and R2O focus and the necessary supporting infrastructure to translate improved precipitation forecasts to improved operational hydrologic forecasts that are more accurate and have increased spatial resolution. Efforts toward developing an advanced hydrologic prediction[12] service (NRC, 2006b) have been ongoing for more than a decade and need to be sustained and intensified.

Hindrances to Progress

The challenges in QPF articulated in the previous section are far from being resolved. However, suppose for a moment that the science and technology had achieved the ability to make virtually perfect precipitation forecasts. A hydrologic modeling system would then be able to translate those precipitation forecasts into accurate, distributed runoff and streamflow by

[12] "Hydrologic prediction" refers to a suite of forecast products that includes hourly and daily streamflow forecasts at specific sites, flash flood guidance for fast-rising floods, water supply forecasts with forecast horizons 2 weeks or further into the future, probabilistic risk of flooding, floodplain inundation, and drought forecasts (NRC, 2006a).

invoking the physical mechanisms of runoff generation, snow accumulation, surface water–groundwater exchanges, river and floodplain routing, river hydraulic routing, agricultural and other consumptive uses, among others. But all of these elements of an advanced hydrologic prediction system are far from being well observed, far from being well understood, far from being appropriately represented in numerical prediction models, and far from being even rudimentarily verified. Therefore, a perfect precipitation forecast would not translate today into a hydrologic forecast that meets user needs. The challenges amplify because the precipitation forecasts are far from perfect. Thus, there is a compelling need for major changes in hydrologic research and infrastructure if we are to successfully translate the investment in improved weather forecasts into improved hydrologic forecasts at the local and regional scales, and meet the pressing societal and economic demands of flood protection and water availability.

To better understand the priorities for hydrologic research and R2O, it is helpful to first understand the impediments to progress in hydrologic forecasting:

- lack of comprehensive and representative observations across a range of space-time scales and across different hydrologic regimes that can be assimilated in hydrologic models to improve the physical representation of water cycle dynamics;
- lack of a coherent distributed hydrologic modeling framework to simultaneously advance hydrologic forecasting research and facilitate the transition of research results into operations;
- lack of systematic verification metrics to track and measure progress; and
- lack of a centralized and sustained mechanism to foster academic, private-sector and intergovernmental exchange and collaboration toward a targeted effort to deliver the next-generation hydrologic forecasting system with demonstrated improvement and robustness.

Hydrologic Prediction and a Changing Climate

Changes in precipitation extremes (storm amounts, frequency, and duration) are already posing unique challenges in water management at the local to regional scales. The assumption of stationarity, on which current hydrologic model calibration practices for hydrologic forecasting are based, is no longer valid (Milly et al., 2008). Revised hydrologic models that are physically based are less reliant on calibration and tuning, take full advantage of real-time observations from multiple sensors, and are a clear necessity for hydrologic prediction in the future. Unfortunately, the physics of water cycle dynamics are not fully understood and physically based predictive models are not yet available, either beyond single investigator research or in operational practice.

In addition to the need to make optimum use of precipitation forecasts in hydrologic forecasting on weather timescales, there also is a need to assess hydrologic impacts and conditions on climate timescales. Theory, simulations, and empirical evidence all indicate that warmer climates will materially change the distribution of precipitation at both local and global scales (e.g., Solomon et al., 2007; Trenberth et al., 2003; Wentz et al., 2007). Generally, drier areas are becoming drier and wet areas are becoming wetter, and the snow season has become shorter by up to 3 weeks in parts of the North American continent owing to an earlier onset of spring. In addition, increased water vapor capacity in warmer climates is expected to lead to more intense precipitation events even when the total annual precipitation remains the same or is slightly reduced (e.g., Karl et al., 2009). This will inevitably increase the risk of flooding and rainfall-induced hazards, such as landslides in steep mountainous terrains, putting increased pressure into the development of accurate, high-resolution, physically based hydrologic prediction models.

Need for Change

Today's operational hydrologic forecasting is performed at the 13 river forecast centers (RFCs) of the NWS. This forecasting heavily relies on calibrated lumped or semidistributed hydrologic models (Box 3.3) based on historical observations and which incorporate subjective information by the regional forecast offices. These forecasts are also restricted to river stages at specific locations only, which are often too widely spaced for local decision making.

There are two important reasons it is imperative to change this process: (1) nonstationarity due to climate and land-use changes makes past observations of limited use in model calibration, and thus there is a need to move to physically based, minimally calibrated models based on assimilated real- or near-real-time observations from multiple sensors; and (2) there is a growing need to provide water cycle forecasts at a range of space and time scales, not only river stages for flood protection, but also for soil moisture (ecosystem functioning), streamflow (sediment transport and river habitat assessment), agricultural use practices and impacts, as well as water quality and renewable

BOX 3.3
Hydrologic Modeling Approaches

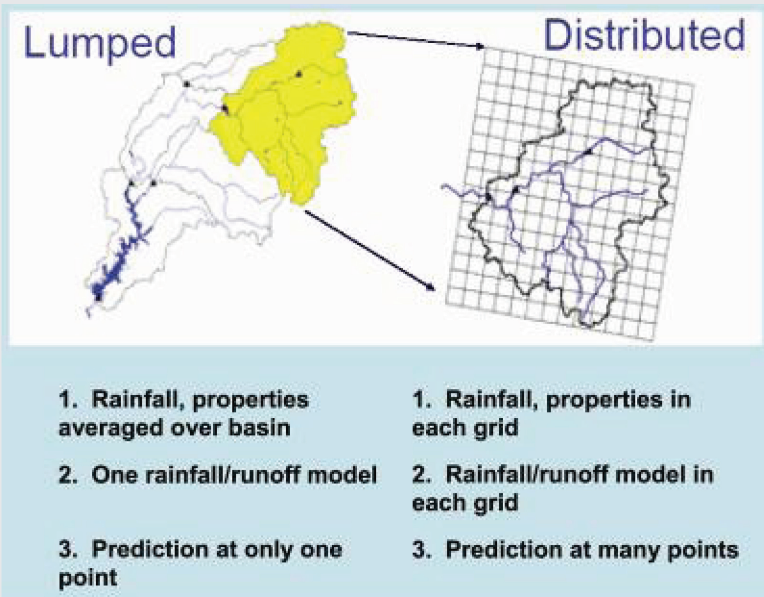

FIGURE Comparison of lumped and distributed hydrologic modeling approaches. SOURCE: NRC (2006b).

Modeling water fluxes in a catchment involves a fundamental philosophical decision as to whether the model needs to be "lumped" or "distributed," and "deterministic" or "stochastic" (e.g., Beven and Freer, 2001; Silberstein, 2006). Lumped models represent a catchment as a single entity, or a small group of entities, such as reservoirs, and simulate state variables and fluxes into and out of the catchment as a whole. Distributed models divide the catchment into many entities, each representing small parts of the catchment, and the state variables and fluxes between the entities are determined across the catchment. There are also models that fall somewhere between these, in which variables are not explicitly distributed across the catchment but are represented as a distribution and can therefore be interpreted anywhere on the catchment. Simulations with deterministic models will always produce the same answer if they have the same input data, whereas stochastic models result in a distribution of results or a result with an accompanying variance. Deterministic models can also be used in a stochastic way to generate a distribution or ensemble of results from many simulations with a distribution of input parameters (the so-called Monte Carlo method).

energy (hydropower and hydrokinetic energy; see also the section on Renewable Energy Siting and Production in Chapter 4) applications.

A recent study by Welles et al. (2007) pointed out some troubling findings: (1) the RFC hydrologic forecasting skill has hardly improved (based on 15 watersheds studied) over the past 10 to 20 years; (2) the skill in above-flood-stage hydrologic forecasts is less than 3 days; and (3) the lack of an objective and systematic hydrologic forecast verification program has hindered progress and effective exchange between the scientific and operational communities.

Development of a Community Hydrologic Modeling System

In the meteorological and atmospheric sciences community, advances in NWP and climate modeling have been enabled to a large degree by the development of community-supported models.[13] Such models (e.g., the WRF and the Community Climate System Model) have provided a framework to test alternative hypotheses and new parameterization schemes, to guide the collection of new observations, to prioritize science investments based on model performance, to support various societal and business applications, and to track the progress of research in a systematic way that allows moving ahead in a robust and traceable fashion.

In the hydrologic community, no such systematic effort exists for the purpose of bringing together the research and operations sectors toward the development of a hydrologic prediction system that can be advanced and extensively tested by the community, provide a frame of reference for tracking improvements, and be highly responsive to end-user needs. Efforts to date to develop a community hydrologic modeling framework include the Modular Modeling System (MMS) developed by the U.S. Geological Survey (USGS; Leavesley et al., 1996, 2005) and the ongoing effort of the NWS (NRC, 2006b) to develop the Community Hydrologic Prediction System (CHPS). These efforts were designed to advance the hydrologic forecasting capacity within the USGS and NWS; they were not designed to create the foundation of a true academic–government–private-sector partnership that could accelerate the development and implementation of an advanced distributed hydrologic modeling system to serve both as a research tool and as

[13] "A community modeling system is an open-source suite of modeling components coupled in a framework. The system emerges through the collective efforts of the community of individuals that code, debug, test, document, run, and apply the modeling system. The community often includes both developers and users, and may be distributed among different institutions and organizations." (Voinov et al., 2008)

an operational platform. Such an effort is currently lacking. It would require a community-led organization toward accelerated research and synthesis of physical-process understanding, targeted observational campaigns for model verification and improvement, quantification of uncertainty and probabilistic forecasting, theoretical advances in scaling and transferability, predictability studies of coupled models including sensitivity to initial conditions and model parameter uncertainty, and full exploration of high-performance computing. Establishing such a modeling framework would foster a more effective dialogue between the research and operational communities, including decision makers across diverse sectors, and would accelerate the R2O and O2R processes.

There is a critical, ongoing need to develop a robust hydrologic forecast capacity; this will require a strategic commitment and investment in research and R2O. Such a systematic hydrologic prediction framework effort would bring together (1) the collective resources of the hydrologic community in establishing a unified hydrologic observational, research, and modeling agenda; (2) the atmospheric and hydrologic communities in developing, testing, and improving a fully coupled atmospheric–hydrologic prediction system; and (3) the research and operations communities as a joint team that identifies research priorities to fill important gaps in the application of hydrologic products by the governmental and private sectors. In addition, a verified distributed model is certain to well serve communities other than water resources, such as the ecologic community that relies on water cycle forecasts at a range of scales for assessing ecosystem performance and species diversity at the local to regional scales under climate and land-use change.

Transitioning Research Developments into Operations

The NWS has the primary responsibility among the federal agencies to provide advanced alerts—flood warnings and forecasts—in the United States. The current operational hydrologic forecasting process at the NWS relies on a combination of observations (including precipitation, soil moisture, evapotranspiration, soil type, and land cover) and atmospheric forecasts that provide input to a land-surface hydrologic model. The rainfall-runoff model currently in use at most RFCs is the Sacramento Soil Moisture Accounting (SAC-SMA) model (Burnash et al., 1973). This model does not explicitly take into account distributed forcings (and thus does not take advantage of improvements in QPF) and other heterogeneities in a watershed, is mostly lumped as opposed to distributed (Box 3.3), and requires considerable local calibration using historical observations. Recent efforts have extended this model to a gridded distributed version, called the Distributed Hydrologic Model,[14] which is used experimentally in some of the RFCs.

Because hydrologic services generate nearly $2 billion of benefits each year through timely flood and weather forecasting (EASPE, Inc., 2002), the NWS Office of Hydrologic Development (OHD) began in 1997 the implementation of the Advanced Hydrologic Prediction Service (AHPS) program aimed to advance technology for hydrologic services (NRC, 2006b). AHPS is a congressionally funded program that had its first prototype implementation in 1997 for the Des Moines River Basin and is slated to be fully implemented nationwide in 2013. As part of the AHPS, OHD is taking critical steps to improve the hydrologic forecast process along two main directions: (1) exploration of the merits of distributed hydrologic models for operational use, and (2) development of a comprehensive verification system.

The NWS OHD has recently led the Distributed Model Intercomparison Project (DMIP). Twelve groups, including other federal agencies, academic institutions in the United States, and representatives from Canada, China, Denmark, and New Zealand, compared differing methods and approaches of distributed hydrologic models for analysis of the same predefined conditions. These results will guide NWS in developing the next generation of hydrologic models Results of the DMIP, Phases I and II, are generally encouraging but the road to full implementation with skill beyond the lumped hydrologic models remains poor. As a result, the new strategic and implementation plan (OHD, 2009) of the NWS OHD spells out a way to move forward and proposes the development of the CHPS, which emphasizes a combination of conceptual and physical modeling approaches. It has the ability to merge distributed hydrologic prediction models with atmospheric models at weather and climate scales, to resolve not only streamflow but also interior fluxes needed for water quality, ecologic, and geohazard applications, and the ability to make hydrologic predictions, including their uncertainty, at ungauged basins. The committee and the 2009 BASC Summer Study workshop participants support these efforts of the NWS and encourage implementation of additional ways of engaging the research community in this activity.

Two examples of complementary activities aimed at developing an advanced hydrologic forecasting capability are (1) the Consortium of Universities for the Advancement of Hydrologic Sciences, currently supported by NSF, which is working toward the development of the Community Hy-

[14] See http://www.nws.noaa.gov/oh/hrl/hseb/docs/AWIPS_OB8.3_DHM_Software_Design_Document_v1.1.pdf.

drologic Modeling Platform and has initiated an ongoing community-wide dialogue (Famiglietti et al., 2008); and (2) the Integrated Water Resources Science and Service[15] initiative currently supported by NOAA, USGS, and the U.S. Army Corps of Engineers. These two synergistic activities further illustrate the timeliness of taking a quantum leap forward now in order to improve the performance and skill of hydrologic forecasts in the next decade. In these efforts, close cooperation between academia and government agencies is important for transitioning the most recent research results to operations and for guiding new research directions based on societal relevance and scientific discovery.

The Need for Hydrometeorological Observations

As the complexity and resolution of hydrologic models increases, new and improved observations are needed for model initialization, improvement of model physics, data assimilation, and metrics for model verification. Several small-scale hydrologic observatories are currently in operation, for example, the Critical Zone Observatories (CZOs)[16] supported by NSF, the Agricultural Research Service (ARS)[17] observatories, and NOAA's HMT.[18]

These observatories provide a variety of high-resolution in situ and remote sensing observations from the vegetation canopy, to soil, to groundwater in order to understand the interaction of physical, chemical, and biological processes in a watershed and accurately predict material fluxes (e.g., NRC, 2001). Coordinating efforts need to be instituted such that full advantage is taken of these observatories for further model improvements. Also, the development of new integrated observatories of the water cycle—from the atmosphere, to the rivers and lakes, to the deep subsurface zone, and to the built environment—are needed. For example, the Water

[15]See http://www.nws.noaa.gov/oh/docs/IWRSS_lp_summary.pdf.

[16]Operating at the watershed scale, CZOs are natural laboratories for investigating the processes that occur at and near the Earth's surface and are affected by freshwater. CZOs are heavily instrumented for a variety of hydrogeochemical measurements as well as sampled for soil, canopy, and bedrock materials. CZOs also involve teams of cross-disciplinary scientists who have expertise in fields including hydrology, geochemistry, geomorphology, pedology, ecology, and climatology. See http://criticalzone.org/.

[17]The ARS watershed network is a set of geographically distributed experimental watersheds that has been operational for more than 70 years and provides essential research capacity for conducting basic long-term hydrologic research. See http://www.tucson.ars.ag.gov/icrw/Proceedings/Weltz.pdf.

[18]The HMT is a concept aimed at accelerating the infusion of new technologies, models, and scientific results from the research community into daily forecasting operations of the NWS and its RFCs. See http://hmt.noaa.gov/.

and Environmental Research Systems (WATERS) Network initiative (NRC, 2009a) proposes a series of observatories to address the challenges of ecosystem sustainability and water availability under changes caused by human activities and climatic trends.[19]

Unique opportunities to use remotely sensed observations from surface and space require exploration (e.g., Yilmaz et al., 2005). These include currently available data (e.g., see the following section on observations) and the new stream of data that will be delivered by NASA's Global Precipitation Measuring mission as well as the satellite soil moisture measurements of the Soil Moisture Active-Passive.[20] The use of satellite observations for improved hydrologic prediction offers ample research challenges and opportunities, such as retrieval algorithm development over land, multichannel integration, bias adjustment, and increasing accuracy and resolution via product blending. Remotely sensed observations are the only observations for many parts of the world and their optimal use in hydrologic forecasting needs to be fully explored. In the United States, the ongoing upgrade of the NWS NEXRAD radars to dual-polarimetric capability will significantly improve the ability to resolve hydrometeorologic variables important for the development of coupled atmospheric–hydrologic models. Also, as clearly articulated in NRC (2009b) and discussed in the following section, a ground-based national network of networks at the mesoscale, inclusive of radio and optically sensed PBL profiles of water vapor and winds is expected to dramatically improve our predictive ability of the coupled atmospheric–hydrologic system.

Recommendation: Improving hydrologic forecast skill should be made a national priority. Building on lessons learned, a community-based coupled atmospheric–hydrologic modeling framework should be supported to accelerate fundamental understanding of water cycle dynamics; deliver accurate predictions of floods, droughts, and water availability at local and regional scales; and provide a much needed benchmark for measuring progress.

To successfully translate the investment in improved weather and climate forecasts into improved hydrologic forecasts at local and regional scales, and meet the pressing societal, economic, and environ-

[19]The overarching science question of the WATERS Network is: "How can we protect ecosystems and better manage and predict water availability and quality for future generations, given changes to the water cycle caused by human activities and climate trends?" (WATERS, 2009).

[20]See: http://nasascience.nasa.gov/earth-science/decadal-surveys/Volz1_SMAP_11-20-07.pdf.

mental demands of water availability (floods, droughts, and adequate water supply for people, agriculture, and ecosystems), an accelerated hydrologic research and R2O strategy is needed. Fundamental research is required on the physical representation of water cycle dynamics from the atmosphere to the subsurface, probabilistic prediction and uncertainty estimation, assimilation of multisensor observations, and model verification over a range of scales. Integral to this research are integrated observatories (from the atmosphere to the land and to the subsurface) across multiple scales and hydrologic regimes.

Continuous support of individual models geared toward improving specific components of the hydrologic cycle is a necessary element of progress. However, the committee recommends that a community organization around benchmark hydrologic and coupled atmospheric–hydrologic modeling systems is necessary at this stage to further advance hydrologic predictions, in both research and operational modes. Such benchmark models will provide for the synthesis of ideas and data, avoid duplication, identify major research gaps, provide metrics of success and track progress, and provide a platform on which communities can share knowledge (e.g., there is a need for ecologists to have access to hydrologic models, and a community-led framework would be useful in the same way that WRF has been useful to decision makers across widely diverse sectors). Also, such a community-based modeling framework will accelerate the development of a focused R2O and O2R strategy based on a sustained and effective academia–industry–government partnership.

MESOSCALE OBSERVATIONAL NEEDS

Improved observing capabilities at the mesoscale are an explicit aspect of every weather priority identified in this study, including socioeconomic priorities such as reduction in vulnerability for dense coastal populations, and improvements in forecasts at the scale of flash floods and routinely disruptive local weather. The 2009 BASC Summer Study workshop participants identified the underlying need for enhanced mesoscale observing networks throughout the oral presentations and in the working group discussions. This high-priority need was the focus of a recent BASC report, *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks* (NRC, 2009b), and many of its authors were participants in the 2009 BASC Summer Study workshop. Accordingly, this section draws heavily on the findings and recommendations contained in that report and supports each of its recommendations concerning observing-system technical requirements.

Observations at the mesoscale are an important part of the national and global observing systems. The global observing system captures large-scale circulation features and their related thermodynamic context. Components of the global observing system include various satellites and constellations thereof; radiosondes and regional electromagnetic profiling devices; and reference surface stations at key locations that maintain and extend the surface climate record. For example, geostationary satellites provide excellent temporal coverage, but new technologies are needed to penetrate clouds for thermodynamic information. Observations based on GPS constellation occultation techniques contribute important temperature and humidity information, principally at the synoptic scale. Observations at the mesoscale are increasingly important to establishing initial conditions for global models as resolution improves.

Mesoscale components include observations that either resolve mesoscale atmospheric structure or uniquely enable NWP at the mesoscale. The emphasis on mesoscale observations is motivated by the scale and phenomenology associated with disruptive weather; the necessity to understand it, detect it, and warn of the potential consequences; and improved capacity to specifically predict or otherwise anticipate it at very short to short ranges (0 to 48 hours).

