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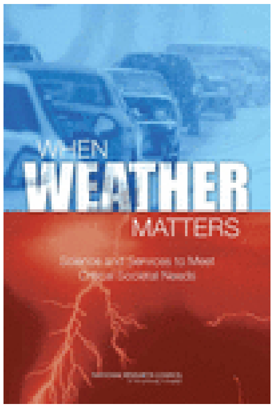

When Weather Matters: Science and Service to Meet Critical Societal Needs

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

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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 achieved by other nations and failed to realize its prediction potential; as a result, the nation is not mitigating weather impacts to the extent possible. This book 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. The book puts forth the committee's judgment on the most pressing high level, weather-focused research challenges and research to operations needs, and makes corresponding recommendations. The book addresses issues including observations, global non-hydrostatic coupled modeling, data assimilation, probabilistic forecasting, and quantitative precipitation and hydrologic forecasting. The book also identifies three important, emerging issues--predictions of very high impact 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--while increasing--has been undervalued and underemphasized in the past and warrants greater recognition and priority today.

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-

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[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 assimi-

lation 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

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[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.**
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> 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.
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> 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.**
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> 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

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[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

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[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.

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

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[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:

RONI AVISSAR, Duke University, Durham, North Carolina
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RUSS SCHUMACHER, Texas A&M University, College Station
SOROOSH SOROOSHIAN, University of California, Irvine
ISTVAN SZUNYOGH, Texas A&M University, College Station

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.

Contents

APPENDIXES