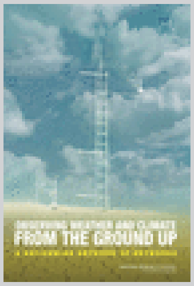

Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks

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FROM THE GROUND UP

A NATIONWIDE NETWORK OF NETWORKS

Committee on Developing Mesoscale Meteorological
Observational Capabilities to Meet Multiple National Needs

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

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Preface

It is well known that the provision of weather and climate information is no longer the sole province of government. Weather information and services now cut a broad swath through the various public and private sectors and have diverse missions and a multitude of applications.

The breadth of this enterprise is increasingly apparent with respect to observations. The advent of inexpensive digital electronics and high bandwidth communications has lowered the barriers to investment in atmospheric observation, especially near the land surface. Literally thousands of organizations including small businesses, Fortune 500 corporations, state agencies, local water management and flood districts, urban air quality authorities, agricultural producers and service providers, and recreation providers, have entered the field of mesoscale observation to further particular interests associated with their mission. These observational assets are clearly market driven and span a wide dynamic range of investment.

Thousands of hobbyists and weather enthusiasts have made sizeable personal investments in meteorological station observations, sometimes of professional quality, and often of considerable utility. They enthusiastically seek to share such information through voluntary networks at local, regional, and national scales. This grass roots participation is further expanded by popular school networks nationwide, numbering in the hundreds, and often financed by local television stations.

Despite this widespread participation, all is not well with atmospheric and related environmental observations, especially in relation to costly infrastructure associated with observations above the atmospheric surface layer, and related data integration, assimilation, and access services. The agency sponsors[1] of this study recognize numerous national vulnerabilities, unmet needs related to their missions, and the impetus to join forces in search of efficient, effective, and affordable solutions. In view of these concerns and aspirations, the Committee was charged to develop an overarching vision for an integrated, flexible, adaptive, and multi-purpose mesoscale meteorological observation network; and to identify specific steps to help to develop a network that meets multiple national needs in a cost-effective manner (see Appendix D for full Statement of Task). The Committee that produced this study (see Appendix E for committee member biographies) represents a broad cross-section of perspectives on the development and application of mesoscale observations and includes a range of public, academic, and private-sector interests. The scientific and technical expertise of the Committee includes operational meteorology and weather forecasting, climate science, air quality observations and modeling, hydrology, agricultural meteorology, coastal meteorology, transportation meteorology, satellite observations, and the human dimensions of the applications of environmental observations. Drawing upon this expertise and consistent with its charge, the Committee has produced a report that (1) broadly summarizes existing mesoscale observational assets, (2) evaluates overall adequacy and suitability to serve some major applications, (3) identifies directions for the way forward to achieve improved capabilities in a cost-effective manner, and (4) considers innovative organization and business model options to enable and to sustain the enterprise toward that end.

In order to address its charge, the Committee assigned itself three tasks. The first was to explicitly consider the role of a U.S. mesoscale observing network in the broader context of weather, climate, and Earth system observations, including the Global Earth Observing System of Systems (GEOSS). Global scale observations are often best conducted from space as reported in the National Research Council (NRC) study "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," hereinafter referred to as the "Decadal Survey." The Committee has explicitly factored an assumed role of space-based observations into the surface-based plans presented herein, seeking to minimize redundancy and to maximize both effectiveness and efficiency of the whole observing system.

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[1] This study was sponsored by the Departments of Commerce (DOC), Transportation (DOT), Homeland Security (DHS), the Environmental Protection Agency (EPA), and the National Aeronautics and Space Administration (NASA).

Secondly, the challenge at hand is broader than meteorological observations per se. While the preponderance of observations in this study are atmospheric, others are not. These other observations involve properties of the land or water surface, or otherwise non-meteorological variables (e.g., constituents that are toxic or otherwise significant in pollution, climate, and global change applications). It follows that the report, while heavily emphasizing mesoscale meteorological requirements, also includes, as appropriate, many ancillary observations that affect or characterize the state of the lower troposphere.

Thirdly, while not commonly referred to as "applications," the utility of a national mesoscale network to research in the geosciences and biogeosciences can be substantial and is therefore considered an important element of the observing system. In many instances, prospective research findings have been and will continue to be pivotal to improvement in services provided by the sponsoring agencies of this study. Furthermore, in the case of the National Science Foundation, we note the National Ecological Observing Network (NEON) as one prominent example among several, where research-motivated observations may immediately contribute to practical applications in the public and private sectors.

In the course of executing our charge, the Committee consulted many individuals and organizations spanning the gamut of public and private interests. We have examined the recommendations and findings of recent NRC studies, such as Fair Weather (2003) and Earth Science and Applications from Space (2007) and others. Meetings were held in the District of Columbia, where agency briefings were emphasized; Boulder, Colorado, where both research and private sector relationships were explored; Norman, Oklahoma, home of the "gold standard" for statewide mesoscale surface networks; and Irvine, California, where we formulated our recommendations. Additional information was obtained from the literature, websites linking to databases, and a recent survey of observing systems, which was conducted under the auspices of the National Science Foundation, Atmospheric Sciences Division. The Committee would like to acknowledge the many individuals who briefed it, provided written information in the form of letters or other technical information. They include David Andrus, Rick Anthes, Albert Ashwood, Walter Bach, Randy Baker, Stan Changnon, Ken Crawford, Andy Detwiler, Paul Dirmeyer, Tim Dye, Robert Dumont, Frank Eden, Gary Foley, Mike Getchell, John Grundmann, Jack Hayes, Dave Helms, W. Hernandez, Rick Hooper, John Horel, Ed Johnson, Nick Keener, Scott Loeher, Teresa Lustig, Don Lynch, Greg Mandt, Cliff Mass, John McGinley, Dave McLaughlin, Phil Pasteris, Paul Pisano, Putnam Reiter, Dave Reynolds, Art Schantz, Dave Schimel, Victor Schisler, Ronnie Warren, Mark Weadon, and Y. Zhang. Our sincerest thanks are extended to

Study Directors Ian Kraucunas and his capable successor Curtis Marshall, and Senior Program Assistant Rob Greenway for their steadfast support and encouragement.

Richard E. Carbone, *Chair*
Committee on Developing Mesoscale
Meteorological Observational Capabilities
to Meet Multiple National Needs

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:

Richard Anthes, University Corporation for Atmospheric Research
Kenneth C. Crawford, University of Oklahoma
George L. Frederick, Vaisala, Inc. (Retired)
Richard M. Goody, Harvard University (Emeritus)
Bruce B. Hicks, MetCorps
John D. Horel, University of Utah
Irving Leveson, Leveson Consulting
Vijay Manghnani, ACE USA
Timothy Matuszewski, United Airlines
Leon F. Osborne, Jr., University of North Dakota
Roger Pielke, Jr., University of Colorado, Boulder
Maria A. Pirone, Atmosphere and Environmental Research, Inc.
Yvette P. Richardson, Pennsylvania State University

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before its release. Louis J. Lanzerotti, New Jersey Institute of Technology, and John A. Armstrong, IBM Corporation (retired), oversaw the review of this report. Appointed by the NRC, they were 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 panel and the NRC.

Contents

APPENDIXES

Summary

Meteorological observations at the mesoscale (see Box S.1) play a vital role in promoting the health, safety, and economic well-being of our nation. Mesoscale observations capture atmospheric phenomena such as thunderstorms, squall lines, fronts, and precipitation bands at horizontal scales ranging in size from the area of a small city up to the size of a state such as Iowa. The data support such services as weather and air quality forecasting, as well as decisionmaking in many sectors including transportation, agriculture, and homeland security.

Although the federal role in weather and climate information services is pivotal, a number of state and local governments, universities, and private-sector interests have developed and deployed dense networks of meteorological observing systems, known as "mesonets." The advent of inexpensive digital electronics and high bandwidth communications lowered barriers to investment and enabled literally thousands of small businesses, Fortune 500 corporations, agricultural producers, recreation providers, and many others to enter the field of mesoscale observations, driven by a wide range of missions and markets at various investment levels.

Despite this widespread participation, all is not well with atmospheric and related environmental observations. The current U.S. enterprise has a solid synoptic scale core (observations of atmospheric phenomenon on a national scale), but its mesoscale observational capabilities are highly variable in quantity, quality, accessibility, instrument set, site selection, and metadata. The U.S. national radar network remains the best in the world, but not by much, and it has some significant deficiencies. The vertical com-

BOX S.1
The Meaning of Mesoscale

The term mesoscale derives from the Greek *meso*, which translates approximately to *intermediate* in English. In meteorology, this term refers to weather phenomena occurring at horizontal sizes that range from the size of a small city to that of an average Midwestern state (e.g., Iowa). 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.

The Glossary notes that from a physical or dynamical perspective, the horizontal extent of mesoscale features ends just short of where the Earth's rotation exerts a significant influence on air motions. Beyond that are macro- ("large") scale features, including *synoptic* features. Synoptic Meteorology, whose name derives from the Greek *sunoptikos*, meaning "seen together," includes the commonly understood low and high pressure systems often shown on weather maps by broadcast meteorologists. Synoptic low and high pressure systems usually come in pairs ("seen together"), and their evolution governs general regional and national weather patterns on the time scale of a few days (e.g., low pressure/stormy days followed by high pressure/fair days). However, mesoscale features embedded within larger synoptic-scale systems, including individual thunderstorms, rainbands, and frontal passages, often provide the high-impact weather at a particular location.

In mesoscale features, vertical air motions can be intense and vary significantly over short horizontal distances, resulting in strong fluctuations in the temperature, moisture, momentum, and chemical species concentrations observed at any given location. These are some of the quantities associated with the weather "sensed" by humans where they live. In general, the vertical variations of these quantities in the ambient atmosphere (i.e., the vertical gradients) are relatively large near the surface of the Earth. Thus, large vertical motions near the surface of the Earth can be very effective at redistributing temperature, moisture, momentum, and chemical constituents. It is this interplay of vertical air motion with sharp vertical gradients in these quantities that results in high-impact weather and air quality events at the mesoscale. Observations of these conditions are the key to improving predictions of high-impact events, because the sophisticated computer models that provide such predictions are inherently limited by the quality and quantity of observations, which serve as a starting point for the calculations.

Standard weather observations typically resolve larger-scale features that enable a computer model to provide skillful predictions of those features while also producing events that are mesoscale in scope. However, because they lack observations that resolve more of the antecedent mesoscale structure, models are limited in their ability to predict specific high-impact mesoscale events. Therefore, a more effective meteorological and chemical weather observing system must include nationwide observations that are faster in time, more densely spaced horizontally, and are designed to capture the detailed vertical structure of the lower atmosphere.

ponent of U.S. mesoscale observations—the ability to measure atmospheric conditions at various heights—is particularly inadequate.

National priorities demand ever more detailed meteorological observations at much finer spatial and temporal resolutions than are widely available today. These priorities include tracking atmospheric dispersion of chemical, biological, and nuclear contaminants from industrial accidents and terrorist activities, as well as smoke dispersion monitoring and prediction for wildfires, prescribed burns, and seasonal agricultural fires; more extensive air quality forecasting, high-resolution "nowcasting," and short-range forecasting of high-impact weather; high-resolution weather information for aviation, surface transportation, and coastal waterways; and support to regional climate monitoring.

The agency sponsors[1] of this study, recognizing numerous national vulnerabilities and unmet needs related to their missions, asked the National Research Council to convene a committee to help define affordable and effective solutions. The Committee on Developing Mesoscale Meteorological Observational Capabilities to Meet Multiple National Needs was appointed to develop an overarching vision for an integrated, flexible, adaptive, and multi-purpose mesoscale meteorological observation network.

This report offers steps that can be taken to affect near-term improvements in U.S. mesoscale observations and the investments that could be made to strengthen capability over the longer term. Although many of the recommendations specify actions to be taken by the federal sponsors of the report, federal agencies alone are unlikely to satisfy the breadth of national needs for mesoscale data. Therefore, the recommendations specifically address the broader community of private, public, and academic partners.

KEY FINDINGS

The committee finds that, overall, the status of U.S. surface meteorological observation capabilities is energetic and chaotic, driven mainly by local needs without adequate coordination. While other providers act locally to satisfy particular regional monitoring needs, the federal government is unique in its capacity to act strategically and globally in the national interest. An overarching national strategy is needed to integrate disparate systems from which far greater benefit could be derived and to define the additional observations required to achieve a true multi-purpose network that is national in scope, thereby fully enabling mesoscale numerical weather prediction and other applications.

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[1] This study was sponsored by the Departments of Commerce (DOC), Transportation (DOT), Homeland Security (DHS), the Environmental Protection Agency (EPA), and the National Aeronautics and Space Administration (NASA).

Increased coordination among existing surface networks would provide a significant step forward and would serve to achieve improved quality checking, more complete metadata, increased access to observations, and broader usage of data serving multiple locally driven needs. A major challenge in implementing this collaboration is to retain the energy, enthusiasm, and diverse investments that have led to our current condition, while also introducing an appropriate degree of centralization for the purposes of coordination, integrity, and integration to maximize the national benefit.

The Committee envisions a distributed adaptive "network of networks" (NoN) serving multiple environmental applications near the Earth's surface. Jointly provided and used by government, industry, and the public, such observations are essential to enable the vital services and facilities associated with health, safety, and the economic well-being of our nation. The recommendations in this report are offered in the spirit of the Committee's broad vision of a NoN.

A NoN cannot deliver a net benefit to users unless comprehensive metadata are supplied by all operators. Although provision of quality metadata is an exacting and demanding task, metadata are the key to the effective accommodation of diverse data sources and the widest possible utility of such information. Comprehensive metadata enable customized network configurations to best meet custom user needs as specified by the users themselves, including all aspects of observing system performance that are germane to a given application.

Infrastructure Needs

Beyond collaboration among existing surface networks, additional types of observations are critical to achieving the desired result of a comprehensive and integrated national mesoscale observing network of networks. Mesoscale observations above and below the atmosphere's lowest 10 meters are particularly inadequate. Assets required to profile the lower troposphere above the lowest 10 meters are too limited in what they measure, too sparsely or unevenly distributed, frequently limited to regional areal coverage, and clearly do not qualify as a mesoscale network of national dimensions. Likewise, subsurface temperature and moisture observations are made only at relatively few locations in most states, limiting our ability to forecast mesoscale atmospheric processes and high-impact weather. The solutions to these particular deficiencies require leadership and infrastructure investments from the federal agencies.

The highest priority observations needed to address current inadequacies are:

- **height of the planetary boundary layer**
- **soil moisture and temperature profiles**
- **high-resolution vertical profiles of humidity**
- **measurements of air quality and related chemical composition above the surface layer**

No systematic national capability exists for these quantities, which are critical to the dynamical prediction of high impact weather and/or chemical weather.

Just below the aforementioned highest priorities are quantities for which some capabilities currently exist but fail to meet a serviceable national standard for one or more reasons:

- direct and diffuse solar radiation
- vertical profiles of wind
- subsurface temperature profiles (e.g., under pavement)
- icing near the surface
- vertical profiles of temperature
- surface turbulence parameters

Geography and Demography

The Committee repeatedly returned to concerns about urban, coastal, and mountainous regions as they affect the mix of surface-based mesoscale observing systems. Mountains, coastlines, and cities have greater importance than their surface areas would imply. Ironically, they are consistently undersampled relative to their needs. All three create their own weather, which is often poorly resolved in synoptic-scale models. Considering the danger of traveling in the winter or fighting forest fires in the summer, the need for observations in the mountains goes beyond that for weather forecasting alone. Coastlines and cities, both of which are heavily populated, also take on special importance, particularly when one considers the critical role for observations in response to a release of toxic substances, to treat the roads in response to an ice storm or blizzard, or evacuate people in advance of hurricane landfall.

RECOMMENDATIONS: STEPS TO ENSURE PROGRESS

Several steps are required to evolve from the current circumstance of disparate networks to an integrated, coordinated NoN. First, it is necessary to firmly establish a consensus among providers and users that a NoN will yield benefits in proportion to or greater than the effort required to establish it. This consensus-building step is essentially political, requiring agreement in principle at various levels of public and private participation, which leads to the collaborative development of an implementation plan. The new elements of a NoN are twofold: (1) the provision of services and facilities that enable individually owned and operated networks to function, more or less, as one virtual network, and (2) the provision of new observing systems or facilities to enable national objectives. The first is largely separable from the second, since considerable benefit may be achieved from improved functionality with existing observational assets.

> **Recommendation: Stakeholders, including all levels of government, various private-sector interests, and academia should collectively develop and implement a plan for achieving and sustaining a mesoscale observing system to meet multiple national needs.**

The plan should recognize and account for the complexity associated with the participants' differing roles, responsibilities, capabilities, objectives, and applications, as well as lessons learned from past experiences. To launch the planning process

- A mesoscale environment observing system summit should be convened to discuss and recommend the implementation of a NoN and to prescribe a process through which a plan will be developed. Participants from the private sector, federal executive branch, U.S. Congress, national organizations of governors and mayors, and key professional societies should attend.
- Forums to further discuss and recommend implementations of the mesoscale observing system should be organized by professional societies and associations such as the American Meteorological Society, National Council of Industrial Meteorologists, American Geophysical Union, Commercial Weather Services Association, National Weather Association, American Institute for Chemical Engineering, American Society for Civil Engineering, and American Association of State Highway and Transportation Officials. A leading role should be assumed by the Commission on the Weather and Climate Enterprise of the American Meteorological Society, the constitution of which is particularly well suited to this task.

> **Recommendation: To ensure progress, a centralized authority should be identified to provide or to enable essential core services for the network of networks.**

Essential core services are defined as those services required to derive levels of function and benefit from a NoN that markedly exceed those currently realized from the assemblage of relatively independent networks. Essential core services include but are not limited to

- definition of standards for observations in all major applications,
- definition of metadata requirements for all observations,
- certification of data for all appropriate applications,
- periodic "rolling review" of network requirements and user expectations,
- definition and implementation of data communication pathways and protocols,
- design and implementation of a data repository for secure real-time access and a limited period for post-time access,
- generation of a limited set of products based upon the raw observations, most notably, graphical presentations of data fields and analyses thereof,
- pointers to more sophisticated products generated externally, such as analyses produced from a short-term model prediction and multiple observation sources,
- pointers back to data providers, where more products and services are available,
- establishment of a link to the National Oceanic and Atmospheric Administration's (NOAA's) National Climate Data Center (NCDC) for archival of selected data, as deemed appropriate by NCDC,
- development and provision of software tools and internet connectivity for data searches, information mining, and bulk data transmissions,
- development and provision of a limited set of end-user applications software, which would enable selection of default network data configurations for major applications as well as tools for creation of custom network data configurations, and
- provision of a data quality checking service with objective, statistically based error-checking for all major categories of data, including manual intervention and feedback to providers.

The premise for these services is to:

- have expert assistance in establishing and maintaining standards for the data provided,
- know which additional data are available and suitable to one's own application,
- have compatibility with and ease of access to selected observations and analyses,

- ensure the archival of selected data commensurate with their useful lifetimes, and
- gain ease of access to the products and services of other providers.