Challenge: Why Are Enhanced Mesoscale Observations Needed?

Perhaps the simplest answer to this question is that high-impact weather happens at the mesoscale, and because the lowest 2 to 3 km of the atmosphere are, at once, underobserved and most important for processes such as convection, chemical transport, and the determination of winter precipitation type.

A more complete justification for mesoscale observations resides in the requirements to serve a wide variety of stakeholders inclusive of basic and applied researchers, intermediate users associated with weather-climate information providers, and a wide variety of end users at all levels of government and numerous commercial sectors. Some examples of these requirements include

- **Basic research** in the geosciences and biogeosciences, including studies of mesoscale dynamics, gravity waves, climate science, atmospheric chemistry, micrometeorology, hydrometeorology, cloud physics, atmospheric electricity, biogeochemistry, ecosystems, biogenic emissions, and urban-scale processes;

- **NWS-related R2O activities** to enable very short- and short-range predictions that employ advanced nowcasting techniques in the 0- to 3-hour range; to improve analyses of initial and boundary conditions and short-range predictions for mesoscale model forecasts in the 12- to 48-hour range; to enable the merging of probabilistic guidance associated with nowcasting and dynamical predictions in the 3- to 12-hour range; to provide a basis for object-oriented verification of probabilistic forecasts resulting from ensemble techniques; and to facilitate technique development for advanced applications of mesoscale observations to locally disruptive weather such as fog, surface icing, thunderstorm initiation and motion, assimilation of precipitation measurements, conditions near hurricane landfall, other hazardous lake and coastal ocean conditions, hazardous urban conditions, fire weather predictions, and hydrologic predictions and warnings such as seasonal flooding from main stem rivers and flash floods;
- **Directly serving the missions of numerous federal, state, and local agencies** including NOAA, the Department of Transportation, DOD, the Environmental Protection Agency, DOE, USGS, the Department of Agriculture, NSF, the Department of Homeland Security, and NASA at the federal level; and several agencies in all 50 states, including transportation, emergency management, water resources, and air quality applications;
- **Directly serving and improving productivity in commercial sectors** such as renewable (discussed in detail in Chapter 4) and conventional energy production industries; agricultural cooperatives and suppliers; the commercial air, sea, and land transportation industries; weather and climate information corporations; broadcast media; commodities exchange; insurance/reinsurance industries; among many others.

Progress in the Past Decade

As reported in NRC (2009b), mesoscale *surface* observations have proliferated enormously in the past decade; so much so that the mesoscale surface observations enterprise is ubiquitous across approximately 20 federal agencies, all 50 states, countless local water and air quality districts and authorities, numerous Fortune 500 corporations, countless small- and medium-sized commercial applications, the private weather information industry, and others. However, progress in application of these data is impeded (NRC, 2009b) by a lack of cohesion, coordination, and knowledge of standards, thus limiting most surface networks to a single use status when much of the same data could, in principle, serve multiple national needs.

Despite the proliferation of surface stations, there continues to be a paucity of vertical profile data, which are badly needed to support monitoring of the PBL from 2 m below the land surface to 2 km above; and to enable improved weather, chemical weather, and hydrologic predictions.

Research and Development Topics Dependent on Mesoscale Observations

Mesoscale Data Assimilation

There is a pressing need for research and development leading to improved mesoscale data assimilation techniques in operational forecast systems. Improved analyses require better knowledge of error covariances in observations. The basis for this knowledge is weakened by the fact that mesoscale data are often sparse or patchy, and relatively poorly documented compared to those from standard synoptic observations. The structure and variability of the lower troposphere is not well known owing to the fact that vertical profiles of water vapor, temperature, and winds are not systematically observed at the mesoscale (Schlatter et al., 2005). The sensitivity to these observation gaps is not well understood but is likely to be substantial in urban (Dabberdt et al., 2000) and coastal (Droegemeier et al., 2000) regions, where population density is high, and in mountainous regions, which are a proximate cause for major forecast errors ("busts") downstream (Smith et al., 1997). The relative absence of high-resolution PBL profiles is a vexing problem that greatly impedes progress in skillful predictions at the mesoscale over both land and coastal waters. Whereas mesoscale weather events can be produced by forecast models from purely synoptic-scale initial conditions, mesoscale predictability is also dependent, to some considerable degree, on knowledge of the mesoscale initial condition. This is especially true with respect to specific predictions of deep moist convection and attendant heavy rainfall and severe weather (Fritsch and Carbone, 2004).

Verification

Research and development are needed that lead to improved forecast verification and from which errors in the forecast system can be quantified, understood, and rectified. Especially with respect to verification of precipitation, statistical scores such as equitable threat can be misleading and are relatively uninformative at the mesoscale. Unlike threat scores, object-oriented approaches (e.g., Davis et al., 2006a, b) can allow for both intermittency and relatively small spatial and temporal uncertainties. This permits the quantification of errors and enables a useful characterization of skill in predictions within regions containing, for example, rain bands, mesoscale convective systems, and isolated storms.

For example, current operational verification techniques are insufficient, for hydrologic predictions. There exists considerable sensitivity to small-scale variability in precipitation spatial distribution; the probability density function of precipitation rate; subsequent melt rate in the case of ice-phase precipitation; and surface losses such as evaporation of liquid water and sublimation of snow and ice. Several of these factors argue for verification methods that can better inform the hydrologic user of precipitation estimates and forecast data than an equitable threat score. Object-oriented methods can include specific location, size, shape, rate, and translation information in addition to cumulative amount. Both improved observations, such as those from polarimetric radar, and catchment- and convection-resolving models are necessary to achieve this level of sophistication, as well as this level of verification and near-real-time input to distributed hydrologic models.

Surface and Boundary-Layer Fluxes

Research is needed as well that leads to improved knowledge and representation of meteorological and chemical fluxes, emissions, and deposition in high-resolution weather and climate system models. This includes natural and polluted terrestrial boundary layers; marine boundary layers; land–atmosphere exchange dependencies on canopy properties, soil moisture and temperature; urban surface energy exchange and emissions; upper ocean heat content and surface wave properties; biogenic emissions of volatile organic compounds; gas phase-to-aerosol conversion, total aerosol burden, and its vertical distribution and transport. Several of these fluxes are either known or suspected to modulate precipitation and the harmful effects of pollution.

Observing System Testbeds

It is important that mesoscale observations are a focus of testbeds, which are intended to develop and introduce new ideas and new procedures in environmental observation. For example, advanced concepts in mobile, targeted, adaptive, and collaborative observing networks require extensive exploration. This includes the dynamics among various surface-based observing networks as well as the exploration of optimal and cost-effective divisions of responsibility between observations from space and those from airborne and surface platforms.

Forecast System Testbeds

Another focus of testbeds can be to examine the role of mesoscale observations for new paradigms in the end-to-end forecast process. This is particularly important and urgent with respect to merging methods in nowcasting with those of dynamical prediction in the 0- to 6-hour range. This strategy may be central to improved performance in severe weather, flash floods, other hydrologic forecasts, and metropolitan area applications in routinely disruptive weather.

Mesoscale Observing Needs

Atmospheric and Subsurface Profiles

These mesoscale observing needs and recommendations consolidate and follow the general sense of recommendations of NRC (2009b), where more detailed discussion and analysis can be found. The highest priority observations needed to address current inadequacies include those items *for which there are essentially no systematic national capabilities* to resolve or enable mesoscale prediction; these include

- height of the PBL,
- soil moisture and temperature profiles,
- high-resolution vertical profiles of humidity, and
- profiles of air quality and related chemical composition above the surface layer.

Improvements are also needed in measurements of direct and diffuse solar radiation, wind profiles, temperature profiles, surface turbulence, subsurface temperature profiles, and near-surface icing.

Humidity, wind, and diurnal boundary layer structure profiles are the highest priority for a national mesoscale network, the sites for which need to have a characteristic spacing of approximately 150 km but could vary between 50 and 200 km based on regional considerations. Such observations, although not fully mesoscale resolving, are essential to enable improved performance by high-resolution NWP models and chemical weather prediction at the mesoscale. Through advanced data assimilation techniques, it is estimated (NRC, 2009b) that data from approximately 400 sites, when used in combination with advanced geostationary satellite infrared and microwave soundings, GPS constellation "wet delay" and radio occultation measurements, and commercial aircraft soundings, will effectively fill many of the critical gaps in the national mesoscale observing system.

Among observations from space, the geostationary platform component is especially important for water vapor and clouds because it preserves the integrity of time-domain sampling with respect to mesoscale variability in the lower troposphere. Owing to the high orbit, visible and infrared instruments are preferred in maintaining horizontal resolution at the expense of obscuration by clouds. Notably, NRC (2009b) recommends *both* infrared hyperspectral instruments as well as synthetic thinned aperture array instruments at cloud-penetrating microwave frequencies on geostationary platforms. A reasonable performance expectation is for satellite observations to assume a primary role at altitudes above the continental PBL.

The core set of air quality and atmospheric composition profiles above the atmospheric surface layer would include measurements of carbon monoxide (CO), sulfur dioxide (SO_2), ozone (O_3), and particulate matter less than 2.5 microns in size ($PM_{2.5}$); these chemical composition profiles are needed at about 200 sites, which would yield a characteristic spacing of approximately 200 km. These observations would constitute a national pollutant constituent backbone and would be especially effective in enabling air quality (chemical weather) prediction when collocated with surface meteorological observations and related vertical profiles. The selected core chemical species have various impacts (e.g., on human health), may be harmful to natural and managed landscapes, may serve as precursors to other hazardous compounds, and can help to extend the utility of parameters observed from space. Additional important parameters (e.g., NO_2) could be added as soon as appropriate and when affordable technology is developed for the applications envisioned. The proposed network would improve chemical weather prediction nationally and also support urban air pollution monitoring, for which it is not a substitute.

Soil moisture and temperature measurements are needed to a depth of 2 m at a characteristic spacing of about 50 km, which corresponds to about 3,000 multiple-sample or area-integrated sites. These soil measurements are required, together with surface atmospheric measurements, to quantify surface fluxes of latent and sensible heat. Although this spacing is insufficient to capture the full spectrum of short-term spatial variability of surface soil moisture and temperature, it is small enough to represent seasonal variations and regional gradients, thereby supporting numerous important applications such as land data assimilation systems in support of NWP, water resource management, flood control and hydrologic forecasting, and management of forestry, rangeland, cropland, and ecosystems.

Network Architecture and Testbeds

To serve multiple national needs, the United States needs a system that is a network of networks in an architectural sense (NRC, 2009b). The term "architecture" includes the fundamental physical elements as well as the organizational and interfacial structure of the mesoscale network. It also describes the internal interfaces among the system's components, and the interface between the system and its environment, especially the users. This architecture would facilitate a thriving environment for data providers and users by promoting metadata, standards, and interoperability, and enabling access to mesoscale data, analysis tools, and models. The effort would also include a process that continually identifies critical observational gaps, new measurement systems and opportunities, and the evolving requirements of end users.

Applied research and development would include but not be limited to transitional activities, including the operation of prototype networks and evaluation of their forecast impact (i.e., testbeds); development of tools to facilitate data access for real-time assimilation; development of additional tools to serve the general public and educate the citizenry; and exploration of advanced and innovative technologies to serve multiple national needs better, cheaper, and sooner than otherwise might be possible. Testbeds may be operated by national laboratories, universities, or joint institutes as appropriate to the application. Such activities are inherently multidisciplinary and must be tightly coordinated if R2O objectives are to be achieved. Testbeds may have a sharply focused, limited term of activity that fully integrates users in the transition to operations.

Collaborative and adaptive sensing and related technologies can efficiently enhance the detection and monitoring of adverse weather for hazard mitigation and other applications, particularly for convective scales and in complex terrain, coastal, and urban environments. High-density networks of less expensive remote sensors are capable of operating intelligently to increase detection efficiency while controlling costs. If current trends in technologies are a guide, many new instrumentation networks will be composed of intelligent sensors that can be tasked to interact with nearby nodes and self-directed efficient network coverage by standard rules of engagement.

This concept is being explored and tested by the CASA project (McLaughlin et al., 2005, 2009).

Recommendation: Federal agencies and their partners should deploy a national network of profiling devices for mesoscale weather and chemical weather prediction purposes. Such devices should incorporate capabilities that extend from the subsurface to 2 to 3 km above the surface level. The entire system of observations in support of mesoscale predictions should be coordinated, developed, and evaluated through testbed mechanisms.

As a high infrastructure priority, optical and radio-frequency profilers should be deployed nationally at approximately 400 sites to continually monitor lower tropospheric meteorological conditions. To meet national needs in support of chemical weather forecasts, a core set of atmospheric pollutant composition profiles should be obtained at approximately 200 urban and rural sites. To meet national needs for representative land–atmosphere latent and sensible heat flux data, a national, real-time network of soil moisture and temperature profile measurements should be made to a nominal depth of 2 m and deployed nationwide at approximately 3,000 sites.

Federal agencies, together with state, private-sector, and nongovernmental organizations, should employ mesoscale testbeds for applied research and development to evaluate and integrate national mesoscale observing systems, networks thereof, and attendant data assimilation systems as part of a national 3D network of networks.

Other Considerations

Other essential attributes and considerations of a national mesoscale observing system include the following:

- Augmentation of observations in the coastal ocean and marine boundary layer, particularly where small-scale variability in sea surface temperature gradients and surface waves are climatologically common. These quantities strongly modulate the interfacial fluxes and therefore tropical and mid-latitude cyclone amplification. Whereas similar satellite observations are reasonably quantitative over the open ocean, special requirements apply to the coastlines.
- The national network architecture needs to be sufficiently flexible and open to accommodate auxiliary, research-motivated observations and

educational needs, often for limited periods in limited regions. If history is a proper judge, many of the research-motivated sensors and observations will evolve to operational status, serving existing societal needs better and serving future additional societal needs well. The impact of research-based systems is likely to be felt at or near the Earth's surface, relevant to both managed and natural terrestrial and marine ecosystems, and issues unique to the heavily built environment. A more seamless blending of formal university education with observations, operational forecasting, and research will promote the capacity building required to satisfy personnel needs of the future.

- Extensive metadata will be required of every component in an integrated, multiuse observing system. Observational data have high value only if they are accompanied by comprehensive metadata. Provision of metadata would be needed for participation in a national network of networks, and incentives could be offered to the operators of networks to provide it. The contents of a metadata file would need to be carefully defined and, once assembled, a frequently updated, national database of metadata would be accessible to all. If action is taken to improve metadata and fill gaps by supplying comprehensive information on undocumented systems, the value and impact of existing data will be improved far beyond the cost of gathering the metadata.
- Stakeholders could commission an independent team of social and physical scientists to conduct an end-user assessment for selected sectors. The assessment could quantify further the current use and value of mesoscale data in decision making and also project future trends and the value associated with proposed new observations. Upon implementation and utilization of improved observations, periodic assessments would be conducted to quantify change in mesoscale data use and the added societal impact and value. In addition to the involvement of known data providers and users, a less formal survey could capture user comments from blogs and webpage feedback.

4

Emerging Weather Research and Transitional Needs

Several research and transitional needs have come to be recognized in the United States as increasingly important but are only in the early stages of understanding or implementation. The committee refers to these as *emerging* weather research and transitional needs—in contrast to the established needs discussed in Chapter 3. Three high-priority emerging needs were identified in the 2009 BASC Summer Study workshop and subsequent committee meetings. The three emerging needs discussed here include very high impact (VHI) weather, urban meteorology, and renewable energy production.

The reader may wonder why VHI weather is included here as an emerging need rather than in the preceding chapter as one of several established needs. The answer lies in the emphasis here on impact forecasting rather than the traditional focus on weather prediction per se. Urban meteorology was recognized in the United States in the 1960s as an important topic, and much seminal urban meteorological research was conducted until the early 1980s when it was abruptly deemphasized as a research priority. A reemphasis on the meteorology of the urban zone and its societal import began again in the 1990s and continues today. In contrast, Europe has focused steadily on urban issues for many decades, as has Japan. Lastly, the meteorological challenges associated with the special needs of the renewable energy industry have come into sharp focus over the past 5 or so years. In all three emerging areas, much remains to be done. As mentioned previously, virtually all research and R2O needs have both established and emerging aspects, and so many of the challenges and needs cited in Chapter 3 are relevant as well, and are closely coupled to those discussed here in Chapter 4.

VERY HIGH IMPACT WEATHER

Weather-related disasters result in loss of life and disruption of communities as well as billions of dollars in damages in the United States annually. Between 1980 and 2009 there were 96 major disasters caused by VHI weather events that resulted in losses exceeding 1 billion dollars each (NCDC, 2010). It goes almost without saying that there is a great need for accurate forecasts and warnings of severe, hazardous, and disruptive weather conditions so that the resulting economic and societal impacts can be minimized.

VHI weather can be defined as weather that endangers public health and safety or causes significant economic impacts. VHI weather generally falls into two categories:

1. severe and disruptive weather hazards—including tropical storms and hurricane-induced extreme winds, rain, and storm surges; severe thunderstorms and tornadoes; lightning; flash floods; ice and snow storms; dense fog; and wildfires—which change rapidly on the timescale of minutes to hours or a few days; and
2. persistent weather hazards—including long-lasting heat/cold waves; drought; and flooding due to persistent rain events—which occur on longer timescales of days to weeks or even years (e.g., drought).

Advancing the understanding, monitoring, and prediction of VHI phenomena requires improving the accuracy and timeliness of observations, forecasts, and warnings in order to develop an efficient response system that helps minimize and mitigate the impacts of hazardous weather. An expansion in emphasis from weather prediction alone to the prediction of weather *and* related impacts is warranted. This would necessitate development of new modeling and observational tools, innovative forecast guidance products, and methods of information and warning dissemination to decision makers and stakeholders. Accordingly, new research and R2O priorities for VHI weather need to be established. Also required is the close collaboration of physical and social scientists in setting priorities and developing effective research and implementation programs. Social scientists, especially, will also play a critical role in developing O2R needs and priorities. To facilitate a rapid R2O transition, it is critical to train a new generation of researchers, forecasters, and decision makers in the need for, and use of, a fully integrated forecast and response system.

Current State of Affairs and New Opportunities

Weather research over the past several decades has led to many advances in monitoring, understanding, and predicting VHI weather, which have contributed to major improvements in forecasts and warnings such as more accurate hurricane tracks and longer lead times for tornadoes and severe thunderstorms. Although the number of VHI weather phenomena is extensive, this section aims to illustrate the variety of phenomena that have major impacts on society and identify emerging needs and opportunities for weather research to better serve critical societal needs. A number of previous studies (Table 1.1) by the U.S. Weather Research Program (USWRP; e.g., Emanuel et al., 1995) and the National Research Council (e.g., NRC, 1998b) can serve as benchmarks for comprehensive reviews, because they identified many pressing needs and opportunities for atmospheric, hydrologic, and related research and development that still exist today.

A New Impacts Paradigm

The atmospheric community has for many years worked diligently to improve the accuracy and resolution in space and time of the raw quantities predicted by numerical models, such as temperature, humidity, wind, and precipitation. Statistical techniques have been used to predict additional quantities and to introduce probability of precipitation and other derived forecast parameters. With some exceptions, users have largely taken these weather predictions and used them in their own decision support and risk management processes. However, this approach has not always produced the desired or optimal outcome, especially when complex weather forecasts are difficult to understand and yet require public action in response to the forecast. For instance, probabilistic forecasts of a landfalling hurricane's track and intensity, without specific impact information such as timing and location of storm surge, extent of flooding, extreme winds, and power outages, are insufficient for effective responses from emergency managers.

A new paradigm for the coming decades is for end users and scientists (both physical and social scientists) to work together toward also providing improved, explicit *impact forecasts* as well as advancing human comprehension of complex information. The paradigm shift from forecasting weather to forecasting weather and impacts will challenge the traditional weather forecasting approach and demand a full integration of the physical sciences with the socioeconomic sciences that is relevant to weather impacts and societal and environmental responses. Because of the implications for public safety and economic resilience, VHI weather phenomena are key targets for such integrative research and the transition of research results to operations.

As one example, consider the information in Figure 4.1, comparing traditional portrayals of weather forecasting, and the potential for impacts

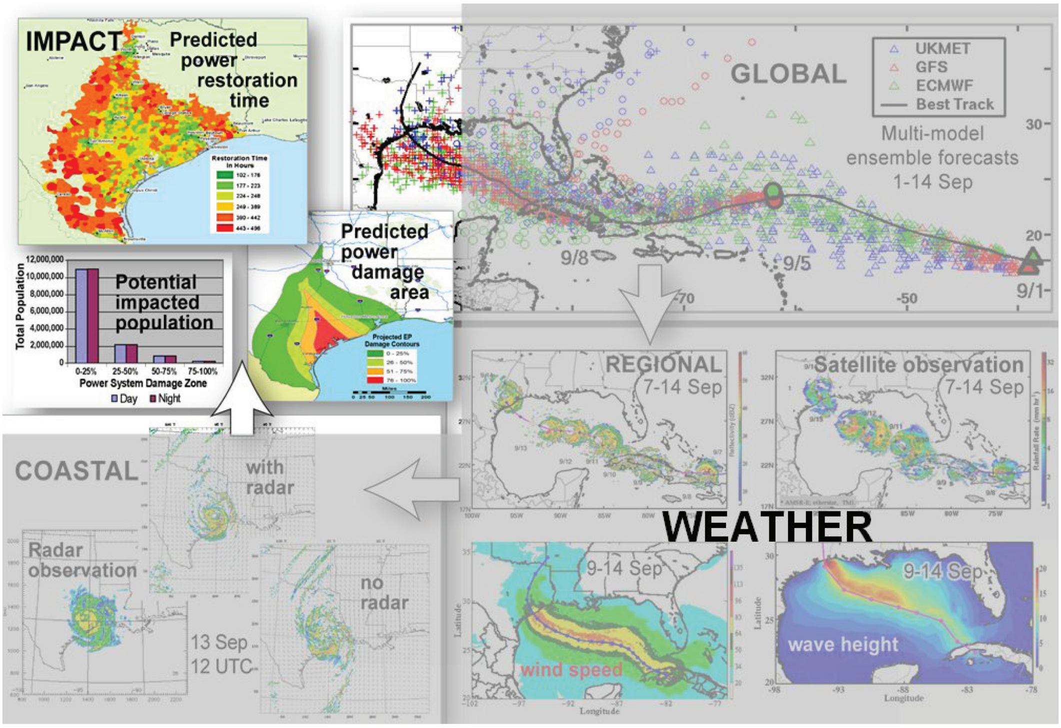

FIGURE 4.1 Schematic representation of the paradigm shift from weather forecasting to impacts forecasting. At upper right and lower right are traditional depictions of predicted hurricane paths, wind and wave height swaths, rain, and satellite and radar observations. At lower left are radar observations and numerical-model radar renditions of a hurricane. The figure in the upper left illustrates the new impacts paradigm, which predicts areas of power outages and restoration times. SOURCE: Shuyi Chen, committee member.

forecasting. Traditionally, data from surface-based observing systems, reconnaissance aircraft, and satellites are used in numerical weather prediction (NWP) models to make predictions about a hurricane's trajectory, intensity (wind speed), and precipitation. In the new, impacts forecasting paradigm, these models would be used in conjunction with decision support models to yield projections of possible impacts such as the extent of power outages and the time to power restoration for the region affected by the hurricane. In fact, there are private weather and risk management companies that are now working with electric utilities, insurance and reinsurance companies, and others to make industry-specific impact predictions for a variety of severe weather events. However, impact prediction remains to be implemented more widely—not only by the private sector but also by the public sector with its responsibility to support and protect public health and safety.

One key component of, and a major challenge for, the prediction of impacts is to more fully exploit the capabilities of ensemble modeling of the atmosphere to produce probabilistic forecasts of atmospheric quantities, and for these to then be used to generate probabilistic forecasts of the impacts and risks of pending VHI weather situations, thereby enabling improved decision making. Rather than the meteorological community and the end-user communities working separately, teams of atmospheric scientists, social scientists, and professionals from user groups[1] need to work together to define the needed observations and the desired predicted impact parameters. This approach has been recommended for hydrometeorological forecasting (Krzysztofowicz, 1998) in a seminal paper on the development and application of joint decision-making probabilities of river stage predictions and user risk tolerances.

Severe and Disruptive Weather Hazards

Hurricanes and Tropical Storms

Although there has been significant improvement in hurricane track forecasts, progress has been minimal with regard to storm intensity forecasts. The improvement in track forecasts is largely attributed to the advancement in satellite and dropwindsonde observations (Franklin et al., 2003) over the oceans and model improvement and data assimilation in global models over the past few decades. Limiting factors for hurricane intensity forecasts include the lack of understanding of rapid changes in storm structure and intensity, routinely (and continuously) available in situ observations, and high-resolution coupled air–sea–land models (Chen et al., 2007) in operational centers. Although some issues were identified by PDT–5 (Marks and Shay, 1998), many questions and problems remain unresolved. Other new issues have emerged since then.

Major landfalling hurricanes between 2004 and 2008, such as Katrina, Rita, and Ike, revealed many critical needs not only for improved weather forecasts but, more importantly, for forecasts of storm impact directly related to societal responses to these events. These are highlighted in four recent national reports calling for action to substantially improve hurricane forecasts (AGU, 2006; NSAB, 2006; NSB, 2007; OFCM, 2007); they particularly cite

[1] In this context, user groups include both end users and intermediate users who typically are commercial weather providers and so-called value-added resellers.

the rapid intensity changes of hurricanes threatening the United States as a major challenge. Recent advances in science and technology, especially in high-resolution coupled modeling, ensemble model forecasting, high-performance computing, and social behavioral studies related to hazardous weather events, have presented a great opportunity to develop a strategy and action plan for an integrated forecast-and-response system that will support risk assessment, emergency management, and decision making.

Tornadoes and Severe Thunderstorms

There has been considerable improvement in understanding, predicting, and warning for these hazardous phenomena as a consequence of successful research programs, deployment of a national network of Doppler radars, and other National Weather Service (NWS) modernization activities in the 1990s. Lead time for tornado warnings has increased from about 6 minutes in 1993 to about 13 minutes in 2008. However, questions still remain concerning why only a small fraction of supercell thunderstorms produce tornadoes while most do not. As a consequence, the false alarm rate for tornado warnings is high, at 75 percent in 2008, which is virtually unchanged from 1993 when it was 73 percent. Research programs such as VORTEX2 need to continue to address that question, reduce false alarm rates, better understand tornado genesis and dissipation processes, deduce how and why some tornadoes become strong and violent while others do not, and explore other unknowns about tornadoes and severe thunderstorms. Radars in the national operational NEXRAD (or WSR-88D) network are spaced too far apart to detect the low-level portions of most supercells, which is critical to detection of tornadoes.

Research needs to continue the development of low-cost, adaptive scanning radars as a means to fill these gaps (e.g., Brotzge et al., 2006) both to reduce false alarm rates and improve detection of tornadoes now missed. Recent studies by the NRC (e.g., 2002, 2008a) recommend additional upgrades to the national radar network. To dramatically improve tornado warning lead time will likely require a shift away from warnings based on detection to warnings based on forecasts. Much needed research is ongoing toward the development of a warn-on-forecast system (e.g., Stensrud et al., 2009), which will involve many of the improvements in numerical modeling and probabilistic forecasts recommended here and elsewhere in this report. There is also a continuing need for improved understanding of the four-dimensional structure of tornadoes, with practical applications such as improved building construction standards.

Flash Floods

In many ways, flash floods are among the most difficult phenomena to predict (see the discussions in Chapter 3). Many issues related to quantitative precipitation forecasting and hydrologic and flood prediction have been discussed previously by USWRP PDT–8 (Fritsch et al., 1998) and USWRP PDT–9 (Droegemeier et al., 2000). There is little skill in predicting the exact location of an upcoming flash flood until the rain is well under way. Even then, the area of heaviest rainfall tends to be small and not always well observed. Improvements in precipitation estimation through use of multiparameter radars will help with this problem; the NEXRAD agency partners (Department of Commerce, Department of Defense [DOD], and the Department of Transportation [DOT]) have initiated a program to provide dual-polarization capability on all 166 WSR-88D radars with completion targeted for early 2013.[2] Improvements in satellite-based precipitation estimation and in cloud-to-ground lightning detection (a useful surrogate for convective precipitation) can help in remote, mountainous areas not well sampled by radar.

Flash floods are an excellent example of VHI weather that can reap the benefits of a new impacts forecasting paradigm by utilizing numerical model forecasts and observations in a coupled hydrology–land–atmosphere model for flood impacts forecasting. The need for a coupled distributed hydrologic modeling framework is discussed at length in Chapter 3. A recent flash flood in the Atlanta, Georgia metro area illustrates the challenging nature of flash floods. On September 20–21, 2009, more than 15 inches of rain in less than 24 hours (with a maximum of more than 21 inches in 38 hours) fell in a narrow corridor generally less than a county wide. Although a broad area of the Southeast was under a flash flood watch owing to the presence of an unusually moist air mass, there was no obvious way to predict the exact location or magnitude of the event, even in hindsight. While a mesoscale boundary was oriented generally west–east through the area, a band of thunderstorms set up and moved roughly perpendicular to the boundary. However, all of this was unresolved by the operational regional models, and forcing for the location of formation of the initial storm was not obvious either from observed data or numerical model guidance. It remains to be determined whether a network of enhanced observations providing inputs to improved data assimilation techniques and cloud-resolving regional models can improve forecasts of heavy mesoscale precipitation. This issue

[2] See http://www.roc.noaa.giv/wsr88d/DualPol/DualPolOverview.aspx.

is further addressed in the Mesoscale Observational Needs and QPE/QPF sections of Chapter 3.

Wildfires

Wildfires are another opportunity to apply a new paradigm for impacts forecasting. Temperature, humidity, and dry lightning can play a role in wildfire initiation, development, and spread, while winds and terrain typically play key roles in spreading major wildfires. The wildfires themselves often develop their own weather, becoming firestorms. There is a need for continued improvements in satellite sensing, including fuel availability and the detection and monitoring of fires and their intensities. Fire models can be coupled with atmospheric and land-use models to generate impact forecasts of threatened areas (e.g., Clark et al., 2004). Numerical model improvements are crucial, including terrain and urban effects. A prediction system of this type has been proposed (e.g., Bradley et al., 1999).

Surface and Air Transportation

According to a recent NRC (2004) study, weather significantly affects the safety and capacity of the nation's roadways. Adverse weather is associated with over 1.5 million vehicular accidents each year, accounting for approximately 800,000 injuries and 7,400 fatalities (FHA, 2009). Poor road or visibility conditions often cause drivers to slow down, thereby substantially reducing roadway capacity, increasing travel times, and in some cases contributing to chain-reaction accidents. It is estimated that drivers endure over 500 million hours of delay annually on the nation's highways and principal arterial roads because of fog, snow, and ice. This conservative estimate does not account for considerable delay due to rain and wet pavement. An improved strategy for addressing the impacts of weather on surface transportation has the potential to help mitigate roadway congestion and save lives. High-quality weather observations and forecasts specific to the roadway environment could help users make better decisions, thereby increasing travel efficiency and safety during adverse weather conditions. Improved road weather information could also help those who construct, operate, and maintain the roadways to better respond to weather problems.

Weather also is a major factor in causing delays (about 65 to 70 percent of the total occurrence) and economic losses to commercial aviation. According to the Joint Economic Committee of Congress (U.S. Congress, 2008), air traffic delays in 2007 cost airlines $19 billion in increased operating costs and the United States economy $41 billion. As the volume of air transportation increases, the demand for even greater efficiency will require improved quality and use of weather information. NextGen[3] is a multi-agency (DOT, DOD, Federal Aviation Administration, National Aeronautics and Space Administration [NASA], and White House Office of Science and Technology Policy) initiative to dramatically improve the management of air transportation by 2025. Weather information plays an important role in NextGen, enabling the identification of where and when aircraft can and cannot fly. In building NextGen, weather information is being designed to integrate with, and support, decision-oriented automation capabilities and human decision-making processes. Weather information supports trajectory-based planning and decision making. The NextGen weather and automation capabilities will support cataloging and analyzing flight plans and provide recommended routes to pilots and dispatchers. Weather information in the form of meteorological variables that are observed or forecasted (e.g., storm intensity, echo tops) need to be translated into information that is directly relevant to NextGen users and service providers, such as the likelihood of a flight deviation, airspace permeability, and capacity. Uncertainty in meteorological phenomena that have significant impact on air system capacity is being managed through the use of probabilistic forecasts that will include the three-dimensional location, timing, intensity, and the probability of all possible outcomes.

Persistent Hazardous Conditions

These VHI weather phenomena generally occur as a result of prolonged anomalous weather conditions lasting days, weeks, or even years. Impacts can result from either excess or deficient precipitation, anomalously warm or cold temperatures, and often in combination with anomalies of wind and sunshine.

River Floods

Although sometimes generated by a single rainfall event, the worst floods are often a combination of prolonged rain and snowmelt, and occur over a longer timescale than flash floods, such as the Midwest floods of 1993, which are thought to be the largest and most significant recorded

[3] See http://www.jpdo.gov/index.asp.

flood in the United States. Flooding occurred across nine states, resulting in 48 deaths and approximately $21 billion in damages (NCDC, 2010).

Improvements in the ability to predict anomalously wet patterns could have an impact on the ability to anticipate river floods and allow emergency and water managers to plan ahead.

Drought

Drought has huge implications for agriculture, water supply, recreational industries, and various commercial enterprises. Shifts in population to low-precipitation areas where water is normally in short supply—and to urban areas where supplies may be limited—have already brought water supply problems, water restrictions, and disputes to many places in the United States. A recent workshop has summarized some of the issues and research needs facing prediction of drought on seasonal to decadal timescales (Schubert et al., 2007). Research needs range from a greater understanding of the forcing factors (oceanic, El Niño–Southern Oscillation [ENSO], aerosol feedback, vegetation, and others), especially with respect to various climate change scenarios, to improved numerical modeling of the coupled land–ocean–atmosphere system.

Heat and Cold Waves

Each of these, typically lasting up to a few days, can have serious implications for human health, agriculture, and other industries. Hundreds to thousands of fatalities (CDC, 2006) result annually from heat waves in the United States alone, including about 700 excess deaths during the 1995 heat wave in Chicago alone. There is also a strong correlation between heat waves and pollutant levels, and the synergistic effects of heat and poor air quality lead to elevated morbidity levels. Because heat waves with the largest impacts last for many days, there is a pressing need to improve medium- to extended-range forecasting. Temperature anomalies have huge economic implications for energy use and for commercial utility providers. For example, urban electricity usage increases 3 to 5 percent for each 1°C increase in ambient air temperature above about 22°C (Sailor and Dietsch, 2007).

Air Quality

Air quality and its impacts on health and the economy involve far more than just the pollutants emitted into the atmosphere. Weather factors such as inversions, wind speed and stability, precipitation, and other factors are often controlling influences. Air stagnation episodes often involve a pattern of strong, low-level inversion and light winds that persists for a few days. One study (Schwartz and Dockery, 1992) indicated that 60,000 people die in the United States each year because of poor air quality.

Improvements in Impacts Forecasting

The impacts of VHI weather episodes tend to be maximized in urbanized areas where large numbers of citizens and infrastructure are concentrated. Even for the smallest of the VHI weather phenomena (e.g., tornadoes and flash floods) significant portions of an urbanized area can be seriously impacted. Further issues specific to the urban environment are addressed in following sections.

Research that leads to improved understanding, monitoring, prediction, and communication of VHI weather phenomena will result in fewer injuries and fatalities and reduce the impacts of the tens of major natural disasters that annually impact the United States. In addition to the economic impacts of VHI weather already described, there are countless applications in which improved weather information can result in enhanced cost-effectiveness and savings for public entities, business, and industry. Social scientists and economists are needed to help quantify the benefits of weather data and forecasts to these applications and to define key impact parameters (as distinct from traditional weather parameters).

Impacts of Climate Change on Very High Impact Weather

A major challenge is to understand the effects of climate change on VHI weather and its potential long-term socioeconomic implications. Potential changes in storm tracks and intensity, and the frequency of severe drought and flooding events are of great value in risk assessment, adaptation, and mitigation. Although recent studies have suggested that the intensity and perhaps even the number of extreme weather events may increase (e.g., Anthes et al., 2006; Knutson et al., 2010; Trapp et al., 2007; Trenberth et al., 2003), it is difficult to evaluate and validate the results because of the lack of observations and limitations in climate models to represent “weather.” The relatively low resolution and insufficient physical representation in the current climate models have led to great uncertainty in the assessment of the impact of climate change on VHI weather. A well-designed systematic approach is urgently needed to improve climate model physical parameterizations (in consequence of increases in model grid resolution), model prediction of VHI weather statistics, downscaling of local impacts of changing climate using high-resolution cloud-resolving and impact models, and rigorous model verification with observations;[4] this would require

- fundamental research to improve understanding of VHI weather phenomena, especially how underpinning dynamical and physical processes are impacted by larger scale forcings;
- better understanding of predictability and predictive skills of VHI weather on shorter timescales as well as weather statistics on longer timescales (e.g., the persistent large-scale flow patterns that produce drought and flooding events); and
- development of a seamless, integrated weather–impact prediction system from global to regional and local scales, which can be used for risk and benefit assessment and decision making.

Research Priorities

To improve predictive skills, research is needed to better understand and identify the "sources" of predictability for various VHI weather phenomena. For instance, improving severe weather forecasts requires very high resolution cloud-resolving models with improved data assimilation techniques on short timescales of hours or less. On the other hand, improving forecasts for heat waves and prolonged cold outbreaks as well as flooding from persistent rain events requires better global model prediction on extended timescales beyond a few weeks. For the latter, monitoring and data assimilation of soil moisture may be especially critical. Prediction of drought extends from seasonal to interannual and decadal timescales (Schubert et al., 2007). The use of ensemble model prediction for probabilistic forecasting requires new systematic verification methods with quantitative uncertainty estimates. These priority research needs for improved weather prediction on all scales are common to those presented in Chapter 3. Beyond that, research is needed to develop, test, and verify impact predictions for multiple applications.

Recommendation: The federal agencies and their state and local government partners, along with private-sector partners, should place high priority on providing not only improved weather forecasts but also explicit impact forecasts. An effective integrated weather–impacts prediction system should utilize high-quality and high-resolution meteorological

[4]Refer also to the discussion in the modeling and observations sections in Chapter 3.

analysis and forecast information as part of coupled prediction systems for VHI weather situations.

This will require

- fundamental research in both the physical and social sciences to improve understanding and prediction of VHI weather phenomena, and the provision of warnings and risk assessments in support of decision making;
- development of impact parameters and representations for multiple applications (e.g., morbidity, electric grid vulnerability, surge and flood inundation areas);
- research to determine and obtain critical and timely observations;
- end-to-end participation by multiple sectors and disciplines (including modelers, observationalists, forecasters, social scientists, and end users) to jointly design and implement impacts-forecasting systems; and
- multidisciplinary undergraduate and graduate programs that can address the emerging field of VHI weather–impacts prediction, risk assessment and management, and communication through fully integrated research, education, and training for the new generation of scientists, forecasters, emergency managers, and decision makers.

Research-to-Operations Priorities

A key aspect of the VHI weather impact recommendation is to encourage diverse government agencies, academia, and the private sector to work together in defining and addressing problems in which meteorological information—in current or future improved fashion—can be used as part of impacts forecasting. In many cases, this will involve use of weather information in coupled models or as data for input to specific impact models. Examples include the prediction of wind, rain, storm surge, and inland inundation from hurricanes, coupled with detailed topographic, land-use, and population mappings, to delineate in a probabilistic manner which locations will be most impacted. This will make it possible for emergency managers and the public to make more effective decisions regarding hurricane evacuations, and for utility companies and disaster recovery organizations to better anticipate the scope of the relief and recovery efforts likely to be necessary.

Moving forward, there needs to be recognition of the extensive efforts of the private sector in predicting weather-related impacts and assisting in decision making and risk management for their clients. Obvious examples include preparation for storms, crop forecasts, energy management and trading, airline operations, ship ocean routing and port operations, and recreational enterprises, to name but a few. Some years ago, NWS abandoned impacts forecasting because it could not serve some industries directly while ignoring others, while needing to focus on its primary goal of promoting public health and safety. The current NWS strategy,[5] stated simply (perhaps overly so), is to obtain the observations and provide the forecasts necessary for the protection of life and property and then make that information readily available to the public and the private sector to serve their special needs, including prediction of impacts. However, impact forecasts are needed as much in the domain of the NWS and other public agencies as they are needed in the domain served by the private sector. Some examples of impact forecasts that fall within the purview of the public sector include heat stress (in contrast with temperature and humidity), respiratory stress (from the synergies of elevated air pollution levels and temperatures), wind chill (temperature, humidity, and wind speed), and so forth.