Initially the focus of such activities should be on markedly improved use and value of data from existing observing systems. As new observational, computational, and communications infrastructure is added, the focus should shift to the prompt and seamless accommodation of these new elements and their related objectives. The provision of core services is essential for adequate access to and the utility of mesoscale observations as applied to multiple national needs.

The recommendation for a modest degree of centralization is tightly focused on essential core services. It specifically excludes centralization for the purpose of acquisition and operation of observing systems, which are owned and operated by agencies, corporations, and other organizations to serve their specific missions. The centralized authority is an enabling element of the broader enterprise that comes into play only as is necessary to derive added utility and functionality from the network of networks. It does not speak to the ownership, operation, upgrading, or maintenance of the individual networks themselves. It follows that the centralized authority is envisioned as a relatively small but vital fraction of the entire NoN enterprise.

Recommendation: The centralized authority should require metadata of every component in an integrated, multi-use observing system.

Observational data have high value only if they are accompanied by comprehensive metadata. Provision of metadata should be mandatory for membership in the NoN, and incentives should be offered to the operators of networks to provide it. The contents of a metadata file should be carefully defined, and, once assembled, a national database of metadata should be frequently updated and 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.

Recommendation: A national design team should develop a well-articulated architecture that integrates existing and new mesoscale networks into a national "network of networks."

To serve multiple national needs, the United States needs a system that is a network of networks in an architectural sense. The term "architecture" includes the fundamental 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 user. This architecture should 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 must also include a process that continually identifies critical observational gaps, new measurement systems and opportunities, and the evolving requirements of end users.

> **Recommendation: The national network architecture should 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 future societal needs as 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.

> **Recommendation: Federal agencies and partners should employ testbeds for applied research and development to evaluate and integrate national mesoscale observing systems, networks thereof, and attendant data assimilation systems. Among other issues, testbeds should address the unique requirements of urbanized areas, mountainous terrain, and coastal zones, which currently present especially formidable deficiencies and challenges.**

Applied research and development should include but not be limited to transitional activities, including the operation of prototype networks and evaluation of their forecast impact; 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 labs, universities, or joint institutes as appropriate to the application, and may have focused limited terms of activity that integrate users in the transition to operations.

> **Recommendation: The United States should establish a robust and economically viable organizational structure to effect the national**

implementation of a multi-purpose environmental observing network at the mesoscale. It may be preferable for this organization to take the form of a publicly chartered, private nonprofit corporation. A hybrid public-private organizational model would stimulate both public and private participation over a wide, dynamic range of investment and applications; maximize access to mesoscale data; and effect a synergism between the public good and proprietary interests.

Historically, the U.S. Congress has chartered private non-profit corporations for various purposes, where the scope of activity is truly national, yet major components of the effort are cooperatively resourced federally and locally through both governmental and private resources. While all of the entities providing mesoscale data are important to the enterprise, all have a limited mission and therefore a limited role where provision of infrastructure and services is concerned. A hybrid public-private organization would encourage the leadership and prominence of pivotal federal agencies such as NOAA, while also protecting, facilitating, and enabling the role of other interests, which are essential to the success of the collaborative enterprise.

RECOMMENDATIONS: MEASUREMENTS AND INFRASTRUCTURE

Recommendation: As a high infrastructure priority, federal agencies and their partners should deploy lidars and radio frequency profilers nationwide at approximately 400 sites to continually monitor lower tropospheric conditions.

Humidity, wind, and diurnal boundary layer structure profiles are the highest priority for a network, the sites for which should have a characteristic spacing of ~125 km but could vary between 50 and 200 km based on regional considerations. Such observations, while not fully mesoscale resolving, are essential to enable improved performance by high-resolution numerical weather prediction models and chemical weather prediction at the mesoscale. Through advanced data assimilation techniques, data from these 400 sites, when used in combination with advanced geostationary satellite infrared and microwave soundings, Global Positioning System (GPS) constellation radio occultation measurements, and commercial aviation soundings, will effectively fill many of the critical gaps in the national observing system.

Recommendation: To meet national needs related to public health and safety, including the growing need for chemical weather forecasts, a core set of atmospheric pollutant composition parameters should be

> **part of the mesoscale observing system. The core set should include carbon monoxide, sulfur dioxide, ozone, and particulate matter less than 2.5 microns in size at approximately 200 urban and rural sites (~175 km spacing).**

These observations would constitute a national pollutant constituent backbone and should 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, such as on human health; may be harmful to natural and managed landscapes; may also serve as precursors to additional hazardous compounds; and can help to extend the utility of parameters observed from space. Additional important parameters (e.g., nitrogen dioxide) should be added as soon as appropriate and affordable technology is developed for the applications envisioned. The proposed network would enable chemical weather prediction nationally and also would support urban air pollution monitoring, for which it is not a substitute.

> **Recommendation: A national, real-time network of soil moisture and soil temperature observations should be deployed nationwide at approximately 3000 sites.**

This number corresponds to a characteristic spacing of about 50 km for a network that is spatially distributed across the continental United States. Although this spacing is insufficient to capture the full spectrum of short-term spatial variability of surface soil wetness, 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 numerical weather prediction, water resources management, flood control and forecasting, and forestry, rangeland, cropland, and ecosystems management. This characteristic spacing also would provide data at a resolution that complements historical and relevant datasets. Site selection should be biased toward existing networks, provided that the instrument exposure and all siting standards are acceptable and real-time communication is possible.

Knowing soil moisture at any location is critical for apportioning heavy rainfalls into ground absorption and runoff into streams. Soil moisture also exerts a strong control on the partitioning of the sun's energy into evaporation and sensible heating, which feeds back into the atmosphere to influence the evolution of precipitation and clouds. Moisture in the top layers of soil acts on shorter time scales, to influence day-to-day weather, whereas the amount of soil moisture at deeper levels impacts slower processes at regional scales and acts as a source for water that deep-rooting plants bring to the atmosphere during extended periods without precipitation.

Recommendation: Emerging technologies for distributed-collaborative-adaptive sensing should be employed by observing networks, especially scanning remote sensors such as radars and lidars.

Some high-impact weather phenomena (e.g., tornadoes) of limited size and near-surface location can escape detection or be only poorly resolved by the current low-density network of weather radars. 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 and coastal and urban environments. High-density networks of less expensive 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 make measurements in a collaborative manner. These networked sensors will respond to feedback based on input from users and the prevailing environment. Current state-of-the-art communication, computing, and remote sensing technologies facilitate this new paradigm for operation of networked instruments.

Recommendation: As a high satellite instrument priority, the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), in cooperation with foreign space agencies, should seek to improve the quality of geostationary satellite water vapor and temperature soundings within continental atmospheric boundary layers.

Infrared hyperspectral soundings and soundings from microwave synthetic thinned aperture arrays, each in geostationary orbit, offer unique opportunities to improve mesoscale prediction. When assimilated in conjunction with ground-based profiling data, the benefits from improved geostationary soundings will be large, likely enabling more skillful forecasts of convective rainfall and attendant severe weather and flooding. The geostationary platform is unique among satellites, offering the sampling frequency required in this application.

Recommendation: Existing surface observations and observing platforms associated with road and rail transportation, as appropriate, should be augmented to include World Meteorological Organization (WMO)-standard meteorological parameters. Conversely, existing WMO-standard meteorological observing stations near highways and railways should be augmented, as appropriate, to meet the special needs of the transportation sector.

While continuing to satisfy the fundamental needs of the transportation sector, some existing roadway and railway observing stations could easily be integrated into the NoN to provide a broader complement of meteorological and soil measurements at minimal cost. The addition of another measurement or two at existing sites avoids the major expense of establishing a new station altogether, and wireless communication gives the flexibility to locate individual instruments optimally. Likewise, meteorological stations near roads and railroad tracks could have sensors added to them that would provide data that are beneficial to transportation, for example, water depth measurements near culverts.

> **Recommendation: The Department of Transportation should assess and eventually facilitate the deployment of high-density observations through the Vehicle Infrastructure Integration initiative. Similar concepts should be considered for general aviation and marine transportation vehicles.**

The Vehicle Infrastructure Integration initiative proposes to harness the measurements made by vehicle sensors, for example, temperature and rain rate (from wiper speed), employed in the U.S. automotive and truck fleet. Additional development of nanosensor technologies should realize "measurements on a chip," which would replace the 20th-century sensor paradigm.

RECOMMENDATION: THE HUMAN DIMENSION

> **Recommendation: The stakeholders should commission an independent team of social and physical scientists to conduct an end-user assessment for selected sectors. The assessment should quantify further the current use and value of mesoscale data in decisionmaking and also should project future trends and the value associated with proposed new observations. Upon implementation and utilization of improved observations, periodic assessments should be conducted to quantify the change in mesoscale data use and its added societal impact and value.**

In addition to the involvement of known data providers and users, a less formal survey should capture user comments from blogs and webpage feedback. Such a survey would actively seek comments from people who are registered for or who regularly access the data. The broad objectives of a survey would be to

- identify priority areas where training and outreach can be developed to broaden the number and types of users and uses of network data,

- develop ways to acknowledge and broaden the uses of environmental monitoring information beyond weather, to include examination of societal vulnerability and resilience to a broader range of hazards,
- examine whether and how the partnership agreements and applications within one state, group, or region can be used elsewhere,
- discover metrics that measure how well current initiatives meet the data needs of the citizenry, for example, teachers, students, hospital administrators, golfers, homeowners, and individuals of all ages, and
- identify novel ways to build capacity for using environmental monitoring data in society.

THE CHALLENGE FOR THE FUTURE

Today we are faced with a complex collection of mesoscale networks clearly driven by market forces. This condition is both energetic and chaotic and possesses local strengths, national gaps, and operational weaknesses. Local strengths are heralded by the proliferation of surface meteorological stations, which are often tailored to satisfy the monitoring needs of a particular application. National gaps result from weaknesses in the federal government's observational infrastructure pertaining to mesoscale numerical weather prediction and chemical weather forecasts. Observational deficiencies in the mountains, at the coasts, and near urbanized areas require special attention. With respect to mesoscale numerical weather prediction and chemical weather forecasts, three-dimensional observations are paramount and involve heavy infrastructure to which federal agencies must be major contributors.

Nearly every dimension of participation in mesoscale observation is important and worthy of cultivation. The challenge is to harness the strengths of our current condition while creating an organizational circumstance that can stimulate and coordinate diverse assets to serve similarly diverse interests. The Committee believes that it has offered constructive and sometimes novel alternatives toward that end while avoiding prematurely prescriptive or excessively centralized solutions. Much work remains, especially with regard to the elaboration of architecture, the design of networks, and the forging of new relationships among all levels of government, industry, and the earnest contributiosn of our citizenry.

1

Introduction

STUDY APPROACH AND REPORT ORGANIZATION

The Committee envisions a distributed adaptive "network of networks" serving multiple environmental applications near the Earth's surface. Jointly provided and used by government, industry, and the public, such observations are essential to enable the vital services and facilities associated with health, safety, and the economic well-being of our nation.

In considering its vision, practical considerations weighed heavily on the Committee's deliberations and in the formulation of its recommendations. To that end, the study emphasizes societal applications and related factors influencing the implementation of an enhanced observing system, the intent of which is to markedly improve weather-related services and decision making. The Committee considered the various roles to be played by federal, state, and local governments, and by commercial entities. In essence, the study provides a framework and recommendations to engage the full range of *providers* for weather, climate, and related environmentally sensitive information, while enabling *users* of this information to employ an integrated national observation network effectively and efficiently in their specific applications.

This study does not attempt to compile an exhaustive catalogue of mesoscale observational assets, although it identifies and summarizes numerous important sources for such information. Nor does this study attempt to design a national network, although it does identify critical system attributes and the ingredients deemed essential to retain sustained importance and relevance to users.

To lend substance to its vision, the Committee has structured consideration of "national needs" into six broad themes: (1) weather prediction and climate monitoring, (2) research, (3) energy security, (4) public health and safety, (5) transportation, and (6) water and food.

The report is organized as follows: In the remainder of Chapter 1, we describe the historical development of meteorological observations in the United States, culminating in a summary of the current policy and technical contexts.

Chapter 2 surveys existing needs for mesoscale observations within the fundamental categories of weather prediction, climate monitoring, and research. "Fundamental" is the appropriate word, because the infrastructure required to collect, process, quality-check, and incorporate the raw observations into prediction models serves all other applications of economic significance. One may question why climate is considered in this report. Climate is in part a statistical representation of day-to-day weather in terms of means and departures from the mean. As such, it has mesoscale variability just like the weather, dependent upon latitude, topography, and land surface conditions. Thus, mesoscale observations that serve the purposes of weather monitoring and prediction also serve the purpose of climate, even though the standards of measurement may be different. Research is included in Chapter 2 for two reasons: (1) observations both suggest and confirm theories, and (2) research, particularly that involving field programs, often suggests novel ways of observing the atmosphere and prompts new instrument development.

Chapter 3 examines five representative sectors of the U.S. economy that depend heavily upon the mesoscale observing and modeling infrastructure: energy security, public health and safety, transportation, water resources, and food production. For each economic sector, we discuss the importance of mesoscale observing to the national economy and current assets and gaps in the observing system. The Committee hopes that Chapters 2 and 3 will bring into sharp focus the ubiquitous effects of weather and climate on national life and the astounding diversity of needs for mesoscale observing.

Chapter 4 is a guide to current observing capabilities and a preview of emerging instrument technologies. Taking a cue from the title of this report, "From the Ground Up," this chapter first considers surface observations, then moves to sensors attached to platforms that pass through the atmosphere (e.g., balloons, aircraft) or sample it remotely from the ground (e.g., radars). Next, the chapter summarizes satellite observing systems and stresses the complementary roles of space-based and ground-based systems. While this study ultimately focuses on observations that resolve mesoscale features, the utility of such observations is partly defined by a broader suite of observations taken at reduced resolution over larger geographic areas in support of numerical weather prediction.

Chapter 5 brings together the aspects of a network as described in Chapters 2 to 4 in an architecture that can support all the functioning elements. The architecture recognizes that the national-level mesoscale network will be a network of networks (NoN).

Chapter 6 provides a series of steps to ensure progress towards the Committee's vision of an integrated, multi-purpose, nationwide mesoscale NoN. These first steps involve a minimum level of coordination required for the provision of "essential core services," which are necessary before a national NoN is possible, whatever the NoN organizational model might be. Options for such an organizational model are explored in Chapter 7. This exploration includes options for an organizational entity to run the enterprise and recommends a candidate organizational model, which identifies the various roles to be possibly played by federal, state, local, academic, and private partners.

Chapter 8 concludes the report with a list of priorities for the way forward.

THE HISTORICAL CONTEXT

Records of systematic meteorological observations in the United States date back to pre-Revolutionary days, when both George Washington and Thomas Jefferson logged observations from Mount Vernon and Monticello. Although observations and small networks proliferated between the Revolution and the mid-19th century, the systematic collection and distribution of meteorological data awaited the arrival of the telegraph to take off in force. By 1849, 150 volunteers were collecting basic meteorological observations and transmitting the data via telegraph to the Smithsonian Institution. Meteorologists plotted and analyzed the data to produce surface weather maps. On the eve of the Civil war, the number of volunteers in the Smithsonian network had grown to nearly 500. The *Washington Evening Star* collected these data and data from a variety of other networks, including those operated by state weather services.

The first legislative mandate for weather observations arrived in the form of a Congressional Joint Resolution on February 9, 1870. Signed by President Grant, the resolution directed the Secretary of War to collect synchronous weather observations and transmit them via telegraph to Washington, D.C. This effort eventually culminated in the establishment of the Cooperative Observer Program (COOP), under the auspices of the Organic Act of 1890 that established the Weather Bureau within the Department of Agriculture. The Organic Act directed the Weather Bureau to

> forecast the weather; issue storm warnings; display weather and flood signals for the benefit of agriculture, commerce, and navigation; gauge and report the flow of rivers; maintain and operate the seacoast telegraph lines and collect and transmit marine intelligence for the benefit of commerce and navigation; report temperature and rain-fall conditions for the cotton interests; display of frost and cold-wave signals; distribute meteorological information in the interests of agriculture and commerce; and take the meteorological observations that may be necessary to establish and record the climatic conditions of the United States, or that are essential for the proper execution of the foregoing duties.

The COOP network, a volunteer network of observers who collect daily meteorological observations that are archived by the National Climatic Data Center (NCDC), had grown to more than 11,000 stations by the beginning of the 21st century. Moreover, the observational capabilities of the National Weather Service (NWS) and other federal organizations had expanded well beyond surface-based, basic meteorological variables to encompass a broad suite of Earth system observations. Key legislation supported the expansion of these observational capabilities.

In 1926, the Air Commerce Act directed the Weather Bureau to assume responsibility for observation, forecasts, and warnings for atmospheric phenomena impacting the safety and efficiency of civil aviation in the United States and above the high seas. The Act called for the establishment of a specific organizational structure for this purpose. In 1938, the Flood Control Act significantly expanded the role of the Weather Bureau in the realm of hydrology and water resources, calling upon the Bureau to establish the Hydroclimatic Network, an information system for precipitation, with the express purpose of flood control, forecasts, and warnings. This Act resulted in part from the severe Ohio River flooding of 1937 and the realization in hindsight of the utility of detailed hydrologic observations in providing river flood warnings in a timely and economical manner. During that flood, 70 percent of the city of Louisville, Kentucky, was flooded, and downstream Paducah was completely evacuated.

Recognizing that the scope of the Weather Bureau's mission had grown far beyond its original role of supporting agricultural interests, President Franklin Roosevelt put forth his Reorganization Plan No. 4 on June 30, 1940, which transferred the Weather Bureau to the Department of Commerce. President Roosevelt's plan specifically recognized the paramount role of the Bureau in aviation, and stressed that the move should in no way "[lesson] the Bureau's contribution to agriculture." It was about this time that the observational capabilities of the Bureau were revolutionized by the introduction of the radiosonde, which provided systematic vertical profiles of wind, temperature, pressure, and humidity in a much safer and cost-effective manner than the aircraft missions that had been employed by various civilian and military agencies since the early 20th century. Just a few years earlier, the Bureau had begun collecting systematic observations over marine waters by placing instruments on floating buoys.

The need for detailed meteorological observations grew significantly with the entrance of the United States into World War II, and was mainly associated with military operations. Additional upper air and surface observations were taken systematically at the synoptic scale, and awareness of the mesoscale began to emerge. Soon afterward, the Thunderstorm Project (Byers and Braham, 1949) observed the mesoscale through the introduction of World War II military radar and instrumented aircraft. In the decades after the war, several legislative mandates were enacted to establish new observational programs and organizational structures, in order to advance the new capabilities and apply them to enhancing the safety and economic well-being of the American public. The Federal Aviation Act of 1958 significantly expanded the role of the Department of Commerce in meteorological applications for aviation, specifically by extending observations into the polar regions and directing the department to form international agreements with the weather services of other nations for the express purpose of sharing data. On June 26, 1959, the Weather Bureau commissioned the first operational modern radar for weather surveillance, the WSR-57, at the new Hurricane Forecast Center in Miami, Florida.

Concurrent with these post-War legislative developments, the National Research Council (NRC) Committee on Meteorology recommended a 100 percent increase in federal funding of university-based meteorological research and the establishment of a national institute to provide research facilities and equipment beyond the reach of any single university (NRC, 1958). Thereafter, the National Center for Atmospheric Research (NCAR) was established, university research flourished, and the federal government supported sustained growth in the development and deployment of meteorological observing systems.

During the 1960s and 1970s legislation was enacted that established observational programs across and within a variety of agencies. The Weather Bureau was renamed the National Weather Service and was reorganized under the auspices of the new Environmental Science Services Administration (ESSA) in 1967, and President Nixon issued an executive order that established the National Oceanic and Atmospheric Administration (NOAA) in 1970. Research developments continued to expand environmental observation capabilities. The application of satellite technology provided a parallel revolution in our ability to observe Earth's atmosphere.

With the arrival of the 1980s, the research and technological advances necessary to modernize mesoscale observing capabilities were in place. What had previously been established in the United States provided sufficient data on the synoptic scale, but operational capabilities still lagged for observations of mesoscale phenomena. A new framework was needed to implement research advances in in-situ technology, radar, and satellites to real time, mesoscale observations of weather, water, and climate. The 1992 Weather Service Modernization Act provided such a pathway. Several major new observing systems were deployed as part of the NWS modernization, including the NEXRAD network of WSR-88D Doppler radars and the Automated Surface Observing Systems (ASOS). Other systems were deployed with varying degrees of operational stability, including a demonstration network of vertically pointing radar wind profilers. The Advanced Weather Information Processing System (AWIPS) provided a workstation environment for integrating these datasets and putting them at the hands of operational forecasters at newly constructed Weather Forecast Offices(WFOs) around the United States. In its final report, *A Vision for the National Weather Service: Road Map for the Future* (NRC, 1999), the National Weather Service Modernization Committee (NWSMC) recognized the significant potential advances in numerical weather prediction that could result from such observations.

Developments in mesoscale observing capabilities have continued since the NWS modernization. Many state and local governments, universities, and private-sector interests have developed and deployed dense networks of meteorological observing stations ("mesonets"). Broadcast media operate ground-based radars that are in some regions spaced comparably to NEXRAD radars. Other sensors provide chemical weather and air pollution information at spatial and temporal resolutions beyond traditional meteorological observing systems. Yet, at the end of the first decade of the 21st century, these observational systems are not national in scope, and a national-scale infrastructure for systematically collecting and disseminating the observations does not exist. A new mandate may be necessary both to expand capabilities and to leverage existing systems for the next advance in the United States' mesoscale observing capabilities.

Shortly before the NWSMC released its final report, the NRC released *The Atmospheric Sciences Entering the Twenty-First Century* (NRC, 1998), which designated its two highest-priority recommendations as "imperatives," calling upon "the atmospheric science community and relevant federal agencies [to] develop a specific plan for optimizing global observations of the atmosphere, oceans, and land" and to

> commit to a strategy, priorities, and a program for developing new capabilities for observing critical variables, including water in all its phases, wind, aerosols, and chemical constituents and variables related to phenomena in near-Earth space, all on spatial and temporal scales relevant to forecasts and applications.

Since the release of this report, a number of additional reports have addressed the need for enhanced mesoscale observing capabilities for specific systems and applications, including use of satellite data in numerical weather prediction systems (NRC, 2000), dispersion and hazardous releases (NRC, 2003a), transportation (NRC, 2004a), and the need to reinvigorate the U.S. environmental space program (NRC, 2007a).

Other recent reports have focused on data management and the organizational and programmatic structures that could facilitate partnerships among public, private, and academic interests. *Fair Weather: Effective Partnerships in Weather and Climate Services* (NRC, 2003b) proposed mechanisms whereby NWS could modify its approach to agreements with private-sector interests. Most recently, *Environmental Data Management at NOAA* (NRC, 2007b) provided recommendations for archiving and assessing data and metadata at NOAA, including the recommendation that NOAA "should establish and codify an enterprise-wide data management plan that explicitly incorporates all the principles" set forth in that report.

A goal of this report is to build upon the recommendations provided in previous reports, while taking into account current policy and technical contexts to provide a framework for the advancement of a multi-purpose mesoscale observation network that meets multiple national needs.

CURRENT POLICY AND TECHNICAL CONTEXTS

Capabilities related to the development and delivery of accurate, reliable, and useful mesoscale (i.e., the scale of high-impact weather systems) atmospheric forecasts have improved in the past decades as computing power and modeling capabilities have improved, but the benefits of these increased capabilities have not been fully realized in practical applications. There is an emerging consensus in the observational, modeling, and forecast communities that a carefully designed, integrated three-dimensional national mesoscale network will yield markedly improved short-range forecasts (Dabberdt et al., 2005a). Such forecasts could provide concrete benefits to decision making in areas such as severe weather, flash flooding, water management, energy production and management, transportation management, forestry and coastal ecosystem management and monitoring, agriculture, air quality, urban area management, homeland security, and public health and safety.

A number of national priorities require meteorological observations at spatial and temporal resolutions that are much finer than widely available today. These priorities include tracking atmospheric dispersion of chemical, biological, and nuclear contaminants from industrial accidents and terrorist activities; predicting and monitoring smoke dispersion from wildfires, prescribed burns, and seasonal agricultural fires; providing information for air quality forecasting, high-resolution nowcasting, and short-range forecasting of high-impact weather; providing high-resolution weather information for aviation, surface transportation, and coastal waterways; and supporting regional climate monitoring. Improved mesoscale observation networks in urban areas are particularly important for addressing many of these priorities. Identifying ways to enhance and design mesoscale meteorological observing systems (including calibration of environmental data from satellites) so they effectively and jointly serve these and other needs provides an opportunity to dramatically improve analysis and prediction capabilities while sharing infrastructure and costs.

Therefore the current technical context demands an overarching national strategy to integrate existing disparate systems and to define the additional observations needed to achieve the desired result. Furthermore, guidance must be provided on how best to implement a practical, useable, and cost-effective system of truly multi-purpose mesoscale observations. A major implementation challenge is to retain the energy, enthusiasm, and diverse investments that have led to our current condition, while also introducing an appropriate degree of centralization for the purposes of coordination and integration to maximize the national benefit.

2

Observations Supporting the Fundamental Infrastructure for Mesoscale Monitoring and Prediction

This chapter focuses on an intermediate class of users whose primary functions are provision of current weather information, watches, warnings, and forecasts; generation of weather analyses and predictions by computer; and monitoring climate trends. Their products are publicly available on radio, television, the Internet, or by subscription. The largest user by far in this class is the National Weather Service, whose principal mission is the protection of life and property. Other large users are private-sector firms that provide free access to some of their products via the web and other media as well as specialized, fee-based services. We consider here the broad, observational needs of these intermediate users rather than the more specific needs of their customers.

Tax dollars pay for almost all the observations used by this intermediate class. In most cases, the U.S. government either operates and maintains the observing system or pays private corporations to do so, for example, the National Lightning Detection Network. It is fair to say that the observing systems supporting the intermediate class are the backbone of environmental service systems, ranging from simple displays of weather data to sophisticated products and decision-support tools. Without raw observations, their assimilation into atmospheric models, and computer-generated forecasts, the products tailored for the specific applications to be discussed in Chapter 3 would not be possible.

Given the heavy reliance of intermediate users on the raw observations and computer analyses and predictions, and the emphasis of the National Weather Service on the protection of life and property, this section focuses on observations required to support these functions. More specifically, it focuses on observations for accurate numerical weather analysis and prediction, timely watches and warnings in advance of hazardous weather, and the special requirements of climate monitoring.

The charge to this committee was to (1) focus on time scales less than 48 hours, but keep longer time scales in mind; (2) focus on U.S. and adjacent coastal regions, but keep global observing system requirements in mind; (3) focus on ground-based in situ and remote sensing observations, but keep the utility of satellite observations in mind; (4) focus on the atmospheric boundary layer, but keep the deep troposphere in mind. Within this context, the hazardous weather events most important to detect, monitor, and predict are

- flooding from a large-scale storm
- Nor'easters
- snowstorms and ice storms
  (For the above three items, precipitation type, intensity, and amount [in the case of snow and ice, liquid equivalent and accumulation on the ground] are all important.)
- hurricanes and tropical storms
- air pollution[1]
- thunderstorms, including mesoscale convective systems
  - — lightning
  - — flash floods
  - — hail
  - — straight-line damaging winds (resulting from squall lines or bow echoes)
  - — tornadoes
- windstorms without precipitation
  - — downslope windstorms
  - — pressure-gradient windstorms
- fire weather
- aviation hazards
  - — in-cloud icing
  - — downbursts
  - — aircraft turbulence

The order in the above list is roughly by size and longevity. The time and space scales associated with these phenomena are depicted in Figure 2.1. All

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[1] This report covers the release of toxic substances, accidentally or deliberately. This topic is closest to "air pollution," but, since it is not a natural phenomenon, it is not treated in Appendix A, nor is it mentioned in Table 2.1. The spatial and temporal scales for toxic releases (0.2 to 2.0 km and 15 min to hrs, respectively) are generally smaller than those for air pollution.

these phenomena are "high impact" in that they affect life, property, and the economy. All pose the same problems for forecasters: time of initiation, intensity and intensity variations, and end time. And, although some of the phenomena near the top of the list are large and persist for days, mesoscale features embedded within them, especially convective elements, cause most of the havoc.

Observations useful in the context of this study are equally useful for monitoring phenomena that lie outside the time-space envelope considered

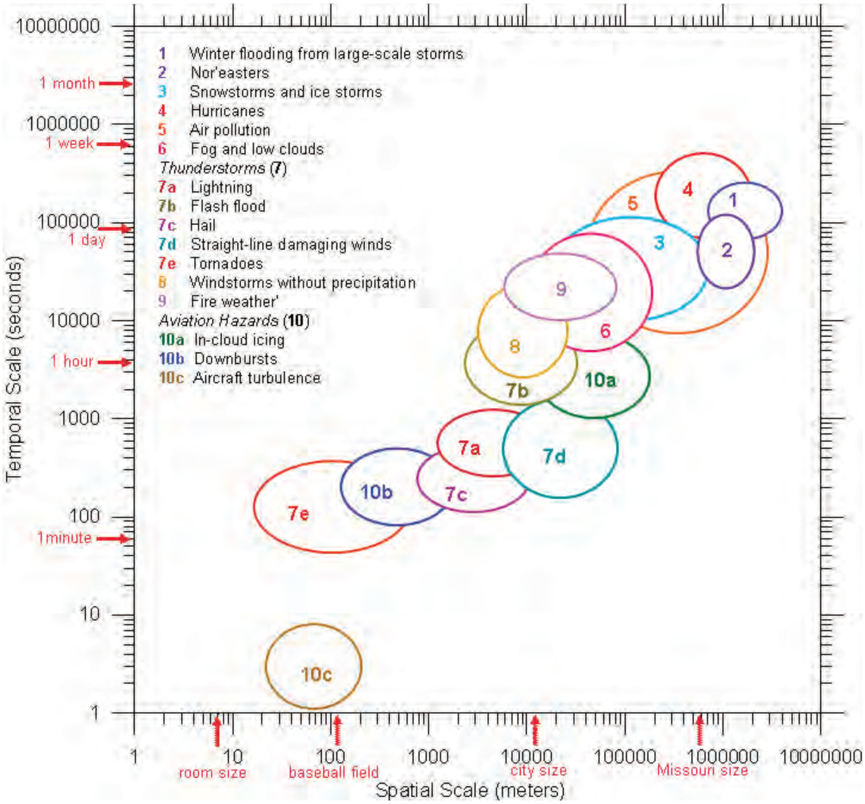


FIGURE 2.1 Time and space scales associated with the "high-impact" weather phenomena that are discussed in Appendix A and summarized here. NOTES: The scale is logarithmic in both directions. Common units of time are noted on the vertical coordinate. Common notions of size are listed on the horizontal axis. The sizes and lifetimes associated with each phenomenon are typical but not necessarily definitive. Not portrayed is the size of mesoscale features that may be embedded within the larger events.

here, for example, a shift in the large-scale hemispheric circulation pattern, heat waves, drought, and climate change. Reanalyses of atmospheric observations collected over many decades with sophisticated assimilation systems, in effect, synthesize all we can know about atmospheric behavior since the dawn of the meteorological satellite era.

A PHENOMENOLOGICAL APPROACH TO OBSERVATIONAL REQUIREMENTS

For each phenomenon listed above, we ask

- Why is the phenomenon important?
- What variables (e.g., temperature, moisture, wind) are sufficient to characterize the phenomenon?
- What spatial density of observations and what frequency of measurement are required not only to detect and monitor the phenomenon but also to describe its internal workings and predict its onset and future behavior?

Appendix A addresses these questions in detail and gives a rationale for choosing a spatial and temporal resolution appropriate for observing each phenomenon. As far as we know, such an analysis has not appeared elsewhere. A summary of the discussion in Appendix A follows in Table 2.1.

The phenomena listed in Table 2.1 are familiar to everyone. Another atmospheric entity, gravity waves, are virtually unknown to the general public, yet they affect many of the listed phenomena. Gravity waves are ubiquitous in the atmosphere. They are wave disturbances in which buoyancy acts as the restoring force on parcels displaced from their equilibrium position. Gravity waves can spawn thunderstorms, generate severe turbulence in the vicinity of mountains, create persistent chinook (warm and dry downslope wind) conditions, increase winds and the snowfall rate in winter storms, and drive trace amounts of gas from the soil through "pressure pumping."

A characteristic wavelength for gravity waves ranges from a few kilometers to several hundred. A characteristic propagation speed is 10-20 m s^{-1}. In order to capture gravity waves, the observational net has to be fine enough to resolve the layer of static stability in which the waves move, most often at the tropopause or in the lower troposphere, and often within an inversion. This implies, roughly, a horizontal resolution of 5-10 km and a vertical resolution of 100 m, in temperature, moisture, and wind measurements.

The main conclusions to be drawn from Table 2.1 and the brief mention of gravity waves are

TABLE 2.1 Emphasizing observation requirements *not currently met* in the vicinity of listed phenomena that would improve definition of mesoscale structure and predictions out to 48 hours

Phenomenon	Size	Duration	Parameters to Observe	Resolution		
				Δx	Δt	Δz
Flooding from large-scale storms	300-2000 km	0.5-5.0 days	Temperature	50 km	3 h	200 m (up to 5 km MSL)
			Moisture			
			Wind			
			Precipitation			
Nor'easter	500-2000 km	0.5-4.0 days	SST	10 km	12 h	
			Temperature			
			Moisture	50 km	3 h	100 m (up to 12 km)
			Wind			
Snowstorms Ice storms	swaths 200 km wide 1000 km long	2 h-2 days	Temperature	30 km	2 h	100 m (up to 5 km MSL)
			Moisture			
			Wind			
			Precipitation			
Hurricanes and tropical storms	100-2000 km	1-7 days	Temperature	Track forecasts		
			Moisture	100 km	6 h	500 m (up to 16 km)
			Wind	Intensity changes		
			SST	10 km	3 h	200 m (up to 16 km)
			Precipitation			
Air pollution and toxic releases	20-1000 km	6 h-5 days	Temperature	Metro areas		
			Moisture	5 km	15 min	50 m | up to top of mixed
			Wind	Rural areas		| layer, generally
			Sources/sinks	20-30 km	30 min	50 m | below 4 km AGL)
			Concentration			

continued

TABLE 2.1 Continued

Phenomenon	Size	Duration	Parameters to Observe	Resolution Δx	Δt	Δz
Fog and low clouds	10-500 km	1 h-1 day	Temperature Moisture Wind	25 km	15 min	30 m (up to 3 km AGL)
Lightning	1-20 km	5 min-1 h	Temperature Moisture Wind Soil moisture Spherics	Prediction of thunderstorm initiation		
				2 km	15 min	100 m (to top of PBL)
Flash floods	2-20 km	5 min-1 h	Temperature Moisture Wind Soil moisture Precipitation	Assess instability		
				50 km	1 h	200 m (up to 12 km)
				Characterize sub-cloud layer		
				20 km	15 min	100 m (up to 2 km AGL)
				Capture low-level jet		
				30 km	2 h	200 m (up to 3 km AGL)
Hail	0.5-10.0 km	2-30 min	Temperature Moisture Wind	Same as for flash floods		
Straight-line damaging winds	5-10 km wide 50-300 km long	10 min-2 h	Temperature Moisture Wind Hydrometeor mixing ratios	1 km	5 min	100 m (up to 12 km)

Tornadoes	20 m-2 km	1 min-1 h	Temperature Moisture Wind	Pre-storm environment 50 km 1 h 200 m (up to 6 km) Non-supercell tornadoes (sub-cloud layer) 0.5 km 5 min 100 m (up to 3 km AGL)		
Downslope windstorms	20 km Along wind 100 km Across wind	2-5 H	Temperature Moisture Wind	Pre-storm environment 100 km 3 h 200 m (up to 15 km) Local variability 1 km 15 min 100 m (up to 15 km)		
Pressure- gradient windstorms	100-300 km	2-12 H	Temperature Moisture Wind Pressure	100 km	6 h	500 m
Fire Weather	10-100 km	2 h to 5 days	Temperature Moisture Wind Insolation	1 km	15 min	100 m (up to 5 km)
In-cloud icing	10-300 km	30 min to 12 h	Temperature Moisture Wind Hydrometeor mixing ratios	5 km	1 h	100 m (within any layer where temperature lies between 0°C and –20°C)
Downburst	100-3000 m	1-10 min	Temperature Moisture Wind Hydrometeor mixing ratios	1 km	1 min	200 m (up to 8 km)

continued

TABLE 2.1 Continued

				Resolution		
Phenomenon	Size	**Duration**	**Parameters to Observe**	**Δx**	**Δt**	**Δz**
Aircraft turbulence (clear air)	10-100 m	1-30 s	Temperature Moisture Wind	1 km	1 min	50 m (where vertical shear is strong)

NOTES*:

km / m	kilometers / meters
h / min / s	hours / minutes / seconds
Δx / Δt / Δz	horizontal resolution / temporal frequency / vertical resolution
MSL / AGL	above mean sea level / above ground level
SST	sea-surface temperature
PBL	planetary boundary layer

*Sizes and durations listed in the table give a typical range but may not cover extremes. The recommended spacing and frequency of observations should be considered rough estimates, not hard numbers.

- Temperature, moisture, and wind are universally required parameters. (Of the three, moisture by far is the most poorly measured.) For a few critical applications, the concentration of atmospheric aerosols and selected gaseous constituents, and hydrometeor mixing ratios are essential.
- Most unmet requirements and the most demanding requirements for observations lie below 5 km altitude. There are several reasons for this: (1) The planetary boundary layer, that part of the atmosphere most responsive to surface conditions and the diurnal cycle, is where many mesoscale phenomena have their roots. Its depth seldom exceeds 5 km, except over deserts. (2) Major exchanges of heat, moisture, trace gases, and momentum occur near the Earth's surface. (3) Atmospheric gradients tend to be stronger in the lower troposphere and are heavily influenced by topography. (4) Current observing systems do not sample atmospheric conditions just above the ground as well as they sample surface or upper tropospheric conditions. For example, infrared sensors aboard satellites cannot see through clouds, and the horizontal density of in-situ observations is much less in the lower troposphere than at the surface. Importantly, rawinsonde sites are hundreds of kilometers apart, and soundings are taken only once every 12 hours (0000 and 1200 UTC, in most longitudes, neither at the peak nor at the minimum of the boundary layer development).
- For smaller and shorter-lived mesoscale phenomena, the recommended spatial density and temporal frequency of observations is high. As discussed below, however, the blending of information from observations and models by means of data assimilation allows for some relaxation of requirements.