To achieve these goals, a mechanism is needed to encourage communication between the meteorological community and those involved in decision making and other types of impact modeling. This would involve socioeconomic scientists and end users as full participants and partners. It may involve creation of an integrated weather–impact modeling testbed or other such mechanism. A great deal of cross-cultural education is needed for each community (meteorologists and impact specialists) to become familiar with the terminology, capabilities, and needs of the partner group(s).

Although the path from research to operations will likely differ somewhat from one VHI weather phenomenon to another, a general methodology to use in implementing the new impacts-forecasting paradigm includes

- Interactions among data/forecast providers, users, and social scientists to identify the user data needs in order to define the nature of the end product impact forecasts.
- Research and development by the data provider and user communities to complete their components of the impacts forecasting system, and by social scientists to help tailor the output of the impacts forecasting system for human end users. When the end users are the general public, social scientists also need to be engaged to help design educational materials and programs to prepare the public to understand and use the new impact forecasts.

[5]The NWS Strategic Plan for 2005–2010 is available at http://www.weather.gov/sp/; the updated strategic plan for 2010–2015 is expected to be available in the third quarter of 2010.

- Testing of the impacts forecasting system and training personnel in its use. Depending upon the nature of the VHI weather phenomenon, this type of activity could be performed in one of the existing testbeds, such as the Hazardous Weather Testbed or the Hurricane Testbed or the urban testbed recommended later in this report.
- When the public is the ultimate end user of the output of the impacts forecasting system, an education and training campaign could be launched to help people understand and appropriately respond to the impact forecasts.

VHI weather phenomena have a significant impact on health and safety and economic vitality in the United States and worldwide. Priority needs to be given to improving understanding and prediction of these phenomena, particularly toward developing and implementing impact-prediction systems in order to meet critical societal needs.

URBAN METEOROLOGY

Global Urbanization

Since the end of the Second World War, urbanization of the world's population has given rise to more than 400 cities around the world with populations in excess of 1 million and more than 25 so-called megacities with populations of over 10 million (e.g., Figure 4.2; Brinkhoff, 2010; Pearce, 2006). Some metropolitan regions now contain between 20 million and 30 million people, including Tokyo, Japan (34.0 M); Mumbai, India (22.8 M); Seoul-Incheon, Republic of Korea (24.2 M); and Mexico City, Mexico (23.4 M. Even greater Los Angeles (17.9 M), which now stretches from Goleta in the north nearly to Ensenada (Mexico) in the Baja, is nearly a virtual "super-megacity." Recent reports published by the United Nations estimate that in 2007, 50 percent of the world's population, and more than 75 percent of the population in developed countries, lived in cities (UN, 2008). All indications are that urbanization will continue through much of the 21st century, though the rate of growth of urban populations may slow somewhat from what was seen in the last decades of the 20th century (Brockerhoff, 1999, 2000).

Urban meteorology is the study of the physics, dynamics, and chemistry of the interactions of the Earth's atmosphere and the urban built environment, and the provision of meteorological services to the populations and institutions of metropolitan areas (usually divided into Metropolitan Statistical Areas [MSAs] and Micropolitan Statistical Areas [μSAs], see Box 4.1

FIGURE 4.2 At about 6,340 people per square kilometer, the population density of Hong Kong is among the highest on Earth. SOURCE: Wikipedia. Available at http://en.wikipedia.org/wiki/File:Crowd_in_HK.JPG.

for a brief discussion on what is considered an "urban area," at least in the United States). Because one of the goals of applied meteorology is to provide services to society, urban regions where people are highly concentrated merit special attention. Urban populations can benefit greatly from a wide range of weather and climate services tailored to their urban environments. Although the details of such services are dependent on the location, geomorphology, and synoptic climatology of a particular city, there are common themes, such as enhancing quality of life and responding to emergencies, which are relevant to many cities. The urban landscape, with its distinct patterns of surface roughness and fluxes of heat, moisture, and pollutants, presents significant challenges to researchers and operational meteorologists. Urban meteorology can benefit from implementation of many of the other recommendations in this report, such as the development of high-resolution mesoscale networks and weather prediction models, hydrologic prediction models, impacts predictions and socioeconomic analyses (see Chapters 2, 3, and 4), which could then be further refined and tailored to the urban landscape.

BOX 4.1
Metropolitan Areas

Identifying appropriate boundaries for a metropolitan area is difficult. In the United States, the federal government has formally defined Metropolitan Statistical Areas (MSAs; see figure below). These regions are composed of counties or equivalents. MSAs are delineated on the basis of a central urbanized area, which is a contiguous area of relatively high population density with a population greater than 50,000. The counties containing the urbanized core are known as the central counties of the MSA; surrounding or outlying counties are included in the MSA if they have strong social and economic ties to the central counties as measured by commuting and employment. As of 1 July 2009, using data developed by the U.S. Census Bureau (2009), the federal Office of Management and Budget recognized 366 MSAs in the United States. Some of the largest MSAs are subdivided into Metropolitan Divisions. These contained about 233 million people in the 2000 census.

Since 2003, the U.S. government has also identified Micropolitan Statistical Areas (μSAs); these are areas centered on a small city with a population in the range 10,000 to 49,999 (Figure 4.3). The area is again based on counties. While individual micropolitan areas do not have the economic or political impact of MSAs, collectively they contribute significantly to the national statistics for population (~30M) and economic activity because of their large number (560 based on 2000 census data). Frequently μSAs have relatively low labor and land costs, and so several have developed surrounding regions of urban sprawl. Because the designation as a μSA is based on the core city, in some cases μSAs are actually more populous than some MSAs. (Note that based on the 2000 census, only ~45 million out of an estimated 308.5 million individuals in the United States did not live in either an MSA or a μSA.)

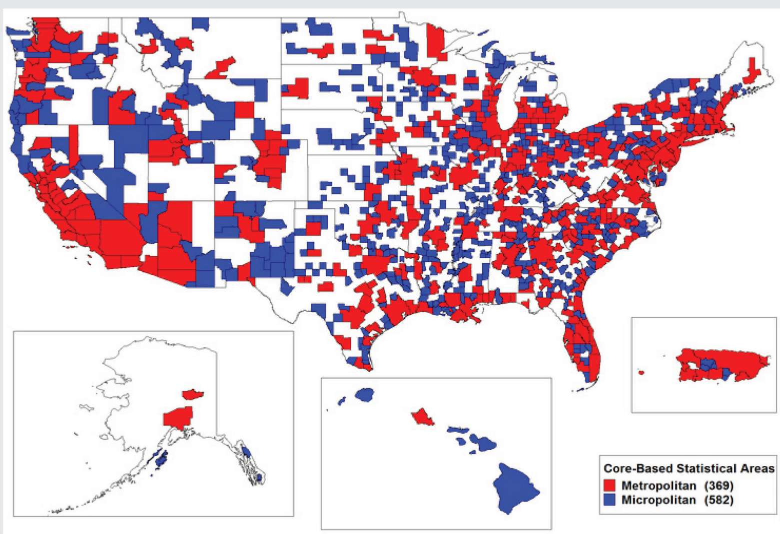

FIGURE: Map of core-based metropolitan and micropolitan statistical areas (MSA and μSA, respectively) of the United States, based on 2005 U.S. estimated census data SOURCE: Created by Rarelibra 19:40, 25 October 2006 (UTC) for public domain use, using MapInfo v8.5 and various mapping resources.

The United States has a population of more than 308,500,000.[6] It is largely an urban population, with about 81 percent residing in MSAs or μSAs as of mid-2005; the equivalent worldwide urban rate was 49 percent (UN, 2008). Cities and suburbs are home to the large majority of the U.S. population, yet they only occupy between 2 and 3 percent of the land area of the United States.

These urban dwellers and their supporting institutions and infrastructure have needs for tailored weather information and services that differ from those living in rural areas. The most notable shortcoming of current urban meteorological services is the lack of spatial resolution. Current observing and prediction systems are structured to provide more or less uniform services across the whole United States. Observations are more or less uniformly distributed, particularly where terrain is not an obstacle, on scales of tens to a few hundred kilometers. Further, even with the recent shift by the NWS to a digital gridded forecast, the current resolution is still coarse, with only a few points per county. The current observing and prediction systems simply do not provide the level of resolution and surface specificity necessary for the production of meteorological products and services on the urban scales, which range from a few meters to a kilometer or so at most. An example is winds at street level—observing and predicting these can be both a quality-of-life service for those walking in the city and a safety and security issue for emergency responders dealing with dispersion of chemical, biological, or radioactive agents.

The urban environment also merits special products and services dealing with air quality (including pollutants related to respiratory stress, heat and cold stress on humans and infrastructure, and monitoring of conditions on the transportation networks—light rail as well as roads—that tie the urban complex together.

Further, because of the complexity of the urban environment, meteorological support needs to be part of an integrated or multihazard warning system that considers the full range of environmental challenges and provides a unified response from municipal leaders. The World Meteorological Organization (WMO) has responded to this need for a comprehensive response to high-impact weather and weather-related events with its Multi-Hazard Early Warning System (MHEWS)[7] initiative, as exemplified by pilot projects under way in France and Shanghai, China. Examples of urban weather that such a system would consider include winter hazards, such as snow and ice; flash flooding; sand and dust storms; extended periods of extreme temperatures;

[6] See http://www.census.gov/main/www/popclock.html.
[7] See http://www.wmo.int/pages/prog/drr/projects_en.html.

adverse air quality; tropical cyclones with attendant high winds, storm surge, heavy rain, and flooding; and drought with attendant water shortages.

The Challenge: Enhance Meteorological Services to Metropolitan Areas

Modern urban meteorology in the United States likely had its beginnings in the provision of support to ice and snow removal efforts. It expanded in the 1960s with the mandated monitoring of atmospheric conditions to meet air quality standards. As cities have grown larger, local and regional governments, as well as local industry, have sought more environmental input to aid their decision making. Today, urban meteorology is recognized as a type of regional-scale meteorology where the region is highly populated and a large portion of the surface is covered with built infrastructure.

All metropolitan areas face a number of serious environmental challenges. Air quality management is one; another is effective response to many types of emergencies, such as heat waves, large fires (including wildfires), and toxic chemical spills. Some MSAs are located in regions prone to particular hazardous atmospheric phenomena, such as Miami, which is threatened by tropical cyclones, and Chicago, which deals with severe thunderstorms, wintertime cold and snow, and summertime heat waves. A major concern in recent years is that cities have become targets for terrorist attacks with possible releases of dangerous airborne agents into the urban environment. As a consequence, a number of homeland security issues are strongly tied to urban meteorology (NRC, 2003c). Furthermore, all MSAs rely on surrounding regions to produce continuous supplies of food, water, raw materials, and energy. As a consequence, metropolitan areas are sensitive to meteorological events at a distance, such as wildfires or strong winds damaging electrical services or a decline in mountain snowpack reducing the available supply of water.

The Need: A National Initiative to Enhance Urban Meteorological Services

A national initiative to enhance meteorological services tailored to and provided in MSAs is a high-priority need for a wide variety of stakeholders, including the general public, commerce and industry, and all levels of government. Enhancements would improve the quality of life and the public safety of those living and working in urban areas, increase the efficiency and competitive positions of urban-based industry and commerce, and aid emergency, medical, and law enforcement services in addressing threats to life, property, services, and urban infrastructure. Some of the activities that need to be included in such an initiative include

- **Conducting basic research and development** in boundary-layer meteorology; observations and network design; meso- and microscale meteorology; data assimilation and prediction systems; road, rail, and aviation weather; air quality and atmospheric chemistry; and hydrometeorology.
- **Prototyping and other R2O activities** by the NWS to enable very short- and short-range predictions that employ advanced nowcasting techniques in the 0- to 3-hour range together with short-range mesoscale models; to improve analyses of initial and boundary conditions and short-range predictions for mesoscale model forecasts in the 12- to 48-hour range; to enable the merging of probabilistic guidance associated with nowcasting and dynamical predictions in the 3- to 12-hour range; to provide a basis for object-oriented verification of probabilistic forecasts resulting from ensemble techniques; and to facilitate technique development for advanced applications of mesoscale observations to locally disruptive weather such as fog, surface icing, thunderstorm initiation and motion, assimilation of precipitation measurements, conditions near hurricane landfall, other hazardous lake and coastal ocean conditions, hazardous urban conditions, fire weather predictions, and hydrologic predictions and warnings.
- **Supporting and improving productivity and efficiency in commercial and industrial sectors**[8] such as minimizing energy consumption in manufacturing and transportation; optimizing electric energy generation (see the following section on Renewable Energy); efficient building management; wholesale and retail sales across a broad range of projects; the commercial air, rail, maritime, and road transportation industries; the broadcast media; commodities exchanges; and insurance industries.
- **Urban planning for long-term sustainability** that includes minimizing releases of polluting materials; minimizing the urban carbon footprint by reducing or eliminating greenhouse gas emissions from mobile and stationary sources; development of comfortable urban microclimates to enhance the quality of life; minimizing the impacts of potentially hazardous weather phenomena; and informing the inhabitants of current and expected future weather conditions. Fostering local solar and wind power, green roofs, and urban gardening in green spaces are other activities.

[8]Such information is provided in large part by private-sector meteorologists using basic data and forecast information from the NWS together with special observations and models.

In the United States, the expertise needed to carry out the activities described above is distributed. The NWS has a national observing system and produces a wide range of forecast products each day. However, it is often private-sector meteorologists (less frequently, meteorologists employed by state or local governments) who tailor the general government forecasts to provide urban-focused weather products and services. These private-sector meteorologists usually target and are employed by niche markets, such as local departments of transportation, which need very specific information to plan for clearing ice and snow. So, although expertise and experience exist to address the above topics, they are not currently organized in any coherent way. The federal government, in particular the NWS, is unlikely to obtain the resources necessary for it to provide the full range of urban services described here. However, the NWS is in a position to provide leadership within the professional community and seed development and demonstration projects in such a way that the full spectrum of needed products and services becomes available, some from the government and some from the private sector.

Progress in the Past Decade

The importance of urban meteorology has been recognized in the past. For instance, in 2000, PDT–10 (Dabberdt et al., 2000) stated,

> The urban weather problem is multidimensional in scope. Weather has special and significant impacts on a large fraction of the U.S. population who live in large urban areas. Conversely, large urban areas can impact the local weather and hydrologic processes in various ways. It is important to recognize that urban users have different needs for weather information than do their rural counterparts.

Further, recognizing the critical role of accurate information about the atmospheric conditions for predictions of transport, diffusion, and removal of atmospheric pollutants, the PDT–11 (Dabberdt et al., 2004) stated, “Improving atmospheric forecasts to provide improved air quality forecasts suitable for decision makers and the public is a major challenge.” As the key measurement problem for urban areas, they identified “the specification of vertical wind, turbulence, and temperature profiles, both below and above the urban canopy.”

Although some progress has been made to develop the special services that target the MSAs as recommended by PDT–10 and –11, recent studies in both the United States and elsewhere agree that there continues to be a critical need to significantly improve weather and environmental monitoring and prediction services for metropolitan areas and their supporting regional infrastructure. A fundamental issue is that most observing system and NWP model output, and hence the resulting products and services, are too coarse in resolution and lack representative surface conditions (i.e., aerodynamic roughness and displacement height, surface heat capacity and conductivity, and so forth) to provide the degree of detail necessary for true urban forecasts. In urban products, the meteorology needs to be done on scales representative both of where people live and work and of the relevant atmospheric processes.

Recognizing the need for increased attention to urban issues, the WMO devoted a session of its Third World Climate Conference to a discussion of climate and more sustainable cities.[9] The session resulted in a statement of three priorities in urban weather and climate: climate research for hot cities, urban climate modeling, and education, training, and knowledge transfer in urban climatology (WMO, 2009). Relevant to the present discussion, Grimmond et al. (2009) identified and prioritized where improvements in observations, data, understanding, modeling, tools, and education are needed to ensure that in the next decade urban meteorology supports the development of more sustainable cities (Appendix A).

Around 2001 and running through 2006, the IBM Corporation demonstrated *Deep Thunder*, an experimental weather prediction service using very high performance computing facilities. The demonstration system provided local, high-resolution short-range weather predictions customized to weather-sensitive business operations. A goal was to provide weather forecasts, more or less on demand, at a very high level of precision. A prototype operational system provided 24-hour-, 1-km-resolution forecasts, updated twice daily, for the New York City area. It also produced forecasts at 4-km resolution covering the greater tri-state region and beyond, and then 16-km resolution for the rest of the northeastern United States. That capability was extended to include other parts of the United States. Although efforts were focused on refining the forecasts for the New York area, IBM also extended the system to provide forecasts for six additional metropolitan areas in other parts of the United States, including the Miami/Fort Lauderdale area. *Deep Thunder* demonstrated that with adequate computational resources it is possible to produce useful prediction products for the urban environment.[10]

Since the publication of PDT–10 and –11, new challenges and opportunities have arisen. For example, some urban and regional planners, public health officials, and meteorologists have developed an appreciation

[9] See http://www.wcc3.org/sessions.php?session_list=WS-8.
[10] See http://www.research.ibm.com/weather/DT.html.

of the connections between weather, public health, and concerns regarding long-term sustainability of large cities (Patz et al., 2000; Penney and Dickinson, 2009; WHO, 2009). In addition, both observations and critical weather information are being provided to large numbers of people using cell phones, personal digital assistants, and other such personal communication devices.

Observing systems, including traditional meteorological observing systems (providing measurements of temperature, pressure, moisture, wind, and precipitation), air and water quality monitoring systems, road weather sensors, and especially video cameras have proliferated in all urban areas. However, these systems are operated more or less independently by a wide range of governmental and private organizations and generally are utilized for narrow purposes; few of these data are shared with others. Options for developing partnerships to share data and services have been discussed at a recent USWRP workshop (Dabberdt et al., 2005) and in a recent BASC study report (NRC, 2009b).

Opportunities for Continuing Progress

Meeting the challenges of urban meteorology—monitoring and forecasting weather, hydrology, and air quality on the meso- and microscales in and around the complex urban built environment—requires that phenomena unique to the urban environment be better understood. Examples of urban phenomena warranting study include

- **Street-level weather**: Winds, temperature, precipitation, and surface water (in all its phases) all impact quality of life, business operations, and transportation. Careful building design, urbanwide planning based on local climatology, and operational decision support systems are examples of actions that can be taken to minimize negative effects and make urban areas more effective and pleasanter places to live and work.
- **Wind in the urban canyon**: Helical street-canyon circulations formed as air flows through the artificial canyons created by multistory buildings are a special element of microscale weather in the urban area. These wind circulations are complex and critical in the local transport and diffusion of pollutants, particulates (snow, sand, and dust), and toxic materials.
- **Evolution of the urban boundary layer**: Urban surface properties (roughness, albedo, emissivity, heat capacity and conductivity, and permeability) and their changes with location in the metropolitan area contribute to the evolution of the urban boundary layer across the city. Account also

needs to be taken of local bodies of water and regional topography that can produce land and sea breeze effects and various types of slope-related winds.

- **Urban heat island**: Ambient temperatures are moderated locally by surface heating, producing an urban "island" of warm air as first quantified by Luke Howard in 1833. This increase in temperature occurs because paved areas and buildings absorb (lower albedo) and retain (greater heat capacity) more solar energy than the surrounding natural landscape and so become relatively warm. The release of anthropogenic waste heat also contributes to the urban heat island. That stored energy is released slowly and so is retained well into the night. Consequently, cities tend to stay warm even as the surrounding natural landscape cools at night. The heat island effect contributes to and amplifies the number of casualties in urban areas during heat waves.
- **Urban flooding**: All urban areas contain many roads, parking lots, and other areas with hard packed surfaces nearly impenetrable to water. In many urban areas, water courses have been converted into concrete-lined channels that may be either covered or open. Little rainwater is retained in the urban area, and so urban water courses sometimes quickly become raging torrents even for otherwise modest rain events. In this sense, urban flooding can be considered a special form of flash flooding. Not only do the rapidly rising waters threaten the lives of those in them at the time or who subsequently drive into the water courses as the water rises rapidly, the water can become quickly contaminated from the debris that accumulates in the channels between infrequent flushings of these urban waterways. In some cases, stormwater runoff can enter the normal sewage system and result in the release of untreated sewage. The result is a threat to life, the spread of disease, losses of high-cost property and infrastructure, and contamination of the water supply.
- **Wildfire at the wildland–urban interface**: At the periphery of many urban areas, the city blends slowly into the surrounding forests and grasslands. This interface region can extend for many tens of kilometers and contain residences and small business, as well as other infrastructure. These areas can be highly susceptible to wildfire, posing a direct threat to life and property in the urban periphery but also in the urban core (due to atmospheric dispersion of the smoke, resulting in respiratory stress and also the disruption of vehicular and rail transportation routes due to reduced visibility).
- **Air quality**: Poor air quality contributes to serious health issues, especially in the respiratory system. Although there have been decades of

research on air quality in urban areas, important research questions remain regarding pollutant photochemistry, transport and dispersion, as well as the interactions between pollution and humans that cause illness and disease.