DATA ASSIMILATION: SYNERGY BETWEEN OBSERVATIONS AND PREDICTION MODELS

The purpose of data assimilation is to combine in an optimal fashion information gleaned from observations and models (Daley, 1991; Kalnay, 2003; Rabier et al., 2000; Wu et al., 2002). When observations are used to correct a short-term model forecast, the dynamical consistency of models and the temporal continuity between successive model states almost always result in a better subsequent forecast than would have been made in the absence of assimilation. The synergy between observations and the understanding of atmospheric behavior incorporated in the model equations leads to a more accurate representation of the atmospheric state, especially when the assimilation is repeated frequently (at least every 6 hours), as is the case in operational centers. Does this "assimilation cycle" permit relaxation of some of the requirements for observations? Undoubtedly, but the extent to which this is true has not been carefully investigated. Data assimilation is not a cure all for limitations in data coverage or accuracy. Quality control will always remain an important issue. In certain rapidly changing and dynamically complex situations (e.g., severe convection), models are of limited capability, with or without good observational data as input. Even so, a reduction in spatial density and temporal frequency listed in Table 3.1, each by a factor of two, may be possible and would definitely lower the cost of observations.

Here we provide two examples of the synergy between observations and models. In-situ observations of soil moisture are sparse and unevenly distributed over the United States Satellites provide broader coverage, but estimates apply only to surface wetness, and these are degraded in the presence of dense vegetation. In response to these shortcomings, land data assimilation systems (LDASs) have been developed to generate physically realistic soil-moisture profiles for use in initializing computer prediction models (Mitchell et al., 2004). Spinning up LDASs requires frequent input of radiation data from satellites; "Stage-IV" precipitation estimates from the National Oceanic and Atmospheric Administration's (NOAA's) Office of Hydrology based on radar reflectivity measurements, rain gauge data, and sometimes satellite information; and model integration. Spin-up time is measured in months, yet the use of LDASs has led to a more complete characterization of soil moisture than could be obtained by the direct measurements alone and, collaterally, to somewhat improved forecasts of convective precipitation in summer.

Current data assimilation systems are very sophisticated. They invariably require comprehensive information on observation and model errors and their spatial correlation. Two kinds of error characterize an observation:

1. Measurement error—the error intrinsic to the operation of the instrument. Every instrument samples a particular volume of the medium being measured, whether it is a thermometer mounted in a shelter, a moisture sensor rising through the atmosphere on a weather balloon, or a satellite measuring radiation in a particular wavelength interval upwelling from the atmosphere. Also associated with each measurement is a time interval over which the instrument responds to the medium being sampled. The difference between the number associated with the measurement and the true value (never known precisely) integrated over the sample volume and the sampling time is the measurement error. Measurement errors are usually estimated by calibrating the field instrument against a more accurate laboratory standard.
2. Representativeness error—not really an error, but a measure of the discrepancy between the space-time dimensions of the measurement and the space-time dimensions that can be captured by the model (related to the gridpoint spacing and the time step). For example, a summer afternoon

thunderstorm may occupy just one-tenth of the area of a model grid square. A surface temperature representative of the entire grid square (what the model is supposed to compute) may disagree by 10°C with an accurate temperature measured directly underneath the thunderstorm. If the model had sufficient resolution to predict the thunderstorm explicitly, this discrepancy would be far less. Estimating representativeness error is still more of an art than a science.

Thus, information about observation errors can be as important as the value of the measurement itself, because effective data assimilation assigns weights to information from observations and models, taking into account the size of their respective errors.

Good metadata—detailed information about the instrument, its exposure, calibration, and exact location—is vital for estimating both measurement and representativeness error. Metadata receives more emphasis in Chapter 6 of this report.

SPECIAL REQUIREMENTS FOR CLIMATE MONITORING

To reiterate a point made in the introduction, climate, like weather, has mesoscale variability occasioned by topography and land/ocean surface conditions. That is why climate monitoring cannot be ignored in this discussion; it is one of multiple national applications supported by mesoscale observations.

Climate monitoring imposes demanding requirements for absolute accuracy and long-term stability of measurements. As examples, consider the following trends. Global surface temperature has increased about 0.76°C in the past 100 years; global average sea level has risen 1.8 mm/year from 1961 to 2003 (IPCC, 2007). These changes are small but significant, in that they have already affected many regional ecosystems. Only long-term, stable measurements and considerable averaging enable the detection of such trends.

The National Oceanic and Atmospheric Administration is slowly constructing a U.S. Climate Reference Network (USCRN), with a 2008 target of 114 stations nationwide, whose purpose is to provide future long-term homogeneous observations of temperature and precipitation that can be coupled to past long-term observations for the detection and attribution of climate change (see *http://www.ncdc.noaa.gov/oa/climate/uscrn/index.html*). A minimum of five parameters is measured at each site: air temperature, precipitation, wind (speed only), ground surface temperature (with an infrared sensor), and hemispheric solar radiation (with a pyranometer). The lack of a wind direction measurement decreases the value of USCRN observations for weather-related applications.

The USCRN follows the climate monitoring principles developed by the World Meteorological Organization (WMO) over the past decade for the Global Climate Observing System (GCOS). The WMO promulgated an original set of 10 principles, which apply mainly to surface observations, in 1999. It endorsed 10 additional principles, pertaining to climate monitoring by satellites, in 2003. (All principles are listed at *http://www.wmo.ch/pages/prog/gcos/index.php?name=monitoringprinciples*.)

The WMO has designated selected sounding sites to be part of a GCOS Upper Air Network (GUAN) to provide (1) long-term, high-quality climate records, (2) anchor points to constrain and calibrate data from more spatially dense global networks, including satellites, and (3) where possible, a larger suite of co-related variables such as cloud properties, infrared radiation, and trace gas concentrations that have import for climate monitoring. Twelve GUAN sites are in the United States, including three in Alaska and one in Hawaii. (Design principles, accuracy requirements, and a list of best practices are available at *http://www.gosic.org/gcos/GUAN-spec.htm*.)

Because observed climate changes have *very likely* (Intergovernmental Panel on Climate Change wording) been caused by an increase in greenhouse gases, it becomes ever more important to expand measurements of the chemical constituents of atmosphere and ocean, especially greenhouse gases and aerosols, not only their concentrations but also their sources and sinks. Of course, such measurements would also support day-to-day air quality monitoring and prediction.

By design, climate reference measurements are intended to be especially accurate and stable for the long term. Situated in the midst of a denser network of mesoscale observations from diverse sources, the reference measurements serve as control and calibration points. Conversely, the mesoscale observations indicate how larger-scale climate trends are experienced on the regional scale and modulated by characteristics of the lower boundary. The effects of climate change may well have high spatial variability.

To be convinced of this, examine Figure 3 on page 4 of *Hotter and Drier: The West's Changed Climate* (Saunders et al., 2008). The figure compares the average surface temperature for the lower 48 states, from 2000 to 2007, by climate zone, with the 20th century average. There is considerable spatial variability.

MESOSCALE OBSERVATIONS FOR RESEARCH

The research community has a multi-faceted relationship to mesoscale observations that serves multiple national needs. It can both draw from and contribute to the broader enterprise, but often in ways that are unlike those of other prospective partners. Appropriately funded operational observations are stable, reliable, and dependable, often at the cost of flexibility and adaptability and sometimes sensitivity or precision. Research observations are often episodic, ephemeral, and of limited areal extent, and tend to focus on process-level questions in considerable detail. Consequently, research contributions may fail to contribute reliably or consistently to an ongoing operational enterprise and therefore could be viewed as untrustworthy, disruptive, or even parasitic.

However, the research community has a long track record of pointing the way to what eventually becomes routine in operational observing systems. What we now view as core components of an operational weather monitoring network typically had their origin in the academic community and/or national research laboratories. Examples include but are not limited to Doppler radar, polarimetric radar, radio-acoustic sounding systems, wind profilers, eye-safe aerosol backscatter lidar, portable automated mesonet systems, use of geostationary satellites as primary data collection platforms, a data transfer system for dropwindsondes, and solid state sensors and digital electronic systems that enabled markedly improved performance of surface meteorological stations at the dawn of the digital electronics era. One could view the broader research community as a somewhat autonomous development arm of the atmospheric observation enterprise and a major contributor to its infrastructure, while also recognizing that there are highly directed components, for example, in the NOAA labs.

Another role of the research community is that of a user with special needs. Some research needs are so specialized and ephemeral they would constitute an excessive and costly burden on a national network if implemented. Examples might include extensive use of mass spectrometry to detect and quantify thousands of constituent compounds associated with reactive chemistry in the atmosphere; large arrays of sonic anemometers at each surface station to fully characterize turbulence and related land-atmosphere fluxes; or a battery of acoustic, optical, and radio frequency profilers at each surface meteorological station. In the foreseeable future, such demands, as useful as they might be, likely would not serve the broader interests well.

Nearly all tropospheric and related research programs have use for a mesoscale network to provide a high-quality and minimally aliased sampling of the environment. The requirements of the research communities are broadly consistent with those of other users, namely reliability, calibration, documentation, ability to retain at least minimal flexibility and adaptivity, and the general ability to serve broad functions to an acceptably high standard. A *core national network*, by reason of its permanency, reliability, long periods of record, and geographic extensiveness, offers high value to the research community.

If anticipated prior to network implementation, a flexible short list of *auxiliary research-motivated sensors* could be considered for deployment nationwide, or in regions and seasons of greatest relevance. These systems could be funded by various research interests at a fraction of the cost otherwise incurred if fielded independently. These research-motivated observations are collectively referred to as *a national research backbone*, which enables other research-based observations to be placed in a properly documented environmental context. In many instances, research-motivated observations point the way forward to future operational network capabilities, thereby contributing to the developmental aspect of research community participation.

> **Recommendation: The national network architecture should 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 become operational, serving existing societal needs better and future societal needs well. The impact is likely to be felt at or near the surface and be relevant to both managed and natural terrestrial and marine ecosystems and the heavily built environment. The National Ecosystem Observing Network (NEON), sponsored by the National Science Foundation (NSF), is one promising example of beneficial research engagement. 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.

The developmental role carried out jointly by the scientific and research engineering communities is pivotal to successful implementation of a national mesoscale network. This is the transition from a research demonstration of concept to reliable and hardened operational performance. Often this phase of research and development (R&D) is assumed by a mix of national laboratories and industry. It includes robust design and quasi-operational demonstrations with prototype limited-area networks. Data may be assimilated into limited-area models to evaluate and verify forecast impact.

Applied R&D should include but not be limited to transitional activities, including the operation and evaluation of prototype networks and their forecasted impacts; development of tools to facilitate data access for real-time assimilation; development of tools to serve and educate the general public; and exploration of advanced and innovative technologies to serve multiple national needs better, cheaper, and sooner than otherwise might be possible. Testbeds are an appropriate vehicle for these activities (see Chapter 6). Also discussed in later chapters are the concepts for the design of an integrated, nationwide network of networks (NoN) and the services needed to enable such a network. Here we highlight a few research examples to support a recommendation for the accommodation of auxiliary research observations in a NoN:

Research Example 1: Initiation of Convection in Numerical Prediction Models

Weather radars, notably WSR-88D radars, often show quasi-linear boundaries in the clear-air reflectivity display, and Geostationary Operational Environmental Satellites (GOES) visible satellite images show lines of growing cumulus clouds (e.g., Wilson and Schreiber, 1986; Purdom, 1976).

Both features indicate boundary-layer convergence, and thus they often mark favored locations for the initiation of deep convection. Short-term field programs have shown that quite small variations in the vertical structure of temperature, moisture, and wind in the boundary layer determine whether a thunderstorm will form (Weckworth, 2000; Sun and Crook, 2001). The crux of the matter is whether low-level air parcels can be brought to their level of free convection. This is true for both stationary and moving boundaries (e.g., gravity currents, bores, and other trapped gravity waves).

For more than a decade, committees affiliated with the North American Observing System (NAOS) program and the U.S. Weather Research Program (USWRP) have advocated for dense observations in the boundary layer. The Atmospheric Radiation Measurement/Cloud and Radiation Testbed (ARM/CART) site comes closest to meeting the requirement for horizontally dense measurements of boundary-layer structure, but even its observations are not dense enough. Radiometric measurements from space do not have the vertical resolution for this application, and infrared measurements cannot penetrate clouds in any case.

Ground-based remote sensing, perhaps a combination of a profiling Doppler radar, water vapor lidar, radar refractivity from 88D and other radars, and Radio Acoustic Sounding Systems (RASS), seems to have the best prospect for measuring boundary-layer wind, temperature, and moisture at sub-kilometer horizontal resolution and 50-m vertical resolution. Such resolution might be feasible in a small research network.

Model calculations of heat and moisture fluxes at the surface are not very accurate. Because these fluxes influence the evolution of the boundary layer and ultimately the initiation of convection, their calculation must be improved. That will be difficult without more complete observations of soil moisture and temperature and vegetation fraction (Advanced Very-High-Resolution Radiometer [AVHRR] and MODerate-resolution Imaging Spectroradiometer [MODIS] satellite data are relevant for the latter).

Such information will improve land-surface parameterization and the flux calculations that depend upon it.

The objective of this research is to successfully and consistently simulate convective initiation with a numerical model, having incorporated these detailed observations in the initial conditions. This accomplishment will demonstrate at least the minimal observational requirements for successful prediction of this ubiquitous, disruptive, and often dangerous phenomenon.

Research Example 2: A Soil-Moisture Network to Support Short-Range Climate Variability Modeling

Soil-moisture changes are the terrestrial equivalent of sea-surface temperature changes in providing memory to the climate system. Koster et al. (2004) have shown that predictability can be enhanced in selected regions of the globe by better understanding of land-atmosphere interactions that are principally governed by soil moisture. The central United States is one of these regions. Improved measurements of soil moisture would improve climate-forecast model initialization and would allow for more accurate simulation of a significant and slowly changing component of the hydrological cycle. Better simulation of the soil-moisture reservoir in the growing season will improve the realism of the surface energy budget, which in turn affects gradients in boundary-layer stability and the location and timing of convective processes. Improved simulation of water recycling through evaporation and precipitation would improve the prediction of water leapfrogging across the region during extended periods of weak synoptic forcing and strong convection.

Recently refined surface-atmosphere interaction models are capable of more realistically simulating the surface energy, water, and trace gas cycles, but imprecise knowledge of the soil-moisture reservoir is a severe limitation.

The Oklahoma mesonet delivers a soil-moisture measurement every 30 minutes in every county of the state. These measurements calibrate satellite-based estimates of surface wetness and verify model estimates of water and energy exchange between the surface and the atmosphere. Other, less dense soil-moisture measurements are taken by the Illinois State Water Survey and the University of Nebraska, but no systematic nationwide or even region wide effort exists to collect and distribute these data.

Research Example 3: Surface Heterogeneity and Its Impact on Boundary-Layer Structure and Convective Precipitation

Although weather prediction has improved, the prediction of warm season convective precipitation has lagged behind. One of the suspected reasons for this is the influence of vegetation, soil-moisture, and topography on sensible heating and moistening of the atmospheric boundary layer (ABL). Horizontal variability of surface properties results in horizontal variability in buoyancy fluxes. Buoyancy fluxes and their horizontal variability influence the growth of the ABL through development of thermally direct mesoscale circulations.

Long-term surface, subsurface, and boundary layer observations are needed because of the seasonal variability of thermally direct circulations. For example, in Kansas, C3 winter wheat is green in the months of April and May, after which it senesces, and it is harvested by mid-June. On the other hand, the mixture of native grasses starts greening up in May and becomes lush and green by June. This means that the crops and grasses reverse roles, with the largest sensible heat flux over the grasses in spring and the largest sensible heat fluxes over the harvested wheat fields in the summer. If elevated areas are associated with grasses (as they are in Kansas), the “elevated heat source” effect of ridges reinforces the extra heating in the spring, thus increasing the likelihood of topographically influenced circulations.

What kind of observations would enable better prediction of thermally direct circulations? A network of soil temperature and moisture probes, deployed long-term at the mesoscale. Add to that radar wind profilers and lidar water vapor profiles (see Chapter 4) to track the evolution of the planetary boundary layer and to compute vertical air motions, the local level of free convection, and convective available potential energy. These observations permit the documentation of boundary-layer depth and, with knowledge of ambient synoptic conditions, the likelihood and strength of deep moist convection. A good estimate of the horizontal variation of precipitation would be obtainable from network Doppler and polarimetric radars when assimilated with network precipitation gauge data.

The unique contributions of a national mesoscale network would be long-term regional scale observations of soil moisture and temperature, profiles of winds and divergence fields, water vapor distribution, and gauge/radar coverage of precipitation. In combination with research observing systems such as instrumented aircraft and flux towers, considerable advances in the prediction of warm season convective precipitation would be realized. A complementary strategy is to site research flux towers so that different types of land cover, soil types, and topographical settings are sampled at several points for relatively long periods. Long-term observations, of the type well-suited to a national mesoscale network, are needed in order to obtain a representative period of record, with and without thermally driven mesoscale circulations.

Research Example 4: Improving Chemical Weather Predictions

Predicting chemical weather is of growing importance to society. Chemical transport models have become essential tools for providing science-based input into best alternatives for reducing urban pollution levels, designing cost-effective emission control strategies, siting of facilities, interpreting observational data, and assessing how we have altered the chemistry of the global environment. The forecasting of chemical weather has become a new application area, providing important information to the public, decision makers, and researchers. National weather services throughout the world are broadening their traditional role of mesoscale weather prediction to also include prediction of other environmental phenomena (e.g., plumes from biomass burning, volcanic eruptions, dust storms, and urban air pollution) that could potentially affect the health and welfare of the public. Currently hundreds of cities worldwide are providing real-time air quality forecasts.

While chemical weather prediction and weather prediction are closely aligned, there are important differences between the two. One important difference is that weather prediction is typically focused on severe, adverse weather conditions (e.g., storms), while the meteorology of adverse air quality conditions frequently is associated with benign weather. Boundary-layer structure and wind direction are perhaps the two most poorly determined meteorological variables for chemical weather prediction. Meteorological observations are critical to effectively predicting air quality, yet meteorological observing systems are typically designed to support prediction of severe weather and not the subtleties of adverse air quality. Research needs associated with the meteorological elements of air quality prediction have recently been assessed (Dabberdt et al., 2004a). The additional processes associated with emissions, chemical transformations, and removal also differentiate chemical weather prediction from weather forecasting. Because many important pollutants (e.g., ozone and fine particulate sulfate) are secondary in nature (i.e., formed via chemical reactions in the atmosphere), chemical weather models must include a rich description of the photochemical oxidant cycle. It is also important to note that the chemical and removal processes are highly coupled to meteorological variables (e.g., temperature and water vapor), as are many of the emission terms. In the case of windblown soils, emission rates correlate with surface winds, and evaporative emissions correlate with temperature. In the case of emissions associated with heating and air conditioning, the demand responds to ambient temperature.