- **Weather forecasting in support of urban emergency response**: This is a particularly challenging task. Such support requires models that quickly capture essential features of current urban temperature, moisture, and wind fields; generate the necessary information; and provide predictions rapidly to users. Such information then can be blended with other information, such as traffic flow, locations of emergency response assets, critical assets or dangerous materials at the site of the emergency, to provide city leaders with the full picture of what is needed for a proper response. The NRC recently concluded that there exist critical gaps in the ability of operational emergency-response models (NRC, 2003c), especially in observing and prescribing the local dispersion environment and identifying and quantifying the source term.

Urban Weather Testbeds

Urban testbeds are needed in cities with widely different annual climates and settings (topography; water bodies) to conduct the research necessary to understand the phenomena mentioned above, to test observing and modeling techniques, and to develop and test products and services under a wide range of conditions. However, as pointed out by M. Ralph (in Dabberdt et al., 2005), such testbeds are much more than just a physical facility or an assembly of hardware and software:

> A testbed is a working relationship in a quasi-operational framework among measurement specialists, forecasters, researchers, private-sector, and government agencies aimed at solving operational and practical regional [insert phenomenon or forecast challenge] problems with a strong connection to the end users. Outcomes from a testbed are more effective observing systems, better use of data in forecasts, improved services, products, and economic/public safety benefits. Testbeds accelerate the translation of R&D findings into better operations, services, and decision-making. A successful testbed requires physical assets as well as long-term commitments and partnerships.

Urban testbeds would develop, test, and bring together the meteorological and socioeconomic aspects (see Chapter 2) of enhancing services to metropolitan areas. These testbeds would be charged with fostering the necessary basic and applied meteorological and socioeconomic research and with providing for the smooth transition of research findings to operations. Cultural issues, such as how to communicate effectively to the often very diverse population found in urban areas, also require consideration. The advantages of employing a testbed strategy include efficiencies, formal opportunities to leverage earlier results from other researchers and other research activities, and a well-focused R2O mission.

Because most urban areas consist of many different government units and businesses, urban testbeds would need to engage and interact with a wide array of stakeholders. A unique aspect of the urban testbed is the strong emphasis on identifying, understanding, and communicating the impacts of urban weather on people, businesses, infrastructure, wildlife, and the natural environment. Effective communication of this information is an important component of this activity (see Chapter 2).

Operational attributes of an effective urban testbed include the following:

- **Location**: Ideally it would be collocated with an NWS forecast office, and with easy access to a university with researchers in meteorology, engineering, urban and regional planning, etc.
- **Archive**: As mentioned in Chapter 3, the testbed needs to archive both the full set of observations and record copies of products and services produced. Such data are essential for case studies, verification of forecasts, and trend analysis. The archive would also be useful for a variety of urban and building design activities.
- **Staffing**: The testbed would be staffed with an interdisciplinary team from the public sector, academia, and industry that includes observationalists, modelers, forecasters, and socioeconomic researchers and practitioners; and should have close ties to the full spectrum of users. For example, social scientists are needed to evaluate the impact of focused weather products and forecasts on decisions by those living in the urban area, from the city management, to leading industrial and commercial entities, to individuals on the street, and to those at home. Staff should be familiar with and draw up unique local environmental resources, such as nearby sites of the U.S. Long Term Ecological Research Network.[11]

An extended, multiyear period of continuous effort, punctuated with intensive observing and forecasting periods, is envisioned for each testbed. These urban weather testbeds have two major areas of focus: (1) on the measurement and prediction of meteorological fields and phenomena and (2) on assessing, predicting, and mitigating the resulting socioeconomic impacts.

[11] See http://www.lternet.edu/.

High-Impact Weather in the Urban Context

Forecasters and researchers need to work with local government agencies, private weather providers, and end users to identify and prioritize the weather services and products needed to address situations with high-value/critical impacts (see prior discussion of VHI weather). These priorities will then help determine research and development priorities in urban weather model development. The testbed would be an active partner in the city's emergency operations center (EOC), promoting the extension of the EOC to cover more weather-related phenomena. An example is provided by the Shanghai MHEWS, which is a demonstration project of the WMO (Tang, 2006).

Observations and Measurements[12]

A key component of the urban testbed is its meteorological and air quality measurement network—the urban mesonet—which provides observations at high spatial and temporal resolutions from the urban core to the surrounding hinterland. Current modeling and observational expertise does not permit a priori specification of an optimal measurement network design—that is, the specification of the density and sampling attributes of an integrated suite of in situ and remote sensing systems. That, in fact, is one of the principal goals of the urban testbed. The commonly accepted approach is to oversample in the testbed and use data denial modeling techniques to identify an optimal network design (or multiple, optimum designs). Data from the urban mesonet then provide the basis for a number of important activities in the urban testbed: development and testing of data assimilation and prediction models; model-verification metrics; and applications where the observations themselves support various applications (e.g., cloud-to-ground lightning measurements are used to ascertain the hazard to airport ramp workers). Lastly, the urban testbed is a fertile environment for government agencies and industry to test new measurement devices and sampling techniques (such as the value of alternative adaptive and targeted sampling strategies).

The urban mesonet would utilize existent urban infrastructure wherever possible (e.g., communication towers and streetlight and traffic-light towers). Observations from tall buildings, communication towers, and remote sensing profilers provide essential information on vertical atmospheric structure,

[12] The special observing needs of the urban environment are a subset of the issues discussed in detail in the section on Mesoscale Observations in Chapter 3.

such as lapse rate, wind shear, and mixing depth. The network might also include a mobile component with instrumentation on selected vehicles: city utility, police, fire, and emergency response vehicles, and delivery trucks (e.g., FedEx, UPS). New and existing sensors will need to be developed and adapted, respectively, for the special case of the urban street-canyon environment. Extensive and frequently updated metadata will be needed for each observation site and measurement system.

The urban mesonet would not only measure conditions in the urban core—a major challenge given the complex urban topography—it would also measure the atmospheric state over a domain sufficiently extensive to specify boundary and initial conditions appropriate to the temporal scale of the prediction models.

Modeling

In principle, data from the extended urban mesonet would be assimilated in a high-resolution mesoscale numerical prediction model (Chapter 3) and then used to initialize an urban numerical prediction model. The urban landscape is an extremely rough and complex surface, one that makes it challenging to represent in a numerical prediction system. However, it is essential that such data be incorporated, and some schemes have been developed for this "urban canopy"; see, for example, the work by Chin et al. (2005) to develop and evaluate an urban canopy parameterization in a three-dimensional mesoscale model to assess the impact of urban roughness on surface boundary layer over the city.

Modeling the microscale airflows in the street canyons between tall buildings is a particularly challenging problem; however, predictions of such winds have numerous applications, ranging from transport of materials from a toxic release, to operation of large-building HVAC systems, to safety and quality-of-life issues for pedestrians on the street. Strictly speaking, such modeling could be addressed via computational fluid mechanics. However, the degree of complexity needed in models for such situations is a function of both the quantities to be determined and the relevant time frames in which they are to be made available. For example, European researchers have demonstrated that much useful knowledge about street-level conditions can be inferred through the use of relatively simple models, which . Operational examples are being used by the United Kingdom Meteorological Office and the research studies by the Environmental Prediction in Canadian

Cities (EPiCC)[13] program; such efforts have demonstrated the feasibility of modeling at the street scale (Best et al., 2006). However, recent studies evaluating multiple urban land surface schemes, as reported by Grimmond et al. (2010), have documented very different performances, indicating the need for more research and development.

In addition to data from the atmospheric measurement network, model input will need to include anthropogenic fluxes of heat, moisture, and chemical compounds. A companion geographic information system (GIS) database is necessary to maintain information on fine-scale land-cover and building-height data, roadways and parking surfaces, buried infrastructure, soil and vegetation distribution, the urban forest canopy, and location data on critical facilities such as hospitals and residential areas. Many of these quantities evolve seasonally and change on a timescale of weeks to months. A GIS-based land-surface database could include processed, gridded data including important input parameters used in atmospheric and hydrologic models, such as roughness length, displacement height, plan area density, slope, soil type and vegetative cover. Initial efforts have been made to generate an urban database for various U.S. cities with the emerging National Urban Database with Access Portal Tool[14] project, and the further development of such a database would be a high priority.

Urban predictions could be developed using high-resolution, nested, NWP models with advanced data assimilation schemes. Adapting existing models and upgrading them with high-resolution, improved physics might be a practical first step. Research needs arise particularly in testing and improving the boundary-layer and surface flux parameterizations used in these models because they were not designed for the required model resolutions and urban complexities. Representations for the urban canopy need to be developed and tested against observations on the appropriate scales. Development and continuous improvement of such models will be the primary thrust of the urban testbed. These improved models could also account for the surface roughness and modifications in the radiation balance. Evaluation and comparisons of the work being done in Canada (EPiCC) and Europe[15] for street-canyon scale predictions could also be productive.

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[13] See http://www.epicc.uwo.ca/.

[14] See http://www.nudapt.org/.

[15] Megacities: Emissions, urban, regional and Global Atmospheric POLlution (MEGAPOLI) and climate effects, and integrated tools for assessment and mitigation; see http://megapoli.dmi.dk/.

Uniformity of Service

As noted previously, U.S. urban dwellers and institutions have needs for weather information and services that differ significantly from those living in rural areas. It is thus worth revisiting a recommendation made some years ago by Carbone (2000), who suggested that the NWS reconsider its policy of "uniformity of service." Service is currently distributed without consideration of population density. Even with the recent shift by the NWS to a digital gridded forecast, the current resolution is still coarse, with only a few points per county. Also, observing systems are more or less uniformly distributed, particularly where terrain is not an obstacle. As reported in PDT–10, Carbone suggests a different view; he argues for per capita uniformity of service, rather than geographic uniformity of service. The potential for weather-related societal and economic disruption in urban and rural forecast zones would be considered and uniformity could then be based on a comparable minimization of disruptions (Dabberdt et al., 2000). A new approach needs to be considered—one that focuses an increased level of resources and services on where the majority of the people and infrastructure are to be found, the urban areas.

Recommendation: The federal government, led by the National Oceanic and Atmospheric Administration, in concert with multiple public and private partners, should identify the resources needed to provide meteorological services that focus on where people live, beginning with a high-priority urban meteorology initiative to create infrastructure, products, and services tailored to the special needs of cities.

Although NOAA should be the lead agency in such an initiative, its success will require effective partnerships with other federal, state, and local government agencies, academia, and the private sector, as well as with all sectors of the user community, both public and private. Under the leadership of NOAA, a consortium of national and local partners should establish a small number of urban testbeds for the purpose of determining urban user needs for tailored meteorological information and then developing, testing, and evaluating various observing, modeling, and communication strategies for providing those end users with an effective suite of societally relevant and cost-effective products and services to meet those needs. The goal of such testbeds would be to conduct or foster the necessary basic and applied research and then transition the research findings together with the practical lessons learned into operations, and to extend these capabilities, appropriately scaled, to cities across the nation.

WEATHER INFORMATION TO SUPPORT RENEWABLE ENERGY SITING AND PRODUCTION

The Challenge

The production of energy by so-called renewable sources—principally water, biomass, municipal waste, geothermal, wind, and solar—is an integral part of the challenge to reduce reliance on fossil fuels, achieve a meaningful measure of energy independence, and mitigate global warming by anthropogenic carbon dioxide emissions. The U.S. Energy Information Agency (EIA, 2008a) estimates that the maximum electric power consumed domestically today is about 2.1 TW while globally it is 12.5 TW; EIA estimates that by 2030, peak domestic and global power consumption will rise to 2.8 TW and 16.9 TW, respectively, if the mix of power sources does not change. However, if the world switched to renewable sources only, then according to Jacobson and Delucchi (2009), the peak power consumption in 2030 would actually drop to 1.8 TW in the United States and 11.5 TW globally due to the increased efficiencies of direct electric power production and usage.

According to estimates of the Annual Energy Outlook by EIA (2008a, b), U.S. electricity generation in 2010 from all renewables will be a small but important fraction—about 10.7 percent—of total domestic electricity generation. Hydropower represents the largest share (60 percent) of electricity produced domestically from renewable sources, followed by wind (18 percent), biomass (12.4 percent), municipal waste (4.7 percent), and geothermal (4.0 percent). Solar energy presently contributes less than 1 percent of the electricity generated by all renewable resources. EIA estimates that despite the large contributions from these sources today, there will be little growth in electricity generation from hydropower,[16] geothermal, and municipal waste over the next two decades (the extent of the EIA projections). In contrast to other renewable energy sources, electricity production in the United States by both wind and solar is growing rapidly. From 1990 to 2006, wind power production increased at a 14 percent compound growth rate (23 percent from 1997 to 2006) and solar production from on- and off-the-grid sources (e.g., residences and commercial buildings) grew at an estimated 30 percent compound rate from 2000 to 2008. The estimated annual growth rate from 2007 to 2030 is 6.2 percent for wind and 13.3 percent for solar. EIA projects that in 2030, electricity generation from all renewable resources

[16]Hydrokinetic energy production from tides, rivers, and streams is a small contributor today, but the Electric Power Research Institute estimates (Dixon, 2008) that it could produce 13 GW of power by 2025, based on current proposed projects.

will be 14 percent of the total electricity generation from all sources, and that renewable resources will have accounted for 28 percent of the growth of 1 billion kilowatt-hours in projected electricity generation since 2010. And in the same way, wind and solar will contribute more than 24 percent of the growth in generation by all renewable resources.

Compared to fossil fuels, most renewable resources differ in several ways: they cannot be transported to where the power they generate is needed; their energy density is low (and so they must occupy large tracts of land); for many, the fuel is free; and most are weather dependent (directly or indirectly). By the same token, improvements in weather prediction will enable efficiencies in generation or grid operations. Improvements in hydrologic forecasts will lead to some improvements in hydropower production and management, and biomass yields may be increased with more accurate weather predictions. However, in the case of wind and solar generating systems, there are weather dependencies and uncertainties that pose significant challenges to their integration in a production and distribution system that must provide stable, predictable, and reliable electric power. These challenges, in turn, define an emerging set of priorities for weather research and the transition of findings and results into operations, and are the basis for the following discussions.

Wind Energy

Wind energy today provides less than 1 percent of the domestic supply of electricity. At the end of 2007, the United States was ranked second in the world with an installed capacity of 16.8 GW (~18 percent of global total), but wind power generation is growing rapidly (Figure 4.3) in the United States which led the world in new capacity installed in 2007 with 5.2 GW. The Department of Energy (EIA, 2008a) is exploring the feasibility of increasing to 20 percent (300 GW) the total amount of domestic power produced from wind in 2030. Apart from the practical challenges of increasing wind-generating capacity more than 20-fold in 20 years, there is a host of weather-related research and operational challenges that will need to be met in order to ultimately provide power that is reliable and predictable. These challenges pertain to wind turbine design and operation, wind energy exploration and wind plant siting and design, and the long-term challenges of wind resource changes in a changing climate. Like so many of the other weather research and R2O priorities identified throughout this study, those pertaining to wind energy also involve both observations and modeling.

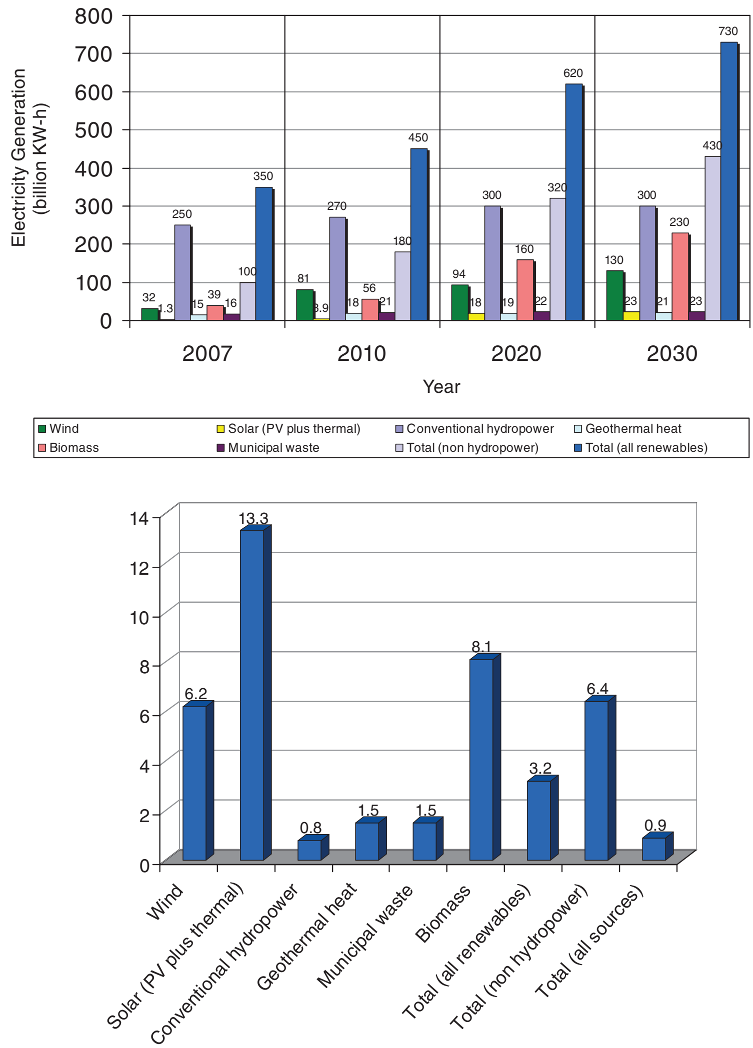

FIGURE 4.3 Estimates of (a) electricity generation from renewable resources and (b) their projected annual average growth rates. Electricity generation from renewable resources represents a small yet significant and rapidly growing fraction of U.S. electricity generation, which totaled 4,200 billion kilowatt-hours in 2010. The estimate of 450 billion kilowatt-hours produced by renewables is 10.7 percent of the total domestic generation in 2010 and increases to 14.0 percent in 2030. Renewables include six disparate resource types, most of which have some weather dependencies. Wind and solar differ from the others in a very important respect; their electricity generation can be highly variable, which in turn places demands on other energy sources to ensure a stable and predictable energy supply. SOURCE: These figures are derived from data contained in the 2009 Annual Energy Outlook produced by the Energy Information Agency (EIA, 2008a,b) and cited in the *America's Energy Future* study report (NRC, 2010).

The newest generation of wind turbines have blades that sweep out an area of up to 126 m in diameter and produce up to 6 MW of power (GWEC, 2009). Most wind turbines typically operate at wind speeds in the range of about 4 to 25 m s^{-1}, although the newer models (Vestas Corp., 2009) are projected to have a threshold speed of about 3 m s^{-1}. Offshore turbines tend to be larger and generate more power (up to 5 to 6 MW) owing to the higher installation and maintenance costs, and the subsequent goal of generating equivalent power with fewer systems. Land-based wind turbines have stabilized in the range of 1.5 to 3 MW, which enables economies of scale in production costs. Modern turbines are able to control their power output by changing the angle of their blades to the wind (pitch control), by turning (yawing) in response to wind direction changes, and operating at variable speed (enabling it to synchronize with the operation of the electric grid). For obvious reasons, wind park revenues are very sensitive to wind speed but the actual sensitivity is enlightening: a difference of 1 m s^{-1} in the annual average wind resource can result in an annual revenue differential of about $1 million for a 200-MW wind park.

The weather-related research and R2O needs of the wind energy industry have recently been discussed and documented by a January 2008 community workshop organized by DOE (2008) and an August 2009 community meeting organized by the American Meteorological Society (AMS, 2010). Each event brought together more than 120 atmospheric scientists and wind energy engineers from the public, private, and academic sectors. This report draws heavily on the recommendations from both events. While the generation and delivery of electric power is the role of the private sector, the challenge of providing secure and sustainable energy is a national priority that involves federal, state, municipal, and regional agencies and the intramural and extramural research efforts that they support. Expanding America's electricity generation capacity using renewable resources is closely linked to our nation's emerging climate change mitigation policy[17] as electricity generation from wind, solar, geothermal, and hydro resources leaves virtually no carbon footprint (notwithstanding the carbon emissions that result from the manufacture of the wind turbines and other renewable energy systems).