The chemical observation networks were designed to support compliance and regulatory functions and not prediction. Chemical weather prediction places greater emphasis on real-time access to data, with broader spatial coverage and vertical extent for initializing prediction models. Advances in our predictive capabilities will require a better matching of the observational capabilities with chemical weather prediction needs (Carmichael et al., 2008). The mesoscale observing system outlined in this report will provide the backbone of data that will enable and accelerate the field of chemical weather prediction.

One important research activity will be the use of chemical data assimilation systems to help design the observing systems needed to produce better forecasts. We need to rigorously quantify the value added to a forecast by adding observations of additional species and above the surface, extending surface coverage; and adding and enhancing the utility of observations from satellites for chemical weather applications.

Research Example 5: Assimilation of Mesoscale Observations into Prediction Models

Only a small percentage of satellite observations is assimilated into prediction models. Debate continues about how to treat measurements of upwelling radiation. Preliminary studies at the UK Met Office have shown that soundings derived from the Atmospheric Infrared Sounder and the Infrared Atmospheric Sounding Interferometer, when inserted into computer prediction models, have had a greater impact on numerical predictions than the direct assimilation of radiance from those sensors, contrary to prevailing opinion. The reason may be that the radiance data are thinned both spatially and spectrally, whereas the derived soundings use all of the spectral information. Only further experimentation will resolve this issue.

The use in prediction models of cloud and hydrometeor information from satellites, surface-based ceiling observations, aircraft observations of clouds and icing, radar reflectivity, and lightning data is still primitive. More sophisticated assimilation techniques are sorely needed.

Correct specification of the statistical structure of model forecast errors is required for optimal performance of three- or four-dimensional variational data assimilation, especially the spatial covariance of model errors. The direct approach to this problem relies on an extensive network of dense observations for the direct calculation of differences between forecast and observed values and their means, standard deviations, and spatial covariances. Another approach is to estimate situation-dependent model errors by means of ensemble forecasts.

Further study is needed on how uncertainty in the initial state (primarily due to the sparsity of observations with respect to the grid resolution of today's operational prediction models) translates into uncertainty in the model forecast.

3

National Needs for Mesoscale Observations in Five Economic Sectors

Chapter 2, along with Appendix A, developed a rationale for spacing and frequency of observations that is appropriate for nationwide weather prediction, climate monitoring, and supporting research. This is the most fundamental application of mesoscale observations in that it seraves many other applications of huge economic import, either directly or indirectly.

This chapter exposes the needs for mesoscale observations in five areas vital to the nation's well-being: (1) energy security, (2) public health and safety, (3) transportation, (4) water resources, and (5) food production. Other areas could have been examined, for example, outdoor recreation or construction, but these five are representative of both the astounding diversity of need and the tremendous value of well-placed and timely observations.

For each sector, we note its importance to the national economy, list current assets and operational requirements for mesoscale observations, and highlight the more critical future needs.

ENERGY SECURITY

Importance to the National Economy

Sufficient and reliable supplies of energy are critical to the security of the nation and for sustained, uninterrupted economic growth. To address the meteorological observations needed to support energy security, we first identify the stages comprising the transition from the primary energy source to final consumption. For example, the use of fossil fuels for energy consumption involves extraction, refinement, transport, conversion, transmission (for electricity), and final end use. Meteorological measurements may or may not be needed for decision making during each of these stages. For instance, the use of coal for generating electricity for residential consumption is relatively weather insensitive (except for disruption by extreme events) at the extraction, refinement, and transport stages, but is weather sensitive for conversion (load planning), transmission (routing and line exposure to weather), and final end use (weather-driven demand).

Recent trends to replace fossil fuels with renewable primary energy sources—particularly biomass, direct solar, wind, and hydroelectric—create somewhat different transition stages from primary source to final consumption and hence somewhat different environmental monitoring needs. Biomass has perhaps the highest vulnerability to weather and therefore the greatest need for weather monitoring, starting with the seasonal weather outlook that favors the planting of one biomass crop over another. Planting, growth, harvest, and transport to consolidation point or conversion facility all present weather-related vulnerabilities not applicable to fossil fuels and call for reliable meteorological measurements and the best-available weather forecasts and seasonal climate outlooks. Direct solar, wind, and hydroelectric power have somewhat different but less complex weather data requirements. In total, renewable primary energy sources call for a wider range of measurements (e.g., soil moisture, direct and diffuse radiation, vertical profiles of wind, snow depth, stream flow, reservoir temperature) at more locations and advances in short-term and seasonal forecasts. In addition, renewable primary energy sources are more vulnerable to extreme events, particularly drought, hail, flood, extreme heat and cold, tornados and hurricanes, than are fossil energy sources.

The emerging wind power industry has meteorological observing needs that are similar to other currently unmet needs discussed elsewhere in this report, particularly observations in the lower part of the atmospheric boundary layer above the surface. Wind resource characterization and forecasting, like chemical weather monitoring and forecasting, requires information about vertical structure of mean and turbulent wind characteristics and temperature throughout the atmospheric boundary layer, including boundary-layer depth. A 1 percent error in wind speed characterization has an estimated $12 million impact on projected output of a 100 MW wind-power plant over its lifetime. Variability and uncertainty of near-term (diurnal cycle) and long-term future power deliverable from wind farms underscores the need for vertical profiles of relevant variables at a frequency exceeding twice-daily raob schedules.

In the energy sector, weather information translates directly into profits and losses on short time scales (minutes to days). Sensitivity of energy demand to climate fluctuations is illustrated by the fact that a fraction of a degree in

Vignette: Duke Power

Background

Duke Energy-Carolinas generates, transmits, and distributes electrical energy to customers throughout western North and South Carolina. Damaging ice storms in 1996, 2002, and 2005 cost Duke millions in restoration dollars. The most severe ice storm in December 2002 affected a large section of the Carolinas Service Area, caused 1,375,000 customers to lose power, and cost the company $77 million in repairs. That storm resulted in the mobilization of over 11,000 workers from Duke Energy and external companies to repair 3,200 damaged poles, 2,300 transformers, and 549 miles of wire. Because of the huge economic impact of damaging ice storms, power companies take a proactive approach to forecasting, planning, and scheduling resources ahead of such events. Millions of dollars in resource decisions are made before and during an ice storm.

Since ice storms are exceptionally damaging and difficult to forecast, real-time mesoscale observations are critical. Two factors affect ice accumulation on trees and power lines: total rainfall and surface temperature (i.e., how far below freezing). Spatial patterns of rainfall and subfreezing temperatures are important in estimating the ice thickness and areal coverage and affect resource decisions for utility management. One recent event underscores the importance of real-time mesoscale observations in making quick resource decisions.

December 2002 ice storm in the Western Carolinas. SOURCE: Nick Keener, Duke Energy.

The Event

Numerical forecast guidance from the National Centers for Environmental Prediction (NCEP) indicated the potential for a significant ice storm on February 1, 2007, across portions of the Duke Energy-Carolinas Service Area. Forecast models indicated the potential of $^3/_8$ to $^1/_2$ inches of ice accumulation beginning in the early morning hours and continuing into the afternoon of February 1. As early as January 29 Duke Energy mobilized its internal workforce and began contacting neighboring utilities and contractors for additional resources in anticipation of significant outages across the service area. During the pre-dawn hours of February 1, freezing rain begin to fall across the area. By mid-morning a light glaze of ice approaching $^1/_8$ inch had accumulated. Radar and forecast guidance indicated that freezing rain would continue well into the afternoon and, if temperatures remained below freezing, would result in ice accumulations approaching ½ inch on trees and power lines before ending. By 10 am on the morning of February 1, Automated Surface Observing System (ASOS) observations showed temperatures rising to near the freezing point. By 11 am the surface temperatures in most affected areas were 32°F. Although the latest numerical guidance at that time and the official forecast from the National Weather Service (NWS) still indicated a continuation of freezing rain, it was apparent that milder air was mixing to the surface from aloft and was eroding the shallow wedge of sub-freezing temperatures. Given the real-time ASOS observations supplemented by other surface reports, Duke Energy's meteorology staff recommended that preparations for significant outages be discontinued, resulting in a significant savings to the company.

Real-time mesoscale observations of temperature, dewpoint, wind, pressure, and precipitation are critical to decision making when a temperature change of a few degrees can mark the difference between a cold rain and an ice storm. The former is a nuisance; the latter causes major disruptions. An increase in the spatial coverage of the mesoscale observational network and the availability of 15-minute reports would enable electric utilities, municipalities, and public transportation entities to make better resource decisions, thereby saving money and possibly mitigating impacts from adverse weather conditions.

mean temperature for planning over a heating season can have huge impacts on profitability. Also, a particular electrical power company will do a daily market analysis for the entire nation (i.e., outside its own service area) and so will need reliable observations and forecasts outside its service area.

Current Assets and Operational Requirements for Mesoscale Observations

The power-generation industry uses a combination of National Oceanic and Atmospheric Administration (NOAA) products and services together with company-managed observations and in-house forecasting. Company-managed observations generally are intended to increase spatial resolution or timely access rather than to introduce new sensing technologies or to observe different meteorological variables.

Below are some examples of measurements and forecast time horizons appropriate for national energy security.

Stationary Power Generation

- Current observations and short-term forecasts for meeting daily load demand, hourly pricing, and risk analysis for load obligation;
- Current observations and short-term forecasts of extreme conditions leading to possible interruptions and storm response;
- Current observations and short-term forecasts of high concentrations of pollutants near the ground as a reason for curtailing operations at coal-fired power plants;
- Climatological databases and seasonal forecasts for monthly and seasonal planning for fuel inventories and revenue projections;
- Climatological databases, and seasonal and interannual to interdecadal projections of climate variability and change. Long-term planning for urban and rural development, and industrial and commercial needs (climate scales).

Biomass Primary Energy Production

- Seasonal climate forecast or outlook for biomass crop choice;
- Current observations and short-term forecasts for planting conditions (soil moisture, soil temperature);
- Seasonal forecasts for projecting crop growth and harvested biomass.

Renewable Energy Generation

- One-to-three-day estimates of atmospheric turbidity and cloudiness for projections of solar power generation;

- One-to-three-day estimates of wind speed for estimates of power generation by wind turbines. In the same time frame, icing on the props must be anticipated;
- Very short-term forecasts of sudden wind shifts or changes in speed. Turbines must be shut down to avoid damage if wind speeds become too high. Air density forecasts are useful in that density affects the force exerted on props when the wind blows.

Needs for the Future

Enhanced observations to meet the needs of the power-generation industry would lead to more accurate initial conditions in model forecasts. Similarly, high-resolution observations needed by the Department of Homeland Security (DHS) for running plume models and coordinating emergency response in urban environments would find profitable use on a 24/7 basis in the energy industry.

Increased attention to energy security under conditions when foreign sources of primary energy are supplanted by national sources, especially more weather-vulnerable sources such as biomass, will call for more intensive weather monitoring and forecasting (short-term and seasonal). At the same time more energy-related measurement platforms may be available for providing new measurements (e.g., wind farm towers, instrumented agricultural machinery, or "smart" power transmission line poles in remote areas).

More fine-scale information is needed in urban centers. Distinguishing the meteorological factors (temperature, humidity, wind, solar radiation) that influence energy send-out by urban divisions (e.g., residential, industrial, commercial, recreational) would facilitate estimation of short-term demand. Real-time surface data should be available from NOAA Port or its equivalent every 15 minutes.

Sites that are able to operate and transmit data through outlier events such as hurricanes and severe thunderstorms are critical for damage assessments prior to restoration of power, normal communications, and safe travel in the affected areas. Multiple options for communicating the data to a central facility often mark the difference between the loss of vital information or continued reception.

More detail about the spatial distribution of total rainfall over individual watersheds is needed to manage reservoir storage. In winter and spring, basin-by-basin data on snowpack and the rate of melting enable decisions about reservoir storage and clarify the potential for flooding on large rivers, which affects inland marine traffic.

Both remote sensing systems and in-situ observations are needed to characterize the planetary boundary layer over the diurnal cycle. Knowledge of the depth of the atmospheric boundary layer is needed to operate conventional power generation facilities and wind parks. Detailed observations aloft of temperature, humidity, wind, and suspended hydrometeors help to inform resource estimates (wind parks), emergency operations (power outages), and curtailment of operations (because of air pollution).

Any observations that would improve extended range (seasonal) forecasts (sea-surface temperatures, temperatures within the thermocline, soil moisture, snowmelt) would immensely benefit the power-generation industry, particularly in the production of biomass fuel.

A national network of soil-moisture measurements (need not be spatially uniform) would benefit several participants in the energy sector. The role of soil moisture as a climate memory for short-term and seasonal forecasts is well known. Such a network would have a multiplicative benefit, since better observations of soil moisture would improve short-term precipitation (and hence short-term soil moisture) forecasts, which, in turn, would improve seasonal precipitation and soil-moisture climate forecasts. In addition, a network of soil-moisture measurements would benefit streamflow forecasts, snow-depth forecasts, biomass production estimates, and reservoir-level estimates. When seasonal forecasts achieve a level of accuracy and quantifiable uncertainty such that they are used routinely in economic projection models, they have the potential to substantially mitigate negative economic impacts of extreme weather events.

One variable not measured by NOAA or other standard networks is the temperature of water discharged from power plants and of adjacent lakes and downstream rivers. Human-caused alterations in natural water temperatures have strong effects on downstream ecology.

Influences of weather on the power-generation industry are event driven. Building upon the analysis provided by Schlatter et al. (2005) and following the methodology we used develop Appendix A, we can summarize the spatial and temporal scales of influences of weather on the power industry (Table 3.1). We can also estimate the measurement resolution (instrument accuracy, spatial resolution, and temporal resolution) needed to meet the needs of the power industry.

PUBLIC HEALTH AND SAFETY

Importance to the National Economy

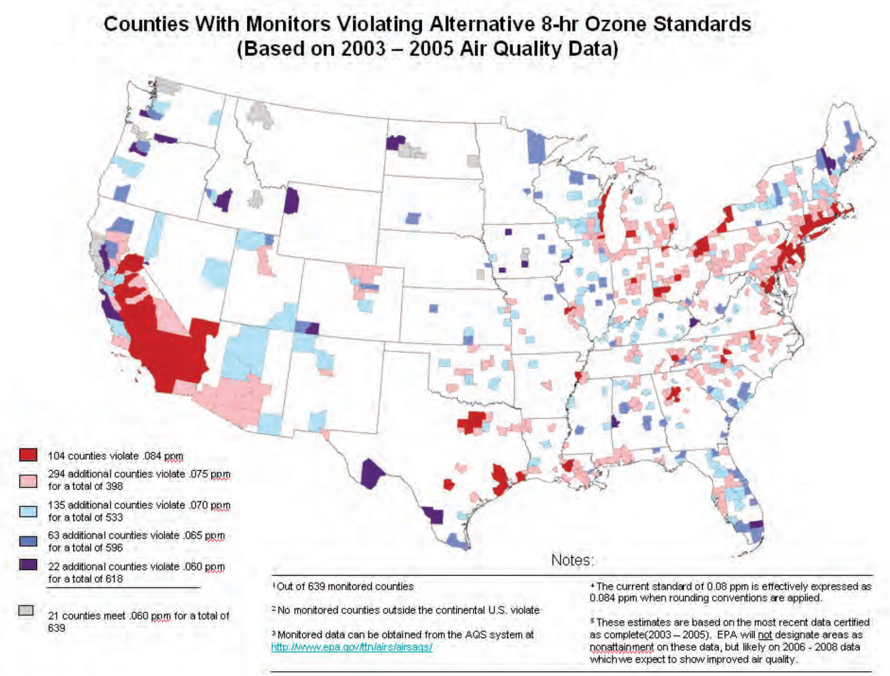
Safety and health concerns extend beyond the traditional weather issues related to transportation, severe storms, and energy to the important issue of air quality. The chemical composition of the atmosphere has been (and is being) significantly perturbed by emissions of trace gases and aerosols associated with a variety of anthropogenic activities. This changing of

TABLE 3.1 Spatial and temporal scales of several meteorological phenomena of consequence for the power-generation industry, and the measurement resolution (instrument accuracy, spatial resolution, and temporal resolution) required to adequately observe those phenomena

Event	Space	**Time**	**Measurement Resolution**
Heat wave (temp)	500-1500 km	2 days-1 week	0.5°C, 10 km, 1 hr
Wind[a]	1-2000 km	1 min-4 days	1 m s^{-1}, 1 km, 1 min
Wind (for wind power)	100 m-1000 km; to 1 km[b]	10 min-1 week	0.5 m s^{-1}, 100 m, 10 min; (1 m s^{-1}, 30 m, 10min)[b]
Snow and ice storms	50-1000 km	minutes-2 days	1 mm snow water equiv. 1 cm snow, 1 km, 30 min
Lightning	region	minutes to hours	location to 0.5 km
Precipitation[c]	basin to regional	Hours-days, seasonal to interannual	1 mm, 1 km, 1 hr.
Cloudiness[c]	local to regional	daytime hourly to monthly	0.1 sky, 10 km, 20 min
Waste heat impact	10 km, lakes and rivers	1 hour-4 days	0.5°C, 100 m, 1 h
Normal weather	urban (2 km) rural (30 km)	20 min-climate	

[a] Could be associated with a Nor'easter (4 days), icing conditions, hurricanes or tornadoes (1 min), straight-line winds, or fire weather.
[b] Measurements in the vertical direction.
[c] Could be from short-term (management) or long-term (planning) for hydropower production.
SOURCE: Derived from Schlatter et al. (2005).

the chemical composition of the atmosphere has important implications for urban, regional, and global air quality, and for climate change. In the United States, 104 counties are currently in non-attainment with respect to the 8-hour National Ambient Air Quality Standards (NAAQS) standard for ground-level ozone (Figure 3.1). The situation is expected to worsen as we move towards even more stringent standards. Safety and health concerns also extend beyond traditional air quality issues to encompass the effects of heat waves, severe cold, and high pollen levels, and to emergency response to release of hazardous substances, bioterrorism, and fires/smoke.


Counties With Monitors Violating Alternative 8-hr Ozone Standards
(Based on 2003 – 2005 Air Quality Data)

Notes:

[1] Out of 639 monitored counties

[2] No monitored counties outside the continental U.S. violate

[3] Monitored data can be obtained from the AQS system at http://www.epa.gov/ttn/airs/airsaqs/

[4] The current standard of 0.08 ppm is effectively expressed as 0.084 ppm when rounding conventions are applied.

[5] These estimates are based on the most recent data certified as complete(2003 – 2005). EPA will not designate areas as nonattainment on these data, but likely on 2006 - 2008 data which we expect to show improved air quality.

FIGURE 3.1 U.S. counties in non-attainment of the NAAQS 8-hour ozone standards. SOURCE: Scheffe (2007).