[17] For example, the Kerry-Lieberman bill calls for a 17 percent cut in emissions below 2005 levels, by 2020, with the emission limits applying in different ways to power plants, petroleum refiners, and trade-sensitive manufacturers. See http://kerry.senate.gov/imo/media/doc/APAbill3.pdf.

Exploration

Assessing the wind energy resource requires quantifying the distribution of wind speed (and vertical shear) as a function of location, time, and height. At present, the number of surface weather stations in the continental United States (CONUS) that monitor wind is about 30,000, which yields an average of about one station per 100 km^2. Unfortunately, their spatial distribution is heavily biased against the areas that have the greatest wind energy potential. Further, there is very little information on vertical shear—there are only about 125 boundary-layer wind profilers in CONUS (and these are not sited for wind energy assessment) and about 100 radiosonde stations that make twice-daily soundings of winds and state variables (again, these are not well sited for wind exploration). Although not measured widely, wind shear is an important factor in wind turbine design and operation.

Wind Turbine Design

Wind turbines must be designed to operate in a very turbulent wind environment for at least 20 years according to the standards of the International Electrotechnical Commission (IEC). Wind turbines must operate with loads that are the result of their own inertial effects, as well as from the spatial and temporal changes in wind speed, direction, shear, and vorticity. These loads have increased as wind turbines have become larger and because they were being installed at many locations that are intrinsically very turbulent. As discussed by Veers and Butterfield (2001), wind turbine failures have been caused by inaccurate estimation of design loads, which mandated analysis and prediction techniques that yield more detail in the inflow—both in the undisturbed ambient flow and in the wake of upwind turbines.

Detailed structural dynamic models have subsequently been developed that include turbulence models (that simulate the stochastic inflow fields), aerodynamic models (that predict aerodynamic loads from the turbulent inflow), and turbine control algorithms (that control turbine pitch, yaw, and braking actions). These load analyses and predictions are especially challenging as they need to capture not only the "normal" wind and turbulence characteristics of the flow field, but also those resulting from external meteorological conditions (apart from classic surface-layer theory), and terrain effects at a wide range of sites. Especially important are the rare events that can impose extreme loads on the system.

In this way, load predictions need to consider a wide range of atmospheric conditions. Because of their large length, wind turbine blades are exposed to variable stresses throughout a significant fraction of the lowest region of the atmospheric planetary boundary layer (PBL) where wind shear and turbulence are typically most severe. At night when the PBL can be very shallow (50 to 100 m), the lower part of the blades can be exposed to stable conditions with little mechanical turbulence but strong vertical wind shear in both speed and direction. At the same time, the upper reaches of the blades can rotate through (and above) the capping PBL inversion where shear and turbulence can both be significant. The nonhomogeneous nature of the environment in which the turbine operates can place significant mechanical stresses on the turbine blades and gearbox. In addition to the natural stresses from ambient conditions, the wind turbines are exposed to wake turbulence created by neighboring turbines within the wind park. These conditions place demands on the design of the wind turbine that, in turn, requires detailed knowledge of the mean and turbulent flow conditions throughout the wind park that can only be achieved through a combination of representative local observations and numerical modeling.

Obtaining reliable summary data on the role of weather (wind, turbulence, icing, temperature, and lightning) on the failure of wind turbines in general and specific subassemblies is difficult. Often the cause of the failure is not known or is not released for proprietary reasons. But there are some studies that summarize the failure rates (without causal attribution) for wind turbine systems and their various subassemblies. Tavner et al. (2008) provide a valuable overview of the reliability of wind turbine systems based on an analysis of more than 6,000 wind turbines in Denmark and Germany that have been in operation for 11 years. They found failure rates for various subassemblies of 1 MW turbines ranged from about 0.05 to 0.5 failures per turbine subassembly per year. The higher rates occurred with the electrical systems and the rotors (blades and hub) while gearboxes had the lowest failure rate. They also found failure rates increased with turbine size, but that failure rates had decreased over time (Figure 4.4).

Wind Plant Architecture

It has long been known that the longitudinal and lateral spacing of individual wind turbines strongly influences the power generating efficiency of the wind farm. If the wind turbines are placed too close together, there will be a reduction in the output of all downwind turbines due to the wake velocity deficits of the upwind turbines. Placing the turbines too far apart reduces the number of turbines in the wind farm and thus reduces the amount of energy that can be generated per unit area of the wind farm.

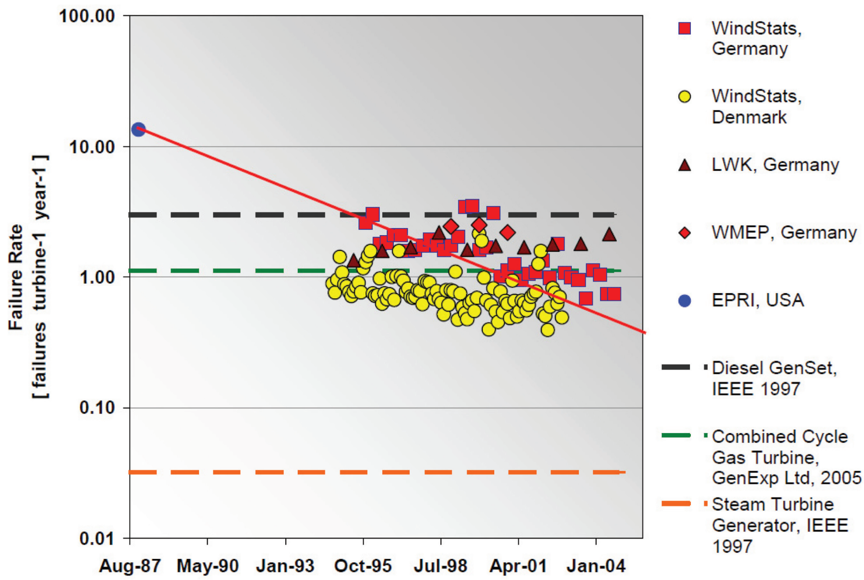

FIGURE 4.4 Wind turbine failure rates (failures per turbine per year), based on an analysis of over 10,000 wind turbines in operation over 15 years. Most of the data come from turbines in Denmark and Germany, although an early data point (1987) comes from the Electric Power Research Institute (EPRI) in the United States. Compared to the 1987 EPRI datum, there has been an order of magnitude improvement in failure rates through 2004. However, the improvement since 1993 is less. Also shown are comparable failure rates for steam turbine generators, which have lower failure rates (around 0.2), combined-cycle gas turbines that have comparable failure rates (~1), and diesel generators that have higher failure rates (~2). SOURCE: Tavner et al. (2007).

Both of these effects negatively influence the cost and efficiency of the wind farm and the power it can generate. Recent studies (e.g., Werle, 2008) have demonstrated that even with the relatively large longitudinal and lateral separation distances of seven turbine-blade diameters, downwind turbines will sometimes deliver only about 65 percent of the power generated by the upwind turbine. Therefore, optimizing the layout of the turbines in a wind farm is critical.

The problem of wind farm configuration is further complicated by the effects of local topography. Often the areas with the highest wind potential are those offshore as well as onshore locations with terrain relief. Both types of sites can present special aerodynamic challenges to the layout of the wind farm. Offshore sites are typically impacted by sea breeze circulations, time-variable surface friction effects, and stable conditions through the lower boundary layer. Wind farms in areas of terrain relief are subject to locally generated mechanical turbulence. In both cases, it is important to also consider the spatial variability of wind and turbulence across the wind park. Such knowledge cannot be gained from ambient wind observations alone, and advanced computational fluid dynamics (CFD) and large-eddy simulation models are needed to locate the wind turbines within the wind farm in order to minimize wake effects from adjacent wind turbines. Models are also instrumental in optimizing the locations of meteorological observing sites, which in turn can provide data assimilated by the models.

Operations

The effective operation of a wind park requires wind forecast information on different timescales and across the spatial domain of the wind park (many of which span hundreds of square kilometers of spatially varying topography). Forecasts on the 0- to 48-hour timescale are important for determining the amount of wind energy that can be provided by the wind park, and also determining how much energy will need to be purchased from conventional fossil energy sources. As wind parks become larger or are aggregated onto the electric grid, their sensitivity to wind variations and to wind-forecast accuracy is lessened to a degree.

On the other hand, wind park operations are very susceptible to so-called wind ramp events, which are abrupt, major changes in wind speed over a relatively short period of time (one simple, quantitative definition refers to a wind power change ≥50 percent over an interval of ≤4 hours). The problem of "wind integration" is a significant operational obstacle facing wind energy production. The term refers to the measures energy system operators must take when winds change rapidly (wind ramp events), causing a sudden increase or decrease in wind power generated by turbines. Electric utility companies usually have a specific generation configuration consisting of a mix of coal, oil, gas, hydro, wind, and nuclear power. When winds pick up, the amount of power generated by the wind turbines increases rapidly, causing excess power to be injected into the generation system. Because the system is not capable of handling endless amounts of power, the utility company must quickly ramp down generation from the wind turbines (some wind turbines are able to have their rotational speed controlled) or ramp down other, conventional sources and route excess electricity to neighboring utilities. In the case when the winds may abruptly decrease, the result is a sudden need to import power and turn gas turbines on quickly, often in minutes. To mitigate the potential for a ramp-up requirement, operating utilities often keep a spinning reserve of gas turbine generators running ready to fill the power gap. This, however, is not an ideal solution because the spinning reserve increases the cost of wind power and can decrease potential carbon savings. There are also costs associated with slowly cycling winds when conventional thermal (coal) units are ramped up and down; in these cases, there are excessive wear-and-tear costs on the thermal units than can be appreciable.

Wind integration costs are difficult to estimate and are not simply the differential between operations with and without wind-generated power (Milligan and Kirby, 2008). In their analysis, they present the example of a system that has sufficient capacity to meet a fast ramp, but in order to meet the ramp, a peaking unit must be utilized. In this case, the baseload unit has an energy price of $10/MWh, but is unable to increase output quickly enough to meet the ramp. A peaking unit is brought online at a price of $90/MWh to meet the ramp. If the marginal unit sets the energy price in a market, the energy price rises during the ramping period because the online base unit is not flexible enough. Had the ramp been sustained during a longer period of time, the base unit could have met the ramp requirement, and the energy price would have remained at $10/MWh. This example points out that ramping can be extracted (at a high price) from the energy market. Further, in a system with significant wind penetration, the ramp scenario can be exacerbated, necessitating even more ramping capability at an even higher price. Milligan and Kirby (2008) further argue that "pooling loads and resources into a larger balancing area holds the promise of allowing additional wind to be integrated into the system at lower cost."

To help mitigate the wind ramp/integration problem, there is a pressing need to develop very short-range NWP and nowcasting methods that can reliably predict wind ramp events on the 30-minute to 6-hour time frame. Providing accurate and reliable, cost-effective forecasts (with equivalently low false alarm rates) of the onset, duration, and magnitude of wind ramp events that are specific to the location of wind farms may be the single most pressing contemporary meteorological need in support of wind power operations.

Need for Improved Meteorological Observations

Meteorological observations—primarily wind and turbulence, but also temperature—are required to aid in wind park assessment, siting, and design and to assess the performance of individual wind turbines. They are also needed to initialize NWP models and for data assimilation models that enhance model performance. They are also required to assess (validate) model performance under different meteorological and topographic regimes. Meteorological observations are also necessary for very short-range prediction (i.e., nowcasting) of wind changes on the 0- to 2-hour timescale. Because of the significant vertical extent of large wind turbines and the effects of wind shear and turbulence, it is essential to have detailed knowledge of the mean and turbulent structure of the PBL (and beyond, in some cases), up to heights of about 0.5 km above the land or water surface. Vertical profiles need to be highly resolved both in space (5- to 10-m height resolution) and time (on the order of 5 minutes).

In some cases, research and development is needed to develop measurement systems that better meet the needs of the wind energy industry. In particular, remote sensing wind profilers—optical or ultrahigh frequency (UHF)—are needed to provide long-term and high-resolution profiles of vector velocities up to 300 to 500 m. They need to be cost-effective as well: affordable, easy to install and maintain, and sufficiently robust to operate unattended for years.

The current state of mesoscale observations is inadequate to support the high-resolution modeling needs of the wind energy industry to predict wind energy at, and within, wind parks. This will require dense arrays of surface observations (both wind and state variables) both for nowcasting and moderately dense arrays for mesoscale NWP modeling, but also remote sensing profilers to adequately characterize wind and turbulence through the PBL. The ability to specify the details of the design of these networks is inadequate, and that also is a research area requiring high priority. The mesoscale observing issues and needs discussed in Chapter 3 would well serve the needs of the wind energy enterprise. There it was recommended that humidity, wind, and diurnal boundary-layer structure profiles are the highest priority for a national mesoscale network, the sites for which need to have a characteristic spacing of approximately 150 km but could vary between 50 and 200 km based on regional considerations. Because the most important timescales for mitigating ramp events is short—less than 1 hour—it can be estimated from Taylor's hypothesis that nowcasting a ramp event with a 15 m s^{-1} wind speed requires wind observations about 55 km upstream, which is consistent with the previous recommendation. The recommended profiler network would, of course, also be invaluable for producing improved NWP predictions of many wind ramp events on longer timescales.

Need for Improved Modeling

A hierarchy of models, each simulating a range of spatial scales, is required to address the various wind-dependent aspects of wind turbine/park design and operation, including the following:

- CFD models are needed to specify turbulence features at, and downwind of, individual turbines and assess the flow interactions among adjacent turbines.
- High-resolution atmospheric (including large eddy simulation) models are needed for the purpose of describing the turbulent flow characteristics and structure of the ambient PBL and interactions with turbulent wakes from individual wind turbines and large arrays of turbines.
- High-resolution mesoscale models (grid resolution of 0.5 to 1.0 km) are required to assess the wind energy potential (for prospecting applications) of regions up to 10^3 km in scale. They are also needed to forecast the wind energy that can be provided by a given wind park—including variations within the park—over forecast periods of 48 to 72 hours. For the latter purpose, ensemble predictions will aid in determining the range of wind power output that can be anticipated, which is useful for assessing the need for alternative power sources. Nowcasting algorithms are needed to provide reliable predictions of very short-range changes in the wind field up to 2 hours.

Need for Improved Collaborations

In spite of the commonalities and feedbacks among research challenges in the four key areas—turbine dynamics, siting and array effects, mesoscale processes, and effects of a changing climate—research in any one area has largely been conducted independent of the research challenges of the other three areas. Enhanced interdisciplinary collaborations among researchers can provide results that are more beneficial, more effective, and timelier. In this way, for example, optimum wind turbine arrays can be designed as a consequence of closer collaboration of fluid dynamicists and mesoscale meteorologists, and improved long-range wind resource planning may result from increased interactions among not only mesoscale and climate researchers but also socioeconomists. In the same way, closer interactions are required among observationalists, experimentalists, modelers, and users. Effort now focused within individual disciplines needs to be augmented by a flatter, more interdisciplinary approach. This applies both to individual researchers and groups as well as to the governmental agencies that support and prioritize the research.

Partnerships are essential in developing the modeling tools needed to design and operate wind parks. There are important complementary roles to be played by the public, private, and academic sectors, and the three sectors need to find effective ways to collaborate.

Solar Energy

Background

Solar power refers to the production of electricity, directly or indirectly, from ambient sunlight. Photovoltaic (PV) systems convert sunlight directly into electricity using arrays of solar cells of various types, such as thin-film, monocrystalline silicon, polycrystalline silicon, and amorphous cells. Arrays of PV panels can provide electricity directly to their hosts (e.g., homes, factories, office buildings, airports) or they can be configured in very large arrays to comprise photovoltaic power stations that provide electricity to the power grid. The Olmedilla Photovoltaic Park in Spain is currently the world's largest PV plant.[18] Built in 2008, the plant has more than 160,000 solar PV panels to generate peak power of 60 MW, which is enough electricity to supply more than 40,000 homes. Concentrated solar power systems produce electricity indirectly by using combinations of mirrors, lenses, and solar trackers to focus sunlight from a large area onto a small area where the concentrated solar energy is used to heat water for use in a conventional thermal power plant. The Solar Energy Generating Systems facility in the Mojave Desert is reported to be the largest solar system in the world, consisting of nine solar power plants that have a combined capacity of 354 MW.[19] Yet, solar energy today only supplies about 0.9 percent of the U.S. domestic energy production from all renewable sources (EIA, 2008b; Figure 4.3a).

The Problem

The availability of electricity from solar energy systems, like that from wind farms, is highly variable in space and time, which poses significant challenges for a power grid that requires stability and predictability. Developers of large solar plants and utilities that utilize distributed PV systems that

[18]See http://www.pvresources.com/en/top50pv.php.
[19]See http://solar.calfinder.com/blog/news/worlds-largest-solar-plant-segs/.

encompass residential and commercial installations have common needs for reliable observations, historical and real-time databases, and accurate forecasts on a variety of scales.

Existing historical, national solar radiation databases are available from the DOE National Renewable Energy Laboratory (NREL, 1995, 2007), the State University of New York at Albany (Perez et al., 2007), and NASA.[20] They are based on in situ measurements from a few tens of surface-based radiometers together with satellite cloud imagery and analytical interpolation algorithms. However, the accuracy of hourly estimates of surface solar irradiance from satellite imagery is only ±20 percent. Additionally, the temporal resolution of 1 hour does not meet user needs for 15-minute data (some users may require temporal resolution as fine as 1 minute); nor is the spatial resolution (≥10 km) of these databases consistent with many user needs for data resolution of 1 km. It is notable, however, that an excellent mesoscale solar and meteorological measurement network and database exists at the Southern Great Plains site of the DOE Atmospheric Radiation Measurement program (Ackerman and Stokes, 2003), which can provide an invaluable resource for testing and evaluating alternative measurement, analysis, and forecasting methods.

Utility operators require solar resource forecasting on several timescales: ≤3 hours for dispatching to enable a steady power supply to the grid; 24 to 72 hours for system operations planning; and seasonal to interannual forecasting for economic analyses and system planning. However, today there does not exist an operational solar insolation forecasting capability that meets user needs.

Needs

The needs of users and the shortcomings of existing measurement networks, solar databases, and forecast models were addressed in a recent AMS community workshop (Weatherhead and Eckman, 2010) and a recent NREL workshop and subsequent extensive needs study (Renné et al., 2008); these findings reflect their conclusions:

- There is a pressing need for high-resolution (15 minutes or less) solar resource data derived from the hourly model results, and/or from additional high-quality measurements. This involves obtaining more reliable site-specific data from extrapolation methods, more spatially refined satellite-

[20] See http://eosweb.larc.nasa.gov/sse/.

derived solar resource estimates, and on-site measurements of downwelling solar radiation (all components) and downwelling infrared radiation.

- Reliable, operational solar forecasting is not available today. Users need 12- to 72-hour solar resource forecasts, as well as very short term (≤3 hours) and seasonal-to-interannual forecasts, for use by system operators in system planning and load-following operations.
- An interactive archive of solar resource information is needed so that developers, utilities, system operators, and system planners can access solar resource information needed for specific analyses and applications.
- Lower-cost solar resource measurements and assessments are needed for key locations (e.g., distributed PV systems).
- Improved satellite datasets are required that encompass improved estimates of aerosols, better detection of snow cover, and higher spatial resolution.

Relationship to Other Weather Research Needs

Improved observations, simulations, and predictions of wind and turbulence and solar radiation are needed with high spatial and temporal resolution and accuracy to optimally locate, design, and operate wind and solar energy facilities. These efforts will require a focused, high-priority national research and R2O program that would be carefully and closely integrated with the observing and predicting initiatives and socioeconomic actions recommended in Chapters 2 and 3 of this report. In this way, previous recommendations pertaining to improved NWP with global nonhydrostatic models (page 58), improved quantitative precipitation estimation and forecasting (page 69), improved hydrologic prediction (page 70), and improved mesoscale observing systems (page 87) will all positively impact the information needs of the renewable energy enterprise as they pertain to electricity generation from wind and solar (but also from hydro resources). By the very nature of these applications, the efforts recommended here need to be a true public–private partnership with significant involvement of academia as well. To be successful, these efforts will require the formation of effective collaborations and partnerships among power system designers, operators, grid managers, observationalistsresearchers, forecasters, and modelers. It is encouraging that the DOE has interacted closely with academia and the private sector, as exemplified by the community workshops the DOE has organized to facilitate improved weather-related support for wind and solar energy production. And NOAA has recently indicated that its Next Generation Strategic Plan (scheduled for release in summer 2010) will explicitly include a focus on support for energy production from renewable resources.[21]

Recommendation: The effective design and operation of wind and solar renewable energy production facilities require the development, evaluation, and implementation of improved and new atmospheric observing and modeling capabilities, and the decision support systems they enable. The federal agencies should prioritize and enhance their development and support of the relevant observing and modeling methods, and facilitate their transfer to the private sector for implementation.

[21] See http://www.ppi.noaa.gov/ngsp.html.

5

Conclusion

The committee was charged with answering questions about the state of U.S. weather research and research-to-operations (R2O) activities and, in so doing, to identify priority needs in each area. In undertaking its task, the committee drew upon the broad range of work that had been reported since 1995 (Table 1.1); convened a workshop in summer 2009 with 50 invited experts in an array of disciplines from the public, private, and academic sectors; and subsequently undertook its own deliberations and examinations to gain insight into research and transitional problems, challenges, needs, and opportunities germane to weather, broadly defined. Eight important areas were identified, each having a certain amount of intrinsic overlap with the others:

- socioeconomics,
- weather modeling and predictability,
- quantitative precipitation estimation and forecasting,
- hydrologic modeling,
- mesoscale observations,
- impacts forecasting,
- urban meteorology, and
- renewable energy production.

Socioeconomic needs were placed first in this report because they cut across all seven other needs, but also because they have been underemphasized, undervalued, and undersupported for too long. Placing socioeconomic needs first was the committee's modest attempt to further emphasize their importance and need of attention. The report next identified four so-called established (or ongoing) research and R2O needs. These are needs that have been recognized for some time as important, with achievable goals, but that have yet to be completed or implemented in practice. The four established needs remain pressing and are high priorities; they are predictability and global nonhydrostatic coupled modeling, quantitative precipitation estimation and forecasting, hydrologic prediction, and mesoscale observations. Finally, three emerging needs were identified. These are research and transitional needs that have come to be recognized or appreciated in the United States over the past 5 to 10 years as increasingly important, but that are only in the early stages of understanding or implementation. They include very high impact weather and impacts forecasting, urban meteorology, and renewable energy production. Socioeconomics could perhaps be considered another emerging need.

In retrospect, there are crosscutting issues that span all eight of the needs areas and the report might as easily have been organized differently. As mentioned, socioeconomics cuts across all areas, but then so do mesoscale observations and modeling—the latter encompassing global, mesoscale weather and hydrology. Lastly, the importance of, and the need for, effective partnerships is intrinsic to all eight areas. In today's science and services environment, partnerships are crucial to the conduct of most research and certainly to the transitioning of research results into operations (as well as transitioning operational needs back to research, or O2R). Partnerships can involve multiple disciplines as well as multiple sectors, and sometimes both. They are necessary because of the inter- and multidisciplinary nature of the science, and also because the task at hand is often simply just too large, too difficult, or too expensive to be undertaken without partners.

Part of the study's statement of task was to assess "what could be done in the short term to reinvigorate agency and interagency planning for weather research and research-to-operations activities in the U.S.?" NRC policy precludes the study from making prescriptive organizational recommendations, but the study's recommendations and findings themselves point to several things that can and should be done to reinvigorate agency and interagency planning. It's clear that an active dialogue needs to be established and maintained that includes stakeholders representing a wide range of disciplines: socioeconomics (broadly defined); atmospheric, environmental, and hydrologic science; measurement and observational science and engineering; urban planning; emergency management; transportation planning; renewable energy production; and more. The stakeholders must come not only from federal, state, and municipal agencies but also from the private sector and academia. An effective mechanism that has worked in the past (albeit with a narrower focus) is for the federal agencies to initiate the dialogue through a community "weather summit" of sorts that would bring the parties together for the purpose of identifying priorities and defining specific actions to establish[1] a cohesive approach to the planning of weather research and R2O. There are several organizations that might be tasked by the federal agencies to bring the parties together and organize such a summit; they include the National Research Council (which organized the 2009 Summit on America's Climate Choices[2] among other such gatherings); the National Oceanographic and Atmospheric Administration (NOAA) Science Advisory Board; NOAA's Office of the Federal Coordinator for Meteorology; and the American Meteorological Society.

In closing, we reiterate that it is crucial that the weather enterprise address these established and emerging issues and vigorously and rigorously undertake the research needed to develop the capacity to deal with them, and then transfer the important research results into operations. This can be started by recognizing that as the world and our nation's challenges have changed, the scientific research priorities and operational priorities need to change as well. As such, this report and its recommendations can provide the beginnings of a framework that is relevant to all parties in the weather enterprise: agency decision makers, policy makers, research scientists, private-sector applications specialists, teachers, public and private user groups and organizations, and the general public.

[1]We have consciously avoided the term "reinvigorate," as called out in the Statement of Task, as that would imply there has been a cohesive and effective approach to the planning of weather research and R2O in the past, which is only partially the case.

[2]Summit on America's Climate Choices, March 30–31, 2009, The National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. (http://americasclimatechoices.org/summit.shtml).

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Appendixes

A

Gaps in Knowledge and Practice for the Next Decade in Urban Meteorology

Grimmond et al. (2009) identified where improvements in Observations, Data, Understanding, Modeling, Tools, and Education are needed to ensure that in the next decade Urban Meteorology supports the development of more sustainable cities. Prioritization is indicated as high (H), medium (M) or low (L). These areas are reproduced below:

OBSERVATIONS

- Need operational **urban meteorological networks** (within and around the city) with optimum balance between resolution and practicability, which include: surface-based instrumentation (soil moisture and air/soil/surface temperature), **vertical profiles** (from within the deep urban canopy layer to the top of the boundary layer) of temperature, humidity, wind, turbulence, radiation, rainfall, air quality (gases and particles, precursors and secondary), reflectivity and refractivity. (H)
- Need observations over and within a larger range of **urban morphologies** to establish universal flow and flux characteristics. Need to ensure that there are long term data sets (rather than short term campaigns) that have wide spatial representativeness. The existing **long term measurement stations** should be preserved. (H)
- Need to measure fluxes of CO_2 using eddy covariance approach combined with isotopic analysis to determine not only the sizes of these fluxes but also to identify emission sources (e.g., background concentration, gasoline combustion, natural gas combustion and respiration) to evaluate the role of cities on the Earth-atmosphere carbon exchange. (H)
- Need to undertake measurement studies to validate quantitative estimates of anthropogenic heat and moisture emissions and improve estimation

techniques at a range of scales starting with the individual building where measurements can close the energy budget on a control volume. (M)

- Need simultaneous measurements of flow properties at various sites and levels to better study coherent structures and intermittent ventilation processes within the roughness sublayer. (M)
- Need to better assess urban surface characteristics (e.g., emissivity to develop methods to correct for thermal anisotropy), and determine fluxes from remote sensing. (M)
- Need to explore the use of new measurement techniques including the use of remote sensing technologies and smaller, more mobile and affordable instruments. (M)

DATA

- Need to meet data requirements to allow translation of research findings into urban/building design tools and guidelines for different climate zones and classes of urban land-use. (H)
- Need to ensure that data are provided in a format that is usable for a broad range of practitioners without compromise to scientific accuracy and integrity. (H)
- Need to ensure metadata to describe instrument, siting, quality assurance and control features and documentation are complete and comparable by creating, and using, a standardized urban protocol. (H)

UNDERSTANDING

- Need to develop methods and frameworks to analyse atmospheric data measured above complex urban surfaces. This includes measurement source areas to ensure representative results and meaningful comparison between sites. (H)
- Need to know more about the outer layer of the urban boundary layer (UBL), i.e., the atmosphere above the internal surface layer (ISL). (H)
- Need to assess for each intervention what scale interventions are needed and possible (e.g., legally, economically, planning, technically, etc.) to make cities more sustainable (e.g., livable, healthy, etc.). (H)
- Need for assessment of human-induced large-scale climate change at the scale of cities to ensure that the signal of climate change is distinguished from the noise of natural variability. (H)
- Need to better understand the coupling of surface and air temperatures. (M)

- Need to examine ventilation and pollutant removal mechanisms (upward and sideward) for 3D street canyons. (M)
- Need to understand if urban canopies are a special class of rough wall or canopy flows and to what extent urban residual surface layer (RSL) turbulence can be described with a possibly modified mixing layer model. (M)
- Need to increase our knowledge on the subsurface heat island. (L)

MODELLING

- Need to evaluate urban land surface schemes in both offline and online mode for a wide range of conditions to ensure that the models are fit for purpose. (H)
- Need to improve **short-range**, high-resolution numerical prediction of weather, air quality, and chemical dispersion in the urban zone through improved modeling of the biogeophysical features of the land surface and consequent exchange of heat, moisture, momentum, and radiation (i.e., the surface energy balance, SEB) with the UBL. (H)
- Need CFD/LES studies of wind and pollutant transport studies in regimes other than skimming flow and with combined effects of wind and buoyancy. (H)
- Need to improve understanding of feedback mechanisms between the urban environmental conditions and human activity. (H)
- Need to incorporate more realistic air pollution chemistry mechanisms (e.g., O_3 titration at urban canopy level) into models. (M)
- Need to further develop multi-scale modeling to allow investigations such as: effect of large-scale atmospheric turbulence on the neighborhood- or even micro-scale turbulence below the canopy levels; interaction between natural and artificial landscapes; to assess street-level comfort, building energy consumption and urban design. (M)
- Need laboratory and CFD/LES studies with structures that more closely resemble cities than earlier idealized, homogenous arrays to inform model development for urban RSL turbulence. (M)
- Need further work on a simple universal **UHI** model for applied users. (L)

TOOLS

- Need to develop tools to allow models to be able to accommodate the wide differences in data availability depending on the application from research to operational situation e.g., in field research studies, extensive wind observations may be available (and detailed building morphology), but for emergency response situations only minimal inputs may be available (e.g., winds from the nearest airport, no 3-D building data). (H)

- Need to develop designs for hot cities which promote shading and ventilation without compromising air quality and natural lighting. (H)
- Need to encourage development of active simulation tools (e.g. www.susdesign.com/tools.php) through community participation (e.g. forums, blogs, wikis). (H)
- Need to develop tools that allow competing and unintended impacts of proposed sustainable design to be assessed (e.g., will urban greening reduce temperatures but increase humidity, resulting in no net increase in comfort levels?) (H)
- Need to develop tools that allow assessment of the best, or ranking of, social, economic and environmental decisions for urban climate management (e.g., urban greening vs. repaving roads and pavements with high(er) albedo vs. low-emissivity materials vs limiting the contribution of anthropogenic heat; investment in expensive multi-functional solutions (e.g., vegetated roofs) vs. cheaper, single benefit solutions such as cool roofs). (H)
- Need to make use of spatial and temporal estimation of transport emissions through vehicle fleet efficiencies and traffic data. (M)
- Need to solve technical challenges such as moisture seepage in vegetated roofs, and hazards to street trees (e.g., pests, new pathologies, soil quality, compaction, drainage, frequent disturbances from utility trenches and excessive paving). (M)
- Need to determine how to link the beneficiaries of urban climate interventions with the costs of implementing them. (M)

EDUCATION

- Need to ensure widespread education of the meteorological community of the needs for planning and managing cities of all sizes in as sustainable a manner as possible. (H)
- Need to encourage communication which crosses traditional scientific discipline and spatial scales (e.g.: http://www.conservationeconomy.net; http://www.sustainable-buildings.org/index.php). (H)
- Need to improve public education and communication of heat/health perception through use of simple language and community access. (H)

- Need for collaboration with stakeholders in the widespread development of heat/health warning systems. (H)
- Need to communicate through conventional publications and to use current (and evolving) electronic media to allow accessibility with depth of content that is up-to date. (M)

B

NCEP Review Executive Summary

Executive Summary of the
2009 Community Review of the
NCEP Office of the Director[1]

Carried Out by the University Corporation for Atmospheric Research

NCEP Review Executive Committee:
Frederick Carr, co-chair
James Kinter, co-chair
Gilbert Brunet
Kelvin Droegemeier
Genene Fisher
Ronald McPherson
Leonard Pietrafesa
Eric Wood

April 2010

[1]This executive summary and the complete report from which it has been extracted are available, together with the detailed individual reviews of the nine NCEP centers, at: http://www.vsp.ucar.edu/events/NCEP_reviews_2009.html.

EXECUTIVE SUMMARY

The University Corporation for Atmospheric Research (UCAR) was requested in November 2008 by the National Centers for Environmental Prediction (NCEP) to facilitate a thorough and thoughtful community review of the nine centers that comprise NCEP, as well as the NCEP Office of the Director. This report summarizes the review of the Office of the Director (OD).

The vision of "NCEP as a whole" being greater than the sum of its parts is being realized but is also a work in progress. NCEP is performing well in its primary mission of providing products and services in support of protecting life and property in a timely manner. Many of its service centers are recognized as world leaders in their particular missions. The interactions between centers are increasing, although improvement is needed in this area. The Review Panel commends the strong leadership of the NCEP Director and his staff members for the significant progress NCEP has made over the past decade. NCEP's mission is unique in the U.S., and has been noted as a "national resource"; as such, it has the opportunity to leverage this leadership and respect to achieve higher goals.

This is a very crucial, perhaps watershed, moment for NCEP in which effective leadership and resources are essential if NCEP is to regain/retain its competitive advantage in the world. Important decisions are imminent on how to lead and resource a large number of key initiatives, possibly in competition with other agencies or even other National Weather Services (NWS) and National Oceanic and Atmospheric Administration (NOAA) programs.

The fundamental challenge within NCEP is that it is under-resourced for its mission. Each center reported that it is providing more services and products, with additional requests in the pipeline, with roughly the same number of personnel since the last review. At the Environmental Modeling Center (EMC) of NCEP, the numerous additional demands for improved or new modeling and data assimilation systems added to an already broad mission has precluded any one system from being considered "world-best."

There is sentiment in the community that EMC is not equipped to fulfill its mission or realize its vision, i.e., it cannot deliver world-leading models with its current structure and broad mission, for which it is under-resourced. The EMC mission should be carefully evaluated and either reduced in scope to align with the resources or the resources should be increased to align with the broad mission. This should be done in combination with a comprehensive plan to initiate partnerships with other modeling groups within

NOAA, other federal agencies and the academic community. The latter is recommended owing to EMC's reputation for being unreceptive to external collaboration, a perception that often (unfairly) characterizes NCEP as a whole. NCEP personnel are correct to note that the research community has a lack of appreciation of the constraints that are imposed by the requirements for timeliness, dependability and accuracy on any operational center. Nevertheless, better understanding and cooperation between operational and research scientists are absolutely essential for NCEP to fully achieve its mission.

For the NOAA numerical weather and climate prediction endeavor to serve the nation adequately and be comparable to those that are the best in the world, NCEP must:

- Create a culture and work environment that attracts an extraordinary cadre of talented scientists skilled in various aspects of numerical weather and climate prediction. This will require innovative personnel policies, a much greater fraction of civil service positions, opportunities for advancement based on scientific and technological contributions, and systematic mechanisms and commitments for ensuring cooperation and collaboration with the national and international modeling communities.
- Deploy computer capabilities that are comparable to or better than those of other major international centers. This will require a substantial increase in computer power and data management and storage facilities.
- Provide adequate human resources to meet the stated operational mission.
- Embrace an entirely new approach to model development and implementation. This will require a substantial effort to focus on creating a single, powerful, flexible, multi-scale atmosphere-ocean-land-surface modeling approach that can be specialized to specific resolutions and time scales. It should be an effort that involves the entire national weather modeling community and engages partners from other agencies, academia, and the private sector.

In addition to taking these steps toward achieving excellence, the Office of the Director should consider the following critical issues:

1. External Advice

The National Centers for Environmental Prediction needs external advice on both scientific aspects of its mission and the further development of its products and services. To enhance its linkage to both the research and private sector communities, NCEP should request from NOAA Headquarters that a science and services advisory board be established.

2. Administrative Workload

The large workload associated with the Office of the Director has grown significantly along with the NCEP mission and budget over the past decade. NCEP requires a Deputy Director who can handle the day to day operations of NCEP as well as many other internally-directed duties, freeing up the Director to think more strategically and forge new collaborations and partnerships within NOAA, the federal government, the US academic community, the private sector and abroad. Also, the vacancy in the position of NCEP Chief Operations Officer should be filled.

3. Future Reviews

In order to preclude large periods of time transpiring before the next set of reviews, NCEP should formalize a periodic review process, to occur every 5–6 years.

These issues are more fully developed in section 5 of this report, and a detailed set of findings and recommendations that address the points above are given in section 6.

C

Acronyms and Abbreviations

3DVar	3-dimensional variational
4DVar	4-dimensional variational
AHPS	Advanced Hydrologic Prediction Service
AMS	American Meteorological Society
ARS	Agricultural Research Service
BASC	Board on Atmospheric Sciences and Climate
CASA	Collaborative Adaptive Sensing of the Atmosphere
CCSM	Community Climate System Model
CFD	computational fluid dynamics
CHI	Communicating Hurricane Information
CHPS	Community Hydrologic Prediction System
CHyMP	Community Hydrologic Modeling Platform
CONUS	contiguous United States
DHM	distributed hydrologic model
DMIP	Distributed Model Intercomparison Project
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ECMWF	European Centre for Medium-Range Weather Forecasts
EIA	U.S. Energy Information Agency
EMC	Environmental Modeling Center
EnKF	ensemble Kalman filter
ENSO	El Niño–Southern Oscillation
EOC	emergency operations center

EPiCC	Environmental Prediction in Canadian Cities
ESRL	Earth Systems Research Laboratory
FAA	Federal Aviation Administration
FIM	finite-volume horizontal transport
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GFS	Global Forecast System
GIS	geographic information system
GPS	Global Positioning System
HMT	Hydrometeorological Testbed
HPC	high-performance computing
HPC	Hydrometeorological Prediction Center
IWRSS	Integrated Water Resources Science and Services
LES	large eddy simulation
MCS	mesoscale convective system
MHEWS	Multi-Hazard Early Warning System
MMS	Modular Modeling System
MSA	metropolitan statistical area
μSA	micropolitan statistical area
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NEXRAD	Next-Generation Radar
NextGen	Next Generation Air Transportation System
NICAM	Nonhydrostatic ICosahedral Atmospheric Model
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NSAB	NOAA Science Advisory Board
NSF	National Science Foundation
NWP	numerical weather prediction
NWS	National Weather Service

O2R	operations to research
OHD	Office of Hydrologic Development
PBL	planetary boundary layer
PDT	Prospectus Development Team
PROBCAST	Probability Forecast Program
PV	photovoltaic
QPE	quantitative precipitation estimation
QPF	quantitative precipitation forecast
R2O	research to operations
RF	radio frequency
RFC	River Forecast Center
SAC-SMA	Sacramento Soil Moisture Accounting
SIP	Societal Impacts Program
SNOTEL	SNOwpack TELemetry
SSWIM	Social Science Woven into Meteorology
TIGGE	THORPEX Interactive Grand Global Ensemble
UCAR	University Corporation for Atmospheric Research
UHF	ultrahigh frequency
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USWRP	U.S. Weather Research Program
VHI	very high impact
VORTEX2	Verification of the Origins of Rotation in Tornadoes Experiment
WAS*IS	Weather and Society*Integrated Studies
WATERS	Water and Environmental Research Systems
WCRP	World Climate Research Program
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting Model
WSR	Weather Service Radar

D

Summer Study Statement of Task

During the 1990s, the federal government supported a number of weather research and research-to-operations planning activities (e.g., the U.S. Weather Research Program; USWRP), to identify key gaps in the understanding and simulation of severe weather of all types and their societal impacts, seeking to accelerate the rate at which weather forecasts were improved. Priorities developed by the USWRP were the starting point for a number of efforts including field campaigns and testbeds. However, these priorities, which were identified in documents published by the USWRP "Prospectus Development Teams" (PDTs), were developed more than a decade ago.

This study will explore the status of weather research and the research-to-operations activities at the federal level. It will discuss whether USWRP priorities remain relevant and how they might evolve to better meet current interagency needs. The goal is not to critique USWRP documents written more than a decade ago or to provide a formal review of current planning documents, but rather to identify emerging agency priorities and opportunities for interagency collaboration. Using the PDTs and briefings on current agency activities as a starting point, the questions to be addressed include:

1. What has been achieved?
2. What has not been achieved?
3. What is no longer relevant?
4. What current issues were not anticipated when the PDTs were written (e.g., extreme weather in the context of climate change)?
5. What could be done in the short term to reinvigorate agency and interagency planning for weather research and research-to-operations activities in the United States?