Dealing with public health and safety issues requires an ability to characterize and predict chemical weather. By chemical weather we mean "local, regional, and global distributions of important trace gases and aerosols and their variability on time scales from minutes to days, particularly in light of their various impacts, such as on human health" (Lawrence et al., 2005). As in the field of meteorology, prediction involves both observations and models, and their close integration. The use of chemical weather forecasts in Public Health and Safety (PHS) management has become a new application area and provides important information to the public, decision-makers, and researchers. Many cities in the United States are providing real-time air quality/chemical weather forecasts and various organizations are broadening their services to include prediction of other environmental phenomena (e.g., plumes from biomass burning, volcanic eruptions, dust storms, and urban air pollution) that could potentially affect the health and welfare of their inhabitants. For example, the National Weather Service (NWS) has recently started to provide mesoscale numerical model forecast guidance for short-term air quality predictions, beginning with next-day ozone forecasts (available at *www.weather.gov/aq*), and plans to expand this air quality capability by extending the forecast period and adding fine particulate matter ($PM_{2.5}$) to the forecasts.

Borrowing lessons learned from the evolution of numerical weather prediction (NWP), chemical weather prediction through the assimilation of chemical data holds significant promise. Careful design and use of observations will produce an expanded capability in chemical weather prediction, which in turn will offer benefits in the following areas:

- Public health: Accurate time- and location-specific health alerts will help the public reduce acute exposure when high pollution levels are expected. Routine daily forecasts will enable the public to make healthier choices (e.g., exercising outside only on low-pollution days).
- Planning: Chemical weather forecasts will allow organizations to plan business activities more effectively. For example, the U.S. Forest Service and other land management agencies will need these forecasts to ensure their planned ten-fold increase in prescribed burning will not result in violations of the NAAQS. Forecasts can be used by government and industry to reduce emissions on predicted high-pollution days, thus avoiding the high cost of continuous emission controls.
- Emergency response and risk management: Effective emergency-response forecasting will help organizations better understand and manage the consequences of accidental or intentional releases of hazardous material into the atmosphere. With that information, they can reduce exposure, both by effective responses (e.g., sheltering-in-place, evacuating) and by planning remedial actions.
- Forensics: Identifying the type and quantity of hazardous materials released into the atmosphere will require not only measurements but also accurate dispersion modeling of plume concentrations and ground deposition.
- Wildfires and smoke: Improved prediction of chemical weather will assist air quality agencies in planning controlled burns, as well as aiding firefighters in setting up command posts, managing or fighting fires, and protecting themselves from exposure to smoke. Additionally, the public will benefit from evacuation guidance and protective measures.
- Assessments: Chemical forecasting simulations and their reanalysis will provide valuable continuous records of air quality and deposition estimates that will inform numerous retrospective assessments such as epidemiological studies, the progress of air program rules, and delineation of meteorological and emissions influences on air quality.

Current Assets and Operational Requirements for Mesoscale Observations

Meteorological Parameters

Air quality and related issues depend strongly on the meteorological conditions that effect dispersion and emissions (e.g., wind-blown soil fluxes depend on surface winds, and evaporative emissions depend on temperature). Thus a better characterization of meteorological conditions directly benefits air quality prediction and management. However, there are some important differences in the spatial and temporal requirements for air quality mesoscale observations. Many PHS problems are associated with benign weather (stagnant conditions) and particular phenomena such as urban heat islands, nocturnal jets, local circulations (e.g., sea-land breezes), which have not been the primary focus of observing systems nor NWP efforts (which have been slanted more toward severe storm conditions). Boundary-layer information, including mixing layer height and clouds, is of particular importance. Key meteorological parameters for PHS applications include temperature, wind speed and direction, boundary-layer characterization, relative humidity, and solar radiation, often at scales of less than a kilometer horizontal spacing (i.e., city-block scale).

Pollutant Parameters

There are observational needs beyond those of meteorology. Measurements of key trace gases and aerosols are required in PHS applications. Many observational networks focus on air quality and related issues and are too numerous to list here. A sampling of air quality networks is presented in the second table of Appendix B Table B.2. Many are operated by the Environmental Protection Agency (EPA). The National Park Service (NPS), NOAA, the Department of Energy (DOE), and the U.S. Forest Service (USFS), state agencies, and tribal governments are involved in the operation of air monitoring networks, and some networks are privately operated by interested industry or research groups (Scheffe, 2007). In addition to the networks summarized in Appendix Table B.2, there are a number of environmental networks comprised of monitors deployed at power and industrial facilities for compliance and other purposes. Examples include those operated by the Tennessee Valley Authority and the Electric Power Research Institute. These networks are developed to meet fairly specific objectives along programmatic lines. Examples include tracking trends of acidity and acid-neutralizing capacity through the surface water Temporally Integrated Monitoring of Ecosystems /Long-Term Monitoring (TIME/LTM) networks, determining compliance with the (NAAQS) in the State and Local Air Monitoring Networks (SLAMs), and establishing vis-

Vignette: AIRNow

> *Each year in the United States, people with asthma experience more than 100 million days of restricted activity, costs for asthma exceed $4 billion, and approximately 4,000 people die of asthma. (National Center for Health Statistics, 2002).*

An excellent example of network integration and application is AIRNow, a national air quality notification and forecasting system. AIRNow provides the public with easy access to national air quality information, including air pollution data and maps, air quality forecasts, information about the effects of air pollution on public health and the environment, and actions that people can take to protect their own health and reduce pollution-forming emissions. AIRNow is operated by the Environmental Protection Agency in partnership with over 130 organizations including NOAA, NPS, NASA, National Forest Service, and state, local, and tribal air quality agencies across the United States, Canada, and parts of Mexico. From its humble start 10 years ago in the Northeast as a regional data collection and dissemination system, AIRNow has grown into the “go-to” resource for current air quality information by providing daily Air Quality Index (AQI) forecasts and real-time conditions.

This voluntary program has grown organically with the integration of air quality and meteorological data from over 2000 monitoring sites operated by more than 130 air quality agencies to provide air quality information in near real time (within 30 minutes of data collection). The AIRNow system receives and quality-checks the data and provides a single access point for health-based information by distributing it via the Internet (*www.AIRNow.gov*) and e-mails (*www.EnviroFlash.info*) and to commercial weather service providers who feed media organizations (television, radio, and newspapers) with weather-related information.

AIRNow is more than just a system; it is a community working together to protect public health. The management dynamics that evolved and continue to sustain this program and community were recently studied by researchers funded by the National Science Foundation. They evaluated the management and leadership characteristics that make some government programs succeed beyond all expectations (Linder, 2007). AIRNow continues to expand its services by distributing raw data to many other operational and research systems and universities that need access to real-time air quality data.

ibility baselines and associated progress in the Interagency Monitoring of Protected Visual Environments (IMPROVE) network. Networks such as UV-Net are focused on solar radiation (ultraviolet [UV], photosynthetically and photochemically active radiation) and provide information on the geographical distribution and temporal trends of radiation for studying the effects of UV on biota and materials. Radioactivity is the focus of RadNet, which has stations in each state and is used to track environmental releases of radioactivity from nuclear weapons tests and nuclear accidents. The BioWatch monitoring program, set up by the Department of Homeland Security, is designed to detect the release of pathogens into the air, providing warning to the government and the public health community of a potential bioterror event.

The geographical distribution of these sites is shown in Figure 3.2. What emerges from Appendix Table B.2 and Figure 3.2 is that in aggregate there are significant numbers of chemical parameters being observed and used to support a wide variety of important health and safety issues.

These observing systems have evolved over the years to reflect national needs. The 1970 Clean Air Act established a framework for the NAAQS and drove the design and implementation of the NAMS and SLAMS networks in the late 1970s. These networks were intended primarily to establish non-attainment areas with respect to the NAAQS for ozone, sulfur dioxide, nitrogen dioxide, carbon dioxide, lead, and particulate matter (PM). The NAMS/SLAMS networks have evolved over time (Figure 3.3) as a result of cyclical NAAQS review and promulgation efforts leading to changes in the measurement requirements related to averaging times, locations, and the various size cuts associated with particulate matter.

Contribution of Satellites

Satellite data support various services, including public health advisories, and assist the community by providing data that cover broad spatial regimes in areas lacking ground-based monitors and information in the vertical. Satellite products complement existing observational platforms by

- detecting fire and smoke plumes,
- providing GOES meteorological data and aerosol optical depth retrievals,
- providing direct observational evidence of regional and long range intercontinental transport,
- enabling emission inventory improvements through inverse modeling,
- assisting in the evaluation of air quality models,
- tracking emissions trends (accountability),
- complementing surface networks through filling of spatial gaps,
- supporting development of wildfire and prescribed burning emission inventories.

FIGURE 3.2 The current state of the U.S. air monitoring networks. Shown are the locations of the sites within various programs, as well as the national coverage of specific air pollution parameters. See Appendix Table B.2 for details regarding the NATTS, PAMS, CASTNet, and IMPROVE networks. SOURCE: Draft National Air Monitoring Strategy, EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, December 2005, available at *http://www.epa.gov/particles/pdfs/naam_strategy_20051222.pdf*.

Needs for the Future

General Considerations

National needs continue to evolve, and the spectrum of current health and safety concerns bring emerging challenges for observing systems (NRC 2004b). Examples include

- developing multiple pollutant integrated management strategies,
- assessing and protecting ecosystem health,

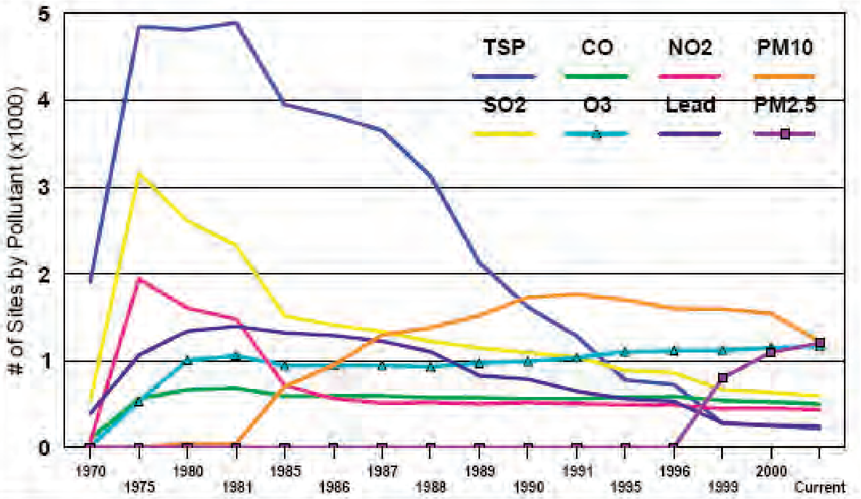


FIGURE 3.3 Evolution of the U.S air network growth. NOTES: TSP = total suspended particulates, PM10 and PM 2.5 refer to particle with diameters less than 10 and 2.5 microns, respectively. SOURCE: Draft National Air Monitoring Strategy, EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, December 2005, available at *http://www.epa.gov/particles/pdfs/naam_strategy_20051222.pdf*.

- observing multiple spatial scales of interest, from street canyons to intercontinental transport,
- adapting air quality management to changing climate,
- mitigating pollution effects that may disproportionately affect minority and low-income communities,
- growing needs for chemical weather forecast capabilities and emergency response applications, which place additional demands for (near) real-time access to data.

In general, these PHS applications need access to a broader spectrum of data and more quickly than is currently possible in existing networks. In addition, the need for rapid assessment of PHS impacts from an incident that might occur anywhere in the United States requires data from more locations than are currently monitored.

Enhanced Meteorological Measurements to Support PHS

Table 3.2 summarizes the major meteorological parameters and the capabilities of current measurement systems that are necessary to meet

TABLE 3.2 Summary of key capabilities of key meteorological observations to meet public health and safety applications; significant gaps exist in aloft, over-water, and hourly data

	Measurement Issue		
Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution
Air Quality			
Surface	Fair		Good
Aloft	Poor	Poor	Poor
PBL Depth			
NBL	Poor	Poor	Poor
CBL	Fair	Fair	Poor
MBL	Poor	Poor	Poor
Winds			
Surface	Good		Good
Aloft	Fair	Fair	Poor
Temperature			
Surface	Good		Good
Aloft	Fair	Fair	Poor
Relative Humidity			
Surface	Good		Good
Aloft	Fair	Good	Poor
Clouds	Good	Good	Good
Precipitation	Good		Good
Pressure			
Surface	Good		Good
Aloft	Good	Good	Good

NOTE: NBL, CBL, and MBL refer to the nocturnal, continental and marine boundary layers, respectively.
SOURCE: Tim Dye, Sonoma Technologies, Air Quality Community's Meteorological Data Needs, presentation to the Committee.

spatial and temporal requirements. The major deficiencies are related to measurements aloft, in urban environments, over water, and in temporal resolution.

The design of the mesoscale observing network should reflect the PHS needs for better characterization of planetary boundary layer (PBL) dynamics and other factors influencing transport and dispersion. Chemical weather predictions play a critical role in PHS management, where they are used by local agencies to issue public health warnings and alerts, and by police and fire departments to respond to hazardous releases. Since the 9/11 attacks, there has been an increased emphasis on developing urban- and building-scale dispersion modeling capabilities and on predicting flows within street canyons at time scales of minutes and distances up to a few kilometers.

Recently, an expert working group met to identify and delineate critical meteorological research issues related to the prediction of air quality. In this context, "prediction" is denoted as "forecasting" and includes the depiction and communication of the present chemical state of the atmosphere, extrapolation or nowcasting, and numerical prediction and chemical evolution on time scales up to several days. The group emphasized the meteorological aspects of air quality. The resultant report, *Meteorological Research Needs for Improved Air Quality Forecasting: Report of the 11th Prospectus Development Team of the U.S. Weather Research Program*, (Dabberdt et al., 2004a), identified the needs for enhancing meteorological observations and predictive capabilities that support PHS. These include

- improved estimation of the temporal and spatial variability and uncertainty of the height of the PBL;
- better parameterization of winds and turbulence above the shallow, surface-based stable layer, and remote sensing of this deeper layer in key areas;
- a nationwide observing network to routinely monitor (with high resolution) the diurnal variation of the height and structure of the PBL that exploits and supplements existing measurement systems;
- enhancements to numerical modeling of the PBL. Associated meteorological observations must be linked with chemical measurements;
- improved depiction of seasonal and interannual vegetation variations that are important for dry deposition; and
- more realistic model treatment of spatial and temporal variations in soil moisture and better soil moisture initializations.

Observations to Better Characterize the Chemical Nature of the Atmosphere

Although Figure 3.2 shows many sites that measure the chemical composition of the atmosphere, there is poorer network coverage in rural areas, in part because the measurements were designed mainly to test for compliance with regulatory standards of concentration, not to increase predictability of air quality or to respond to emergencies. The latter two functions require broad spatial coverage to initialize models and to assess contributions from long-range transport. That the instruments used to measure a given parameter are often different compounds the problem. For example, while the North American networks have deployed over 1000 routinely operating continuous $PM_{2.5}$ mass samplers, the use of different instruments with different errors and sensitivities makes it difficult to combine the datasets.

Major gaps exist in terms of spatial, temporal, and parameter coverage. For example, while greater than 95 percent of air pollutant mass is located above 100 m, 95 percent of the measurements are made near the surface. Observations of pollutant levels above the surface are important because significant amounts of material are transported above the surface before being brought near the surface to impact human and ecosystem health. The vertical measurements generally focus on the meteorological parameters that affect the mixing and transport of pollutants, not on the concentration of polutants. A main source of vertical information, the radiosonde network (with an ozone monitoring component at a few sites), lacks the necessary temporal resolution to adequately characterize diurnal development and collapse of the PBL. The Photochemical Assessment Measurement Stations (PAMS) program and other air agency efforts support a network of radar profilers that provide highly resolved wind profiles, but the national coverage is very limited. Details regarding vertical measurement capabilities are discussed in Chapter 4.

The above facts severely limit our ability to characterize and predict chemical weather.

> **Recommendation: To meet national needs related to public health and safety, including the growing need for chemical weather forecasts, a core set of atmospheric pollutant composition parameters should be part of the mesoscale observing system. The core set should include carbon monoxide, sulfur dioxide, ozone, and particulate matter less than 2.5 microns in size at approximately 200 urban and rural sites (~175 km spacing).**

These observations would constitute a national backbone of urban and rural sites and should be especially effective in enabling chemical weather prediction when collocated with surface meteorological observations and related vertical profiles (as discussed in Chapter 4). The identified parameters play important roles in chemical weather forecasting applications, can be measured effectively at the scale and locations of the mesoscale network, and can be measured or inferred (e.g., $PM_{2.5}$ and aerosol optical depth) from satellites. For these species, the satellite observations can be used to provide additional information regarding the spatial distributions of the pollutants. Additional important parameters (e.g. NO_2) should be added as soon as appropriate and as affordable technology is developed for the applications envisioned.

This aspect of the mesoscale network could build upon EPA's proposed National Core Monitoring Network (NCore). NCore was developed in response to the National Research Council's (NRC's) *Air Quality Management in the United States* (NRC, 2004b). The NCore framework, as shown in Figure 3.4, is a tiered system consisting of three different levels of observations. Level 3 is designed to provide broad spatial coverage of a single pollutant. The Level 2 design includes deployment of 75 surface stations in a "representative" mix of urban and regional areas with a spectrum of measurements to meet multiple needs, including constrain regional model evaluation, link to satellites, and service accountability and epidemiological studies (not compliance sites). Level 1 consists of a small set of advanced sites where new measurements are needed to serve science and technology transfer objectives. The network design addresses many of the shortcomings identified earlier in this section for near surface observations, including the identification of key meteorological and pollutant information. It is important to note that the 75 Level 2 NCore sites are not adequate from a spatial coverage perspective, but are intended to foster additional deployment of collocated measurements as their utility is demonstrated. A national network designed to meet the spectrum of PHS applications requires compositional capabilities at 200 sites with a core set of parameters that should include carbon monoxide, sulfur dioxide, ozone, and particulate matter less than 2.5 microns in size.

These compositional observations should be especially effective in enabling chemical weather prediction when collocated with surface meteorological observations and related vertical profiles. Currently, the NCore plan does not map out a strategy for the inclusion of profiling information from lidars or aircraft. In the national mesoscale network these observations should be collocated with the vertical profile observations, as covered in detail in Chapter 4.

Integrating Surface- and Space-Based Chemical Observations

Gaps exist in mesoscale observing networks that limit the ability to integrate surface- and satellite-based systems for the mutual improvement and leveraging of both systems in characterizing boundary-layer air quality. In order to enable the integration of satellite observations with surface values, the surface-based network must contain surface and boundary-layer information on the same species that is observed from satellites. Emphasis should be placed on providing precision surface measurements of the satellite column species that are well retrieved (ozone, PM optical depth, sulfur dioxide, nitrogen dioxide, carbon monoxide, formaldehyde, and glyoxal),

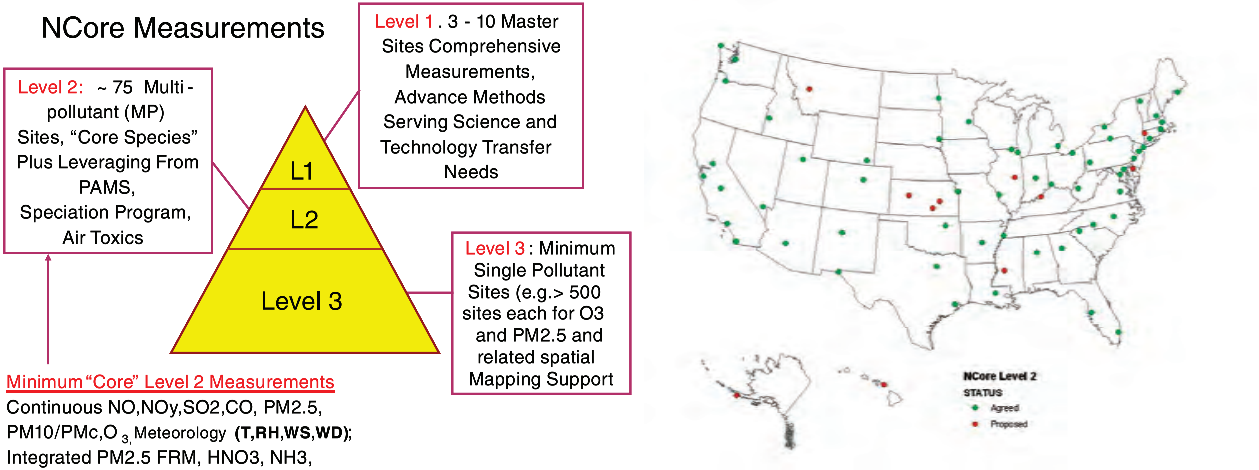


FIGURE 3.4 The NCore network design.
NOTE: PAMS refers to the Photochemical Assessment Monitoring Stations Program, PMc to the coarse size fraction of particulate matter, and FRM to the federal reference method for fine particle measurements. SOURCE: Scheffe (2007).

in order to provide validation for the satellite-derived data (Tinkle et al., 2007). Presently only the first three species have broad coverage in the surface observations. Thus there is a need for expansion of key ground-based measurement systems that offer leveraging of satellite data. Some but not all of these species are included in the planned NCore sites discussed above.

Space-based observations of chemical constituents in the lower troposphere are hampered due to the opacity of the atmosphere in the ultraviolet from Rayleigh scattering, and the limited vertical resolution of infrared retrievals near the surface. Thus mesoscale observations are essential in characterizing the composition of the lower atmosphere.

Observations in Urban Areas: A Special Case

Based on current census data, over 75 percent of the U.S. population lives in urban environments (in cities with more than 200,000 people). The hazards of pollution and terrorism make the requirements for mesoscale observing in urban environments more demanding than those discussed elsewhere in this chapter. The needs for observations at the street canyon level are obvious for some of the agencies that sponsored this report, but review of the cross-cutting nature of the other societal benefit areas has not made urban-scale observing an obvious candidate for enhanced network development. Recommendations from an NRC report on homeland security (NRC, 2003a) identified the need for increased observations, designed to systematically characterize local-scale wind flow patterns (over the full diurnal cycle) in areas deemed to be potential terrorist targets, with the goals of optimizing fixed observations and educating those involved in developing dispersion forecasts about local flows and model strengths and weaknesses. Committee discussions with DHS revealed that improved modeling of airflows at rooftops (i.e. better prediction of the external forcing of weather on the urban area) was the most demanding requirement from a mesoscale observing system. With such boundary condition information available, DHS would rely on separate models of street canyon airflow and street canyon deployable instruments (many of which could not be discussed with the Committee). The required number of observations in an urban environment could be so large that the network models that are being considered for other mesonet structures would most likely be insufficient and would drive responsibility for such observations into the federal realm, where significant resources and directed programs could best manage these needs.

In a similar vein, transportation accidents (air crashes, train derailments, hazardous cargo spills, port spills) also require inputs of weather information at the finest spatial and temporal scales, as addressed by the

NRC in its report on dispersion of hazardous wastes (NRC, 2003a). Confounding these important PHS applications is the fact that the source function is a key driver, yet its location and intensity are often poorly constrained. This places additional requirements on the observing systems. The agencies that are required to respond to such events have indicated that rapidly deployable sensors that could be mobilized to provide additional transient information are a major need. The prototype RAWS observations, deployed around wildfires or special events where public safety could be threatened, serve as one example. Further discussions of the specific challenges and needs for urban applications are presented in Chapter 4.

Integration across Networks for Enhanced Applications

Meeting the multiple needs of health and safety requires increased efforts to integrate the observations, with the primary objective of providing more timely and effective access to ambient monitoring data. Observations from air quality networks serve multiple purposes. For example, data from these networks are used for characterizing the current environmental state, parameterizing physical/chemical processes, tracking changes (trends) in environmental conditions, developing causality associations between observations and responses, issuing public alerts, and providing inputs to and evaluation data for models. These applications often require the data user community to weave together information from disparate networks, despite recognized spatial, temporal, and compositional gaps.

However, there are barriers and challenges to integration across networks. They include accessibility issues, including the emerging need for near real-time data to support forecasting and emergency response; quality issues, including the need for metadata and quality assessment; and human issues, including concerns and incentives to share data. Integration can occur by a number of actions, including adjustments in quality assurance protocols and harmonization of platforms through a combination of instrument modifications and correlation techniques.

TRANSPORTATION

Importance to the National Economy

This section focuses on three major modes of transportation: (1) land transportation, which includes highways (passenger traffic and trucking) and rail; (2) air transportation, which includes commercial airlines (passenger and cargo) and general aviation; and (3) marine transportation (large ships, port operations, and recreational boating).

Highway Transportation

The impact of weather on land transportation is enormous. More than 230 million commercial and passenger vehicles on U.S. roads are driven nearly 3 trillion miles annually. Statistics from the Federal Highway Administration[1] indicate that

- 1.57 million weather-related crashes occur per year, resulting in 7,400 fatalities (more than 10 times the death toll directly associated with lightning, tornadoes, floods, hurricanes, heat, cold, and winter storms combined[2]) and 690,000 injuries;
- weather accounts for 24 percent of all crashes;
- weather causes 25 percent of non-recurrent delays on freeways and 1 billion hours per year of system delay;
- weather-related delays add $3.4 billion to freight costs annually;
- "just-in-time" manufacturing and warehousing means that transportation delays propagate quickly into industrial losses;
- emissions add substantially to greenhouse gases;
- chemical anti-icing and de-icing materials for snow and ice control affect watersheds, air quality, and infrastructure.

Rail Transportation

The effect of weather on rail transportation is also significant. Freight railroads are overwhelmingly privately owned and are only minimally subsidized by the government, but they move about 40 percent of the nation's freight as measured in ton-miles. Their major competitors in moving freight are trucks and barges. Railroads moved about 12.3 million truck trailers or containers in 2006. U.S. freight railroads employed 187,000 workers at the end of 2006 and generated revenues of $48 billion.[3] The weather impacts on rail transportation are as follows:

- The most serious and costly impact centers on track washouts. Just minor washouts can cause several million dollars in damage.
- The greatest rail losses in U.S. history were caused in 1993 by

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[1] Paul Pisano, Road Weather Manager, Federal Highway Administration, Washington, DC, 2007.

[2] Average number of fatalities from 1988 through 2003 from the indicated weather hazards as tabulated at *http://www.hprcc.unl.edu/nebraska/weather-related-fatalities1940-2003.html*. Ultimate source: NOAA's National Climate Data Center and the National Weather Service. Does not include Hurricane Katrina in 2005.

[3] Association of American Railroads, "Overview of U.S. Freight Railroads," January 2007. The document is available at *http://www.aar.org/PubCommon/Documents/AboutTheIndustry/Overview.pdf*.

main-stem flooding along the Missouri, Mississippi, and other large rivers. Many miles of track lie within the floods plains of these and other rivers. The railroads spent $4.8 billion for repairs.[4]

- The direct cost of a derailment from any cause, track failure being the most common, is approximately $400,000, but the indirect costs of loss of lading, train delays, or train rerouting can double that amount.[5]
- Delays due to weather-related problems have significant impact. Railroad revenues are influenced by the demand for energy and the yield of agricultural products—both have a high correlation to the weather. The Association of American Railroads reported in 2000 that coal and agricultural products contributed 21 percent and 8 percent, respectively, to total rail industry revenues. Due to this commodity exposure, railroad revenues often move up and down with the market for these products. Delivery delays are costly.
- Unexpected low visibility caused by fog, smoke, dust, rain, snow, or other atmospheric obscurants along railways and roadways is responsible for many accidents annually.[6]

Air Transportation

The impact of weather on the air transportation sector is perhaps more obvious than the other sectors. U.S. airlines employ over 600,000 people. Commercial aviation helps create and sustain more than 10 million jobs and supports approximately 8 percent of the U.S. gross domestic product through its connection with other industries, particularly travel and tourism. Passenger-miles flown on U.S. carriers surpassed 500 billion in 2003. Passengers boarded a plane over 740 million times in 2006. Air freight amounted to nearly 40 billion ton-miles in the same year.[7]

The primary impact of weather on air transportation is delays. Weather and air traffic control delays, which are highly correlated accounted for about 66 percent of all delays in 2006, according to Federal Aviation Administration data. Nearly half a million delays in 2006 cost the airlines approximately $6 billion and passengers approximately $10 billion. (The Department of Transportation estimates that each *minute* of delay costs $62 per aircraft.)

Aircraft accidents for which weather is a contributory cause account for roughly $42 million in annual losses from aircraft damage and personal injury. This figure is inferred from examination of the accident database of

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[4] Stan Changnon, Illinois Water Survey, University of Illinois, Champaign, Illinois, 2007.

[5] Burlington Northern Santa Fe Railroad, 2007. See *http://www.zetatech.com/bnsf_rts.htm.*

[6] Weather Information for Surface Transportation Report, FCM-R18-2002, Appendix E, Office of the Federal Coordinator for Meteorology, Washington, DC, 2002.

[7] U.S. Department of Transportation Bureau of Transportation Statistics, 2007

the National Transportation Safety Board. However, the potential losses, even from a single major accident, can be much greater, over $1 billion, due to insurance claims.

Marine Transportation

Nearly 80 percent of freight tons in U.S. foreign trade are moved by ship. Ships moved 1.49 billion tons in 2005, of which 0.39 billion were for exports and 1.10 billion were for imports. The total value of these goods was $1.12 trillion.[8] Nearly half the international cargo can be considered hazardous, notably when spilled over water.

Marine weather claims encompass a wide spectrum of offshore and littoral weather-related mishaps, ranging from a salvage operation gone wrong, to cargo loss/damage, and even the injured crew member. The common thread governing many marine claims is the exact role weather or sea played in the alleged loss. No other industry emphasizes safety quite like those with marine concerns. There is a complex interdependency of vessels, waterways, terminals, support services, and intermodal connecting infrastructure that moves people and freight in a safe, efficient, and environmentally sound manner.

Weather impacts just-in-time delivery. The weather affects route conditions, times of departure or arrival, and ports of refuge. Tropical storm avoidance is critical for marine transportation. Other areas that are vulnerable to weather are coastal trade (shipping over short routes near the coast); commercial port operations; the fishing industry; recreational boating; NOAA fisheries management; US Coast Guard Search and Rescue (SAR) and port security operations; and emergency response (e.g., oil spills).

Port operations present a unique set of challenges.[9] A large vessel usually holds position a few miles from breakwater. A pilot boards the ship, calls in tugs, and directs the ship to a safe berth, whether it is a breakwater anchorage or a dock. The width and depth of the channels and the height of any bridges across the channels dictates the size of the ship that can be brought to port. Any sharp bends in the channel and the length of the dock limit the length of the ship that can be accommodated. Very large ships such as 300,000-ton, 1,200 feet long tankers have a very large draft (>60 feet) and are more affected by current than wind. Delays in docking are costly. Even if weather unexpectedly prevents transit to the dock, longshoremen still have to be paid for showing up (typically tens of thousands

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[8] Source: U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, August 2006. Available at *http://ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/docs/06factsfigures/fig2_6.htm*.

[9] Interview with Vic Schisler of Jacobsen Pilot Services, Inc., Long Beach, California.

of dollars); the shipper may lose $100 thousand for each day the ship must spend offshore.

Current Assets and Operational Requirements for Mesoscale Observations

In the highway environment, most road-specific information is available because of collaborations between state departments of transportation (DOTs) and service providers in the private sector. Most roadside meteorological observing stations measure temperature, wind, precipitation, and humidity. Many states also use sensors embedded in the road surface that measure temperature and detect ice, chemicals, or water on the road, and subsurface sensors that determine heat flux. Roadside cameras show how weather is affecting traffic and either substitute for automated observations or give visual confirmation that the pavement measurements are valid. New technology provides remote sensing capabilities from the roadside for road conditions and surface temperature. Some sites also have visibility sensors.[10]

Both the DOTs and their weather service providers use data from these sources to monitor current road conditions and as the basis for web-based products. Roadway forecasts are much more demanding of observations than the monitoring function; they rely upon not only roadway sensors but also all other types of observations, surface and aloft, from an area that grows with the length of the forecast.

State DOTs operate the Road Weather Information System (RWIS).[11] The RWIS relies on a great majority of 2500 state-owned Environmental Sensor Stations (ESS) that collect one or more types of data along roadways: atmospheric (usually temperature, pressure, wind, humidity, and precipitation), road surface (pavement temperature, presence of water or ice, whether the pavement wet or dry, and sometimes the concentration of chemicals on the pavement), and water depth (measurements in streams or culverts that cross under the highway). Communications for the collection of roadway data and a central processing and dissemination center are integral parts of the RWIS.

As with many mesonets, the reliability of state DOT data is variable with regard to documentation (metadata), adherence to siting standards, and regular maintenance and repair of sensors. Proposed standards for siting and communications are in a Federal Highway Administration publication (Manfredi et al., 2005).[12] Some agencies do not share road sensor

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[10] More information on all these sensors is available at *http://ops.fhwa.dot.gov/Weather/best_practices/EnvironmentalSensors.pdf*

[11] See *http://ops.fhwa.dot.gov/Weather/faq.htm*.

[12] Available at *http://ops.fhwa.dot.gov/publications/ess05/ess05.pdf*.

Vignette: Ice Storm in the Columbia River Gorge

The most severe snow/ice event in recent years in northwest Oregon and southwest Washington occurred early January 2004. Portland International Airport closed for nearly 3 days, as did all major highways into and out of Portland. This included north-south Interstate 5 in southwest Washington and Northwest Oregon, Interstate 84 east of Portland along the Columbia River Gorge, and Interstate 205, which runs north-south just east of Portland International Airport. The numerical weather prediction models continually tried to dislodge the cold air trapped in the low-lying Willamette Valley and between the coastal mountains and the Cascades in southwest Washington. Scouring of the cold air never happened; therefore liquid precipitation falling into the entrenched cold air near the surface either froze to ice pellets or froze upon contact with the ground. Ice storms are not uncommon in the Portland area, and forecasters usually expect the cold air to remain in place longer than the models predict, but sometimes even forecasters underestimate the staying power of the cold air.

Because of the complex terrain in the Pacific Northwest and the immense impact of cold low-level flow out of the Columbia River Gorge on winter weather, a denser observation network would be a great help, especially if forecasters could get more information in the vertical. Frequent vertical temperature profiles near the mouth of the Gorge would show how cold air domes erode during cold easterly surface flow. With accurate forecasts of ice storms, crews could treat the roads in timely fashion, and ordinary drivers could plan in advance to stay at home.

Winter-weather-affected traffic in the Portland, Oregon, area, January 6, 2004. SOURCE: National Weather Service, Portland, Oregon.

information with the traveling public because of liability concerns; this is especially true with road surface temperature and surface condition data.

In an effort to coordinate the collection of roadway meteorological information nationwide and to gather comprehensive metadata about the roadway sensors, the U.S. Department of Transportation has established the Clarus system.[13] Not an acronym, *clarus* is the Latin word for "clear," a road condition universally hoped for. During the next few years, the Department of Transportation intends to develop and demonstrate Clarus as an integrated observation and data management system for the improvement of surface transportation. The success of Clarus will depend upon the involvement and cooperation of state DOTs and the private sector. Clarus should lead to more accurate assessments of weather and pavement conditions and could improve short-term forecasts of road weather, thereby alerting drivers to near-term hazards, whether from winter storms or summer flooding. State DOTs will benefit in that road-clearing operations will not be launched unnecessarily.

Railroads have specific observational needs. These include

- precipitation (frozen and liquid) for rails or overhead power lines. Any accumulation of ice on tracks seriously affects braking and makes it impossible for trains to start moving;
- thunderstorms and lightning;
- high or low temperatures (85°F or above, 32° or below). High temperatures cause rails to bend and trains to derail; low temperatures cause switches to freeze and stick;
- visibility less than 3 miles. Poor visibility from any cause (heavy rain or snow, fog, blowing dust) is a problem. Engineers depend upon seeing the tracks and signals ahead;
- high winds (for blown debris and crosswinds in excess of 60 mph).

Railroads or their service providers have installed sensors along the tracks to monitor weather conditions and warn of the above hazards.

The Federal Railroad Administration (FRA) believes that new monitoring technologies will prevent collisions and accidents involving excessive speed, provide greater security, increase railroad capacity and asset utilization, improve service to railroad customers, improve railroad energy efficiency and emissions, enable railroads to measure and manage costs, and increase railroad economic viability and profits.[14]

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[13] See *http://www.clarusinitiative.org/background.htm.*

[14] Steven R. Ditmeyer, Weather Information and Intelligent Railroad Systems, NCAR-FRA-ARA Symposium on Enhanced Weather Information for Improved Railroad Safety and Productivity, Boulder, CO, October 2001.

Many costly aircraft delays result from poor weather at the terminal. Standard instrumentation, typically the NWS ASOS and the FAA Automated Weather Observing Systems, provides the local observations used in decision-making and terminal forecasting. Most airports that experience substantial winter snowfall employ instrumentation similar to roadway sensors to monitor runway conditions.

Specialized observing systems such as radar (WSR-88D and the Terminal Doppler Weather Radar) provide detailed observations of the atmosphere, especially for severe weather that can affect air transportation at or near airports.

Major airports benefit from the Low Level Wind Shear Analysis System, which provides critical wind information when downbursts (strong, sudden gusts of wind from convective showers) pose a hazard for departing and arriving aircraft. Sudden drops in airspeed caused by downbursts can cause aircraft on final approach to land short of the runway, and aircraft accelerating for takeoff to roll off the end of the runway without becoming airborne.

Systems such as the Aircraft Icing Weather Support to De-icing Decision Making (WSDDM) are being deployed at airports to provide aircraft de-icing decision support. Developed by scientists at the National Center for Atmospheric Research, the WSDDM system is based on a complex system of temperature and weather prediction sensors and radar that are controlled and monitored by state-of-the-art software. The sensors for the system are usually installed up to 30 km from the airport in all directions. The WSDDM system's sensors measure temperature, atmospheric pressure, dew point, and wind speed and direction. A hot-plate snow gauge measures the liquid equivalent of snowfall, the most important parameter for deciding which de-icing fluid to use and how much time pilots have between leaving the de-icing station and takeoff.

Marine transportation typically requires information about wind speed and direction, swell/wave heights and direction, and tropical weather. Except for ship reports, few surface observations are available for operational decision-making. Automated reports from marine buoys provide input to forecasts, and satellite observations of sea state and surface winds (inferred from scatterometer data) have been widely used in the near-shore environment. However, recent cancellation of satellite missions calls into question the continuity of such offshore satellite measurements until new missions are launched.

Port operations require good information about water depth (increasing ship draft over the years), tidal current, salinity, wind velocity, sea state, wave heights and direction, and the air gap between structures over water and the water itself in order to avert collisions between vessels and structures.

NOAA's Physical Oceanographic Real-Time System (PORTS) provides critical information for shipping operations at 15 major U.S. ports. PORTS has three major objectives: first, ensure safe navigation in the vicinity of ports, that is, prevent collisions among vessels and between vessels and fixed objects. Second, conduct maneuvers and docking as efficiently as possible, given the constraints of channel width, water depth, bridge heights, and weather. Third, protect the coastal environment, mainly through the prevention of accidents.

Coastal waters provide habitat for diverse biological resources, including the spawning ground for 70 percent of commercial and recreational fisheries in the United States. Maritime accidents involving oil spills stifle biological life forms for years. Clearly, weather and water sensors are an integral part of PORTS.[15]

Needs for the Future

In the mountainous West, avalanches are a significant wintertime threat to highway users, as well as to recreational activities on backcountry trails. Better snowfall, temperature, and wind data in the high mountains would lead to more effective warnings, enhance avalanche control capabilities, and reduce the number of unexpected highway closures.

Snowfall measurements along highways leave much to be desired. Precipitation gauges have known deficiencies in measuring the water content of snow, because of losses from evaporation at low snowfall rates, and because wind reduces the capture of snow within the gauge orifice. The character of the snowfall is usually unknown. Heavy, wet snow is less prone to drifting, but wind can easily clear fluffy, low-density snow from the roadway or deposit it in huge drifts, making for huge variations in road conditions in very short distances. The difficulty in measuring the character of snow and its accumulation rate in terms of liquid equivalent (relevant to salting operations) is often the greatest reason why the prediction of future pavement conditions, even an hour or two in advance, fails. Quite apart from the wind, mesoscale variability in snowfall rates due to convection embedded within larger-scale snowstorms, banded lake-effect snowfalls, and proximity to rain-snow boundaries argues for more closely spaced measurements along roadways and more innovative measurement technologies for measuring snow.

Certain observations such as soil moisture and soil temperature are rarely available; yet they are critical in forecasting pavement temperature, frost heaving of roadways, and the potential for load restrictions.

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[15] For further information, see *http://tidesandcurrents.noaa.gov/ports.html*.

Solar radiation data, rarely measured in the operational environment, are especially important for road surface and rail track temperature forecasting. Sky view information also aids in forecasting pavement temperature. Pavement temperature reacts markedly to variations in the sky view, whether due to road cuts, buildings, mountains, or vegetation. Some agencies have removed vegetation along rights of way or in interstate highway medians in order to increase the absorption of solar radiation by the pavement.

For highway, rail, and air transportation, additional data are needed for improved fog forecasting, including:

- the vertical distribution of humidity in the potential fog layer (surface-200 meters)
- winds in the stable boundary layer
- the ground temperature of the surface beneath the potential fog layer
- cloud cover, precipitation, surface dampness, and temperature

Strong winds affect ground transportation directly. High-sided vehicles and rail cars with double-stacked containers are susceptible to blow-overs. Trucks have been blown off of bridges. More accurate local forecasts of high winds are needed along with more effective methods of alerting truck drivers. Just automated signage based on a local observation can provide sufficient warning.

Finding: Many existing surface observing platforms are in place to enhance the safety of road and rail transportation. Some of these stations are installed in locations prone to hazards, for example, early icing on bridges, early morning fog in low spots, blowing dust in the vicinity of bare ground and fine-grained, loose soil. Other stations are in more broadly representative locations. In both cases, such data are valuable to the mesoscale forecast and warning enterprise.

Lower troposphere and boundary layer data, such as vertical profiles of wind and temperature, are needed by all transportation sectors. Relatively few data are currently available from the standpoint of resolving mesoscale features. Temperature profiles have been shown to be extremely valuable in detecting the melting level in the lower atmosphere. This information is especially useful in deciding how much snow and ice might accumulate on roads.

While continuing to satisfy the fundamental needs of the transportation sector, some existing roadway and railway observing stations could easily be integrated into the network of networks to provide a broader complement of meteorological and soil measurements at minimal cost.

The addition of another measurement or two at existing sites avoids the major expense of establishing a new station altogether, and wireless communication gives the flexibility to locate individual instruments optimally. Likewise, meteorological stations near roads and railroad tracks could have sensors added that would benefit transportation, for example, water depth measurements near culverts.

> **Recommendation: Existing surface observations and observing platforms associated with road and rail transportation, as appropriate, should be augmented to include World Meteorological Organization (WMO)-standard meteorological parameters. Conversely, existing WMO-standard meteorological observing stations near highways and railways should be augmented, as appropriate, to meet special needs of the transportation sector.**

In the coastal boundary layer, energy and momentum exchanges are occurring that need to be measured in order to understand, monitor, and predict mesoscale atmospheric and related environmental processes.

Sea-surface temperature must be more effectively measured in order to improve forecasts. Near-shore water surface temperatures often display strong spatial and temporal variations due to multiple processes such as tidal perturbations, upwelling, wave action, runoff, and diurnal heating. Latent and sensible heat exchanges are critical for gauging mesoscale hydrologic processes, such as coastal convection and stratiform precipitation, fog development, sea breeze occurrence and intensity, tropical storm intensity, and the rain/snow line in coastal winter storms. Satellite retrievals are improving the measurement capabilities, but the quickly fluctuating processes, intricate coastal boundaries, and near constant cloud cover in some near-shore environments still require the need for more in-situ observations.

Other parameters besides sea-surface temperature should be measured within the littoral zone water column, for example, water quality, turbidity, sediment transport, salinity, and nutrient production.

The measurement of wave action is complex and very much governed by mesoscale features within the coastal zone. Many end users require the measurement of wave heights, often broken into dominant and subdominant values based on wave period. Longer period waves, often termed swells, are generated by offshore storms, whereas locally wind-driven waves are often termed chop and have much shorter periods. Wave direction is a much desired parameter but more difficult to measure. A subset of buoys along the U.S. coastline collects this information.

Many stakeholders in the coastal zone request measurements from tide gauges, water-level gauges, and current meters. The U.S. tidal gauge network is comprised of over 500 stations, many of which also collect some meteorological information.

Buoys have been and continue to be the cornerstone platform of littoral and open ocean observing, with satellites becoming more and more of use due to the large spatial expanses they are able to sense. Cloud cover and temporal and spatial resolution continue to be the main limiting factors in an otherwise highly effective method of collecting oceanic information. Other observing systems, some relatively new, are augmenting the data provided by buoys and satellites: gliders, drifters, CODARS (active remote sensors used to measure currents), over-water stationary platforms such as navigational aids and oil rigs for deploying a myriad of in-situ sensors, and t in-situ sensors that are fit on various vessels such a tankers, cruise ships, tug boats, and ferries.

The stakeholders for physical measurements within the littoral zone are numerous and include recreation (tourist industry, fishing, sailing, surfing, etc.), commercial fishing, maritime transit, port security, national defense, energy demands, terrestrial transportation (coastal rain/snow line, fog, etc.), emergency management (hurricane evacuations, etc.), and oil spill tracking.

Future aviation requirements for mesoscale observations will be dictated primarily by the Next Generation Air Transportation System (NGATS). NGATS responds to an expected doubling or even tripling in air passenger and freight traffic by 2025 along with a proliferation of light jets. Planning is coordinated by the Joint Planning and Development Office (JPDO), with representatives from the Departments of Transportation, Defense, Homeland Security, and Commerce, the FAA, NASA, and the White House Office of Science and Technology Policy. A wide range of aviation experts from the private sector advise the JPDO.

A satellite-based technology that broadcasts aircraft identification, position, and speed with once-per-second updates is the backbone of NGATS. Through mutual sharing of flight information among controllers, pilots, and aircraft navigation systems, flight routing will be transformed from the “highways in the sky” paradigm of today to more direct and efficient routing.

It is too early to say in detail what new requirements for weather observations will be, consistent with greater efficiency and improved safety of flight operations, but huge potential exists for smaller commercial carriers and general aviation to supply in-situ observations. Thousands of general aviation aircraft are in the air most of the time, and they generally fly lower than passenger airlines, often in or not far above the boundary layer, where observations are most sorely needed.

Most new automobiles come off the assembly line with temperature sensors and an interior readout. In partnership with automobile manufacturers, the Federal Highway Administration is conducting a Vehicle Infrastructure Integration (VII; Pisano, 2007) to investigate how these millions of temperature measurements might be collected and shared more widely. A crude measure of rain rate is also possible through monitoring windshield wiper speed. Methods for communicating this information from individual vehicles to a processing center are being studied. Additional development of nanosensor technologies should realize "measurements on a chip," which would replace the 20th-century sensor paradigm.

> **Recommendation: The Department of Transportation should assess and eventually facilitate the deployment of high-density observations through the Vehicle Infrastructure Integration initiative. Similar concepts should be considered for general aviation and marine transportation vehicles.**

WATER RESOURCES

Importance to the National Economy

Monitoring water availability and movement in the broadly considered environment (i.e., the atmosphere, land surface and subsurface, and coastal waters) is of utmost importance. Domestic, municipal, industrial, agricultural, and recreational activities all require access to water of adequate quantity and quality. Yet water availability is not evenly distributed over the country, nor is it always available when needed over periods ranging from years to days and often even hours. This variability results from the intricate interplay of many natural processes and human activities. It is manifested by the common observation that we often have too much water or not enough. Everyone is aware of the multi-year drought in the Southeast and the continuing battle among Western states over water rights. The main stem floods along the Missouri and Mississippi Rivers and their tributaries in the summer of 1993 caused $21 billion in damage, and the catastrophic flooding of New Orleans from Hurricane Katrina in 2005 was the worst natural disaster in U.S. history with losses of $125 billion.[16]

The distribution of water resources across the country is a combination of nature-controlled supply and human-controlled storage and consumption. On the supply side we have precipitation in the form of rainfall and snowfall ranging from as little as 200 mm in large parts of the western United States to over 1500 mm in Florida and the coast of the Gulf of Mexico and the Northwest. A portion of the fallen water finds its way to short-term storage in rivers and lakes and long-term storage through

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[16] National Climate Data Center, NOAA, Billion Dollar Weather Disasters, NOAA, *http://www.ncdc.noaa.gov/oa/reports/billionz.html#chron*. Figures not adjusted for inflation.

recharge of the groundwater. The time scale of the short-term storage ranges from hours to weeks in rivers and months to seasons in lakes. The long-term storage is replenished at very slow rates but results in residence time on the order of years. On the consumption side, the distribution of the population density, industrial and agricultural activities, and the tradeoffs between the needs for flood control, energy production, and recreation control water availability or shortage. While certain activities (e.g., municipal, industrial) result in little water loss, others, such as agriculture, require large quantities with significant losses to the atmosphere.

The "big picture" of water quality is even more complicated. Industrial and municipal activities result in water pollution, and the need for water treatment. This treatment is never complete, and natural processes are counted on to assist in the treatment. The plethora of chemicals used in industrial processes prevents comprehensive and complete addressing of their environmental impact. As a result, surface and ground waters contain heavy metals, toxins, pharmaceuticals, and deadly bacteria. As water is a major transport agent, the effects extend thousands of miles in spatial scales and persist in the environment for many years if not biodegradable. Rainfall and agricultural practices result in soil erosion, and the displaced particles carry with them both fertilizers and pollutants. Over time these travel to streams and rivers and affect environments thousands of kilometers away. A prime example here is the problem of hypoxia in the Gulf of Mexico, which traced back to nutrients used in the Midwest for crop production.

This brief overview of national water resources should be sufficient to illustrate the extremely complicated nature of the problem. The processes of water supply, storage, and consumption span a tremendous range of scales both in time (from seconds to decades), and in space from (sub-millimeters to thousands of kilometers). The data and other information about these processes are scattered across many organizations and are difficult to access in a comprehensive fashion despite efforts such as the National Integrated Drought Information System (Western Governors' Association, 2004). Significant gaps exist in our knowledge about the functioning of the natural water systems.

Current Assets and Operational Requirements for Mesoscale Observations

Addressing the problems of "too much water or not enough" requires careful monitoring, skillful prediction, and rational control. Federal responsibilities are organized along those lines with some degree of overlap. For example, the United States Geological Survey and the Bureau of Reclamation monitor surface and groundwater status in terms of quantity and quality using information from some 1.5 million sites, EPA enforces compliance with environmental standards and regulations, and NOAA focuses on the coastal waters and the atmosphere. The National Weather Service has the mandate to routinely forecast stream flow at some 20,000 points across the country. Toward this end, it has established the Hydrometeorological Automated Data System (HADS)[17] to collect raw hydrological and meteorological data from sites operated by a variety of agencies, using the Data Collection Platforms aboard GOES satellites. The U.S. Army Corps of Engineers develops, monitors, and operates engineering structures such as reservoirs, and dams and locks on major rivers. In many regions of the country these responsibilities are shared with state and other local agencies. For example, Florida's water resources are managed by four water management districts that are responsible for providing water for municipal and rural consumption, agricultural use, and ensuring protection of life and property. The Tennessee Valley Authority operates numerous water storage reservoirs for water supply, flood control, and electric energy production in the Southeast. Comprehensive discussion of all the federal, state, and local agencies and their activities related to the nation's water resources is prohibitively complex and beyond the scope of this report. These complexities are also emphasized by an American Meteorological Society policy statement on water resources (AMS, 2008). Since there is no single agency responsible for management of water resources, and there is no national water policy (Galloway, 2006), our discussion will focus on the major mechanism of observational capabilities that we consider critical for addressing multiple national needs.

Serving multiple national needs requires decision-making regarding water apportioning and restricting. These decisions often address the conflicting objectives of different users and are made using incomplete information regarding the current and future state of water resources of interest. To support this decision-making, responsible parties use predictive models that interpolate and extrapolate the available data into the variables of interest that are often not observed directly. Examples of such models include rainfall-runoff transformations, flash-flood forecasting, flood routing along main rivers, groundwater recharge and flow, land-atmosphere interaction with estimates of evapotranspiration, sediment transport and sediment yield, snowmelt, and water storage, just to name a few.

These models are highly uncertain because they describe complicated nonlinear processes that are difficult to observe and that are the result of multiscale interactions of other processes. The predictive skill of these models varies, but uncertainty is an inherent part of any of them. This uncertainty, which is hard to quantify, can be attributed to (1) the lack of complete understanding of the processes involved, (2) suboptimal parameters of the mathematical representations that constitute the models, (3) errors

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[17] See *http://www.nws.noaa.gov/oh/hads/*

in the initial conditions, and (4) errors in the main input (e.g., rainfall in the flash-flood forecasting models). Much of the above uncertainty can be ascribed to the limitations of our observing systems, both for operations and for research, that is, for learning about the processes of interest. These observing systems provide the empirical information that is used to express formally our understanding of the natural processes, calibrate (i.e., adjust the parameters of) our models, and provide the initial condition and the driving inputs. Therefore, the uncertainty due to the limited scope (spatial and temporal sampling resolution and accuracy) of our observing systems propagates all the way to decision-making on the use of our national water resources. For example, Welles et al. (2007) report a lack of significant progress in the skill of stream-flow forecasting models over the past 20 years. Improving the forecast quality by replacing the currently used models with a new-generation of spatially distributed representation of hydrologic processes requires adequate observational input.

Studies of the "forecast worth" in the context of reservoir operation clearly show significant economic benefits if reservoir inflows are known more accurately (e.g., Georgakakos et al., 2000). The inflows taken in combination with the current storage determine water availability. This, combined with predictions of water demand, or the demand for energy that can be produced by releasing water through a turbine system, and subject to environmental constraints (e.g., to satisfy the minimum required discharge to sustain ecology downstream), results in a decision on how to operate the reservoir.

Needs for the Future

The question arises, "What hydrologic model requirements are needed to realize improved prediction relevant to the problem we are discussing?" The answer is not straightforward, and it depends on the spatial and temporal scales involved. Consider first a large river. To make a prediction of the discharge at an arbitrary point downstream, we need to know the discharge upstream and an estimate of the inflow into the main channel between the two points. For this we need channel routing models based on the principles of fluid flow in an open channel. The hydraulic characteristics such as slope, width, bottom and bank roughness, and water height determine the answer. When the river basin is large enough, a convective storm, even one with high rainfall intensity, hardly matters, because what happens at the point of interest downstream is mainly affected by the water flow already in the channel. At the opposite end of the spectrum is flash flooding in a small basin. Here, what happens in the channel is largely irrelevant for the forecasting of discharge at the basin outlet, because it will change quickly (within 10-30 minutes, depending on the location and basin size) if enough rainfall occurs. The amount of rainfall and the physical-topographic characteristics of the basin matter most. Among those characteristics it is the level of water storage in the upper zone of the soil that determines the partitioning of rainfall into runoff. This storage can be estimated if measurements of the soil-moisture profile are known.

Soil moisture plays a major role in several hydrologic processes that affect water resources at many spatial and temporal scales. It controls partitioning of rainfall water into surface runoff and the infiltrated water. Surface runoff constitutes the fast-response component by a basin, with water flowing through the channel network to the basin outlet. The infiltrated water is either consumed by plants or percolates to deeper storage, recharging groundwater aquifers. Soil moisture also controls the partitioning of energy incident on the land surface. Water availability for consumption by plants leads to evapotranspiration, a major component of the surface energy budget. Prolonged water deficit in the root zone affects the life cycle of plants and eventually leads to changes in the surface albedo. Water transported to the atmosphere by evapotranspiration affects thermodynamic processes and, under the right circumstances, precipitates, usually at locations far removed from its origin. Through these processes, moisture in the top layers of soil acts on shorter time scales, to influence day-to-day weather, whereas the amount of soil moisture at deeper levels impacts slower processes at regional scales and acts as a source for water that deep-rooting plants bring to the atmosphere during extended periods without precipitation.

Clearly, knowledge of actual soil moisture from a network of stations can help forecast stream flow, evapotranspiration, groundwater discharge, and precipitation. But measurements of the soil-moisture profile some 2 m deep are needed. Moisture in the near-surface layer controls the infiltration capacity and changes rather quickly. The lower layer includes most of the soil and provides moisture for certain class of plants (e.g., grasses). Water is transported between these two layers by gravity, root suction, and capillary suction. The water content in that layer fluctuates more slowly than in the top layer. A still deeper layer extends beneath the soil and provides water for larger plants (e.g., trees). It fluctuates slowly, and its depletion is a sign of a major drought.

Spatial variability of soil moisture is high and not very well understood. It is controlled by the variability of rainfall, elevation, slope exposure, land use, land cover, and the hydraulic characteristics of the soil. All these characteristics vary, the last one perhaps the most significantly, because it depends on the pore size distribution and the structure and composition of the soil particles. In the absence of a comprehensive national network of soil moisture observations, our understanding of this variable is based on experimental in-situ data (Illston et al., 2008), focused remote sensing campaigns, and modeling studies.

Currently available remote sensing technologies cannot provide moisture observations for the entire soil column. The signal measured by radiometers deployed on