E

Agenda for the 2009 BASC Summer Study Workshop

Board on Atmospheric Sciences and Climate
Committee on Progress and Priorities of U.S. Weather Research and Research-to-Operations Activities
Summer 2009 Community Workshop

Workshop Agenda
July 21–22, 2009

National Academies Jonsson Center
314 Quissett
Woods Hole, MA 02543

Workshop Goals

The past decade and a half has engendered a number of insightful community reports addressing the state of the U.S. weather research and operations enterprise. These reports have described numerous opportunities and provided recommendations for improvements in observations, physical understanding, prediction, socioeconomic impacts, communications, and inter-institutional interaction and collaboration. The goals of the workshop are to undertake a high-level evaluation and assessment of the progress that has been made to date in these areas, identify emerging requirements that were not previously recognized, and provide priority recommendations for new or increased emphasis.

Tuesday July 21, 2009

OPEN SESSION: 8:00 a.m. – 5:30 p.m.: Carriage House

MORNING SESSION—Invited presentations: agency perspectives, summaries, and plans for weather research and research-to-operations activities

8:00 a.m. Welcome, Introduction, Purpose of Workshop

Walt Dabberdt, Chair
Chris Elfring, BASC Director
Susan Avery, WHOI President and Director

8:30 a.m.	NSF	Steve Nelson National Science Foundation
8:50 a.m.	NOAA National Weather Service	Don Berchoff, Director Office of Science and Technology
9:10 a.m.	OFCM	Sam Williamson, Federal Coordinator for Meteorology
9:30 a.m.	NASA	Lucia Tsaoussi, Deputy Director Research & Analysis Program, Earth-Sun System Division
9:50 a.m.	DoD	RADM David Titley, Oceanographer of the Navy and Head, Naval Oceanography and Meteorology Command
10:10 a.m.	*Break*	
10:40 a.m.	A Retrospective Assessment of the (Extramural) USWRP	Rit Carbone, Science Advisor, NCAR
11:00 a.m.	Weather Science and Applications from the Decadal Survey	Rick Anthes, President UCAR
11:20 a.m.	International Perspective	Mel Shapiro, University of Colorado
11:40 a.m.	Weather Research and Operations: Challenges	Cliff Mass, University of Washington
Noon	*Continued Discussion of Weather Research Challenges Over* ***LUNCH*** *in the Main House*	

AFTERNOON SESSION—The afternoon session will consist of five panel discussions in topical areas corresponding to the five Day-2 working group themes. Each panel will be composed of three invited workshop participants. ***Session Moderators:*** *Curtis Marshall and Toby Warden*

1:00 p.m. Socioeconomic Impacts

- Bill Hooke, American Meteorological Society
- Robert Meyer, University of Pennsylvania
- Rebecca Morss, NCAR

1:45 p.m. Observations/Data Assimilation/Model Development

- Chris Davis, NCAR
- Dave McLaughlin, University of Massachusetts
- Xubin Zeng, University of Arizona

2:30 p.m. Very High Impact Weather
- Shuyi Chen, University of Miami
- Greg Forbes, The Weather Channel
- Frank Marks, AOML Hurricane Research Division

3:15 p.m. *Break*

3:45 p.m. Quantitative Precipitation and Hydrologic Predictions
- Rit Carbone, NCAR
- Efi Foufoula-Georgiou, University of Minnesota
- Matt Parker, North Carolina State University

4:30 p.m. The Unique Challenges of Topography and Urbanization
- Petra Klein, University of Oklahoma
- Ron Smith, Yale University
- John Snow, University of Oklahoma

5:15 p.m. Working Groups: Meet Briefly for Introductions and Discussion

5:30 p.m. *Continued Discussion of Working Group Tasks over* ***DINNER****:*
Main House/Grounds

Wednesday, July 22, 2009

OPEN SESSION: 8:00 a.m. – 5:00 p.m.: Carriage House

8:00 a.m. Completing Your NRC Travel Expense Report
Rita Gaskins,
Administrative Coordinator

8:05 a.m. Brief Description of Day's Events
- Chair gives the charge to the Working Groups
- Review of "Working Document"
- Participants raise questions about the process

8:20 a.m. Provocateurs issue challenge to working groups (5 minutes each)
- Socioeconomic: Gene Takle, Iowa State University
- Observations/Data Assimilation/Model Development: Isaac Held, GFDL
- Very High Impact Weather: Rick Anthes, UCAR

- Quantitative Precipitation and Hydro Predictions: Cliff Mass, University of Washington
- Topography and Urbanization: Len Pietrafesa, North Carolina State University

8:45 a.m. Working Groups Convene to Address Their Charge. Breakout Rooms TBA

Noon *Working Groups continue discussion over **LUNCH** in the Main House*

1:00 p.m. Plenary: All Participants Reconvene in the Carriage House

- Working Group Co-Leaders present their "findings" (~15 min each).
- Provocateurs challenge or reinforce the findings

2:45 p.m. General Discussion

- Where do we go now?
- Lessons learned
- Reflections on key issues/questions
- Next steps in the Committee's report/study process

3:30 *Break*

3:45 p.m. Working Groups Reconvene

- Refine their findings
- Complete materials ("working document")
- Make plans to complete any further input to Study Committee

5:00 p.m. *Workshop Adjourns*

F

Workshop Participants

Rick Anthes, *UCAR*
Don Berchoff, *University of Arizona*
Howie Bluestein, *University of Oklahoma*
Laura Bond, *Navy*
Antonio Busalacchi, *University of Maryland*
Paula Davidson, *NOAA/NWS*
Chris Davis, *NCAR*
Jim Doyle, *Los Alamos National Laboratory*
Tim Dye, *Sonoma Technologies*
Pamela Emch, *Northrup Grumman*
John Gaynor, *NOAA/OAR*
Isaac Held, *Princeton University*
Bill Hooke, *American Meteorological Society*
Petra Klein, *University of Oklahoma*
Heather Lazrus, *University of Oklahoma*
Jeff Lazo, *UCAR*
Sandra Knight, *NOAA/OAR*
Frank Marks, *NOAA/OAR*
Clifford Mass, *University of Washington*
Tim McClung, *NOAA/NWS*
Dave McLaughlin, *University of Massachusetts*
Robert Meyer, *University of Pennsylvania*
Steve Nelson, *NSF*
Steve Nesbitt, *University of Illinois*
Matt Parker, *North Carolina State University*
Roger Pierce, *NOAA/OAR*
Len Pietrafesa, *North Carolina State University*
Brenda Philips, *University of Massachusetts*
Yvette Richardson, *Pennsylvania State University*

Pedro Restrepo, *NOAA/NWS*
Mel Shapiro, *UCAR*
Ron Smith, *Yale University*
Soroosh Sorooshian, *UC Irvine*
Gene Takle, *Iowa State University*
David Titley, *United States Navy*
Jeff Trapp, *Purdue University*
Lucia Tsaoussi, *NASA*
Morris Weisman, *NCAR*
Bob Weller, *Woods Hole Oceanographic Institute*
Sam Williamson, *OFCM*
Hugh Willoughby, *Florida International University*
Ming Xue, *University of Oklahoma*
Dusan Zmic, *NOAA/OAR*

Committee

Walter Dabberdt, *Chair, Vaisala*
Rit Carbone, *NCAR*
Shuyi Chen, *University of Miami*
Greg Forbes, *The Weather Channel*
Efi Foufoula-Georgiou, *University of Minnesota*
Rebecca Morss, *NCAR*
John Snow, *University of Oklahoma*
Xubin Zeng, *University of Arizona*

Staff

Chris Elfring
Toby Warden
Rita Gaskins
Laurie Geller
Curtis Marshall
Martha McConnell
Lauren Brown

G

Biographical Sketches of Committee Members and Staff

Walter F. Dabberdt (*Chair*), Walter F. Dabberdt received a B.S. degree (marine transportation and meteorology) from the State University of New York Maritime College and M.S. and Ph.D. degrees (meteorology) from the University of Wisconsin–Madison. He went on to conduct meteorological and air quality research for 15 years at Stanford Research Institute as a senior research meteorologist, followed by 15 years at the National Center for Atmospheric Research (NCAR) as scientist, facility manager, and associate director. For the past 10 years, he has been director of strategic research and chief science officer for the Vaisala Group. Dabberdt was awarded a postdoctoral fellowship from the National Research Council (NRC) and later a research fellowship from the Alexander von Humboldt Foundation in Germany. His professional interests and experience include terrestrial observing systems; boundary-layer and mesoscale meteorology, air quality, and urban-scale meteorology and dispersion. He has served on numerous national and international panels and committees, and currently serves as a member of the National Academy of Sciences' Board on Atmospheric Sciences and Climate (BASC); board chair of the Environmental Prediction in Canadian Cities (EPiCC) research program; chair of the Industrial Advisory Board of the multiuniversity Collaborative and Adaptive Sensing of the Atmosphere Engineering Research Center; chair of the NCAR Earth Observing Laboratory's External Advisory Committee; member of the International Science Steering Committee for the World Meteorological Organization GAW Urban Research Meteorology and Environment Shanghai Air Quality Forecasting Program; and co-chair of the National Oceanic and Armospheric Administration (NOAA) Science Advisory Board Environmental Information Services Working Group. Dabberdt is a fellow and past president (2008) of the American Meteorological Society and is a fellow of the Royal Meteorological Society. He was also recognized as a lifetime national associate of NRC.

Richard (Rit) E. Carbone is a senior scientist and science advisor for the Earth Observing Laboratory at the National Center for Atmospheric Research in Boulder, Colorado. He has authored more than 100 scholarly works. A pioneer in Doppler radar, he has published on physical processes in clouds and storms, topographically influenced circulations, predictability of warm-season rainfall, convection on tropical islands, and severe storms. Mr. Carbone led the U.S. Weather Research Program until 1999. He founded and chaired the World Meteorological Organization's World Weather Research Programme (Geneva) from 1996 to 2001 and served as vice president for the International Association for Meteorology and Atmospheric Sciences of the International Union of Geodesy & Geophysics. He earned an S.M. (atmospheric physics, 1969) at the University of Chicago and was elected a fellow of the American Meteorological Society in 1994. Among other honors, in 2001, Mr. Carbone received the Cleveland Abbe Award for Distinguished Service to Atmospheric Science by an Individual. He was cited for "building consensus in the weather research community on problems of major national and international importance, and for fostering the conduct of collaborative and coordinated weather research." He is also the recipient of the NCAR Publication Prize in 2002 "Inferences of predictability associated with warm season precipitation episodes."

Shuyi S. Chen is a professor of meteorology and physical oceanography at the Rosenstiel School of Marine and Atmospheric Science (RSMAS) of the University of Miami. Professor Chen is a widely published author whose research interests include mesoscale and tropical meteorology, air–sea interactions, high-resolution coupled atmosphere–wave–ocean modeling of tropical cyclones, and numerical weather prediction. She served as an editor for *Weather and Forecasting* journal of the American Meteorological Society. Professor Chen leads a research group at RSMAS/UM that has developed a high-resolution, fully coupled atmosphere–wave–ocean, vortex-following, nested-grids model for hurricane research and prediction. These efforts contribute directly to the development of the next-generation hurricane forecasting models. Professor Chen is a lead scientist for the Coupled Boundary Layer Air-Sea Transfer (CBLAST)-Hurricane modeling team sponsored by the Office of Naval Research. She is also a lead principal investigator for the National Science Foundation–funded Hurricane Rainbands and Intensity Change Experiment (RAINEX) that used three Doppler radar aircraft to collect unprecedented in situ data in hurricanes Katrina, Rita, and Ophelia during the 2005 hurricane season. Currently she is a lead scientist for one of the largest international programs to study the tropical cyclones in the

West Pacific. Her research has received broad national and international recognition. She was invited by the National Academy of Engineering to be a keynote speaker at the Indo-U.S. Frontiers Symposium in 2006 and recently was a keynote speaker at the First U.S.-China Symposium on Meteorology in 2008. In 2006, Professor Chen was awarded the NASA Group Achievement Award. Professor Chen served on a panel of experts for the Congressional Briefing on the National Hurricane Initiative at the U.S. House and Senate in July 2007. She testified as a witness at the Joint Hearing on the State of Hurricane Research and the National Hurricane Research Initiative Act of 2007, before the Subcommittee on Energy and Environment and the Subcommittee on Research and Science Education, Committee on Science and Technology of United States House of Representatives on June 26, 2008. Dr. Chen received her Ph.D. in meteorology from Pennsylvania State University in 1990.

Gregory S. Forbes is a severe weather expert for The Weather Channel, Inc. Dr. Forbes deals with dangerous thunderstorm weather hazards such as tornadoes, damaging winds, hail, floods, and lightning. He received his Ph.D. at the University of Chicago, where he studied tornadoes and severe thunderstorms under Prof. T. Theodore Fujita—world famous for his invention of the F-scale used to rate tornadoes and for his discovery of intense thunderstorm downdrafts called microbursts. Dr. Forbes served as field manager for Project NIMROD, the first measurement program to study damaging thunderstorm winds from downbursts and microbursts. He then joined the faculty in the Department of Meteorology at Pennsylvania State University in 1978, where as assistant and then associate professor he taught courses in weather analysis and forecasting, natural disasters, and other topics until joining The Weather Channel, Inc., in June 1999. Dr. Forbes has had a variety of experiences outside the classroom, including surveying the damage paths left by about 300 tornadoes and windstorms, among them Hurricane Andrew and Typhoon Paka. He has done collaborative research and consulting with the National Weather Service in the United States and with the national weather services in South Africa, Spain, and the Netherlands. He spent three summers performing studies to improve lightning forecasting at the Kennedy Space Center. He has written numerous papers on tornadoes, severe thunderstorms, and other meteorological topics and has co-authored and co-edited two books: *Natural and Technological Disasters* and *Images in Weather Forecasting*, the latter of which deals with the use of satellite and radar imagery in weather forecasting. He is a fellow of the American Meteorological Society, a member of the Board on Atmospheric Sciences and Climate of the National Academy of Sciences, on the International

Editorial Board of the *International Journal of Meteorology;* on the Board of Directors of StruckByLightning.org.

Efi Foufoula-Georgiou is a University of Minnesota McKnight Distinguished Professor in the Department of Civil Engineering and the Joseph T. and Rose S. Ling Chair in Environmental Engineering. She is director of a National Science Foundation (NSF) Science and Technology Center—National Center for Earth-Surface Dynamics—and has served as director of St. Anthony Falls Laboratory at the University of Minnesota. She received a diploma in civil engineering from the National Technical University of Athens, Greece, and an M.S. and Ph.D. (1985) in environmental engineering from the University of Florida. Her area of research is hydrology and geomorphology, with special interest in scaling theories, multiscale dynamics, and space-time modeling of precipitation and landforms. She has served as associate editor of *Water Resources Research,* the *Journal of Geophysical Research, Advances in Water Resources, Hydrologic and Earth System Sciences*, and as editor of the *Journal of Hydrometeorology*. She has also served on many national and international advisory boards including the Water Science and Technology Board, NSF, National Aeronautics and Space Administration (NASA), and European Union advisory panels, and in several NRC studies. She has also served as the chair of the Board of Directors for CUAHSI (Consortium of Universities for the Advancement of Hydrologic Sciences), a member of the Board of Trustees of UCAR (University Corporation for Atmospheric Research), and a member of the Advisory Council of the GEO directorate of NSF. Professor Foufoula has been the recipient of the John Dalton Medal of the European Geophysical Society and the American Geophysical Union (AGU) Hydrologic Sciences Award. She is a fellow of the AGU and the American Meteorological Society, and a member of the European Academy of Sciences.

Rebecca E. Morss is a Scientist III at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, with appointments in the Mesoscale and Microscale Meteorology Division and the Integrated Science Program. She studies meteorological, socioeconomic, and public policy aspects of weather forecasts, floods, hurricanes, and related topics. Her recent research includes studies of the use of weather and climate information in decision making, meteorological and oceanographic observing network design, scale interactions in atmospheric predictability, and communication of uncertainty in weather forecasts. Through disciplinary and interdisciplinary work, she aims to integrate atmospheric science, socioeconomic, and policy perspectives to provide information for the benefit of society. Dr. Morss led the initial development of the socioeconomic component of the international THORPEX program under the auspices of the World Meteorological Organization. She is also a founding member of NCAR's Collaborative Program on the Societal Impacts and Economic Benefits of Weather Information and the Weather and Society*Integrated Studies program. Among other activities, she currently serves on the NOAA Science Advisory Board Environmental Information Services Working Group, and in 2008 she was elected to the Council of the American Meteorological Society. She received a B.A. from the University of Chicago and a Ph.D. in atmospheric science from the Massachusetts Institute of Technology.

John T. Snow is Regents' Professor of Meteorology, dean of the College of Atmospheric and Geographic Sciences, and administrator of the National Weather Center. Dr. Snow's current professional interest is in earth system science, the integration of the best available knowledge from the earth and life sciences to provide a holistic picture of how the world works. His primary research area for many years has been in the dynamics of columnar vortices, ranging in scale from small dust devils to tornadoes. Dr. Snow's second area of research is in meteorological and environmental measurements. He has published widely in these and related areas, and made numerous presentations at professional and scientific meetings. Dr. Snow is a fellow of both the American Meteorological Society and the Royal Meteorological Society of the United Kingdom. He is a certified consulting meteorologist. He recently finished serving on the NOAA Science Advisory Board.

Xubin Zeng is a professor of atmospheric science (since 2004) and director of the Climate Dynamics and Hydrometeorology Center (since 2008) at the University of Arizona in Tucson. Zeng's research in the past 20 years, through over 100 peer-reviewed publications, has covered atmospheric turbulence (theory, parameterization, its interaction with clouds and radiation, and large-eddy simulations), mesoscale modeling of atmospheric flow over complex terrain, chaos theory and its applications to the atmosphere, global land–atmosphere interactions, ocean–atmosphere interactions, sea ice–atmosphere interactions, monsoon dynamics, remote sensing, and most recently, nonlinear dynamics of vegetation. In the past 10 years, he has focused on the land–atmosphere–ocean–sea-ice interface processes of the Earth's climate system by integrating global modeling with remote sensing and in situ data. He has acted as a bridge linking the remote sensing and field experiment community to the weather and climate modeling community. He has given over 70 invited talks at conferences and institutions. His research products (including models, algorithms, and value-added datasets) have been used worldwide by numerous groups (including NCAR, the National Centers for Environmental Prediction, the European Centre for Medium-Range Weather Forecasts). He recently served on the NASA Earth Science Senior Review Panel and the NRC Committee on the NOAA Data Archive and Access. Currently he serves on the Council (governing body) of the American Meteorological Society, the National Academies Board on Atmospheric Sciences and Climate (BASC), and International CLIVAR Asian-Australian Monsoon Panel. He is also the editor of *Advances in Atmospheric Sciences* and co-chairs the Scientific Steering Committee, State Key Laboratory of Atmospheric Boundary Layer Physics and Chemistry, Chinese Academy of Sciences. Zeng earned his Ph.D. in atmospheric sciences from Colorado State University in 1992.

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Curtis H. Marshall is currently the National Mesonet Program manager at the National Weather Service. Prior to his position at the NWS, Curtis was a senior program officer with BASC. He received B.S. (1995) and M.S. (1998) degrees in meteorology from the University of Oklahoma, and a Ph.D. (2004) in atmospheric science from Colorado State University. His doctoral research, which examined the impact of anthropogenic land-use change on the mesoscale climate of the Florida peninsula, was featured in *Nature* and *The New York Times*. Prior to joining the staff of BASC in 2006, he was employed as a research scientist at NOAA. As a BASC program officer, he directed peer reviews for the U.S. Climate Change Science Program and staffed studies on mesoscale meteorological observing systems, weather radar, the NPOESS spacecraft, and the impacts of climate change on human health.

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Maggie Walser is a program officer with BASC. Prior to joining the NRC, she was the AGU/AAAS Congressional Science and Engineering Fellow, working with the majority staff of the Senate Committee on Energy and

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Lauren Brown is a research associate and former Mirzayan Science and Technology Policy Fellow with the Polar Research Board and BASC. She is completing her M.S. degree in marine studies with a concentration in physical ocean science and engineering at the University of Delaware. Her research involves the analysis of tidal currents, velocity structure, and ocean physics off the coast of northwestern Greenland to determine their influence on the larger regional dynamics. She holds a B.A. from the University of Delaware in physics and astronomy. She is especially interested in high-latitude policy issues and the role of the polar regions in global climate change.

JaNeise Sturdivant is a program assistant for BASC. Since joining BASC in 2009, she has worked on studies and workshops involving greenhouse gas emissions, climate choices, and weather studies. Ms. Sturdivant is interested in communications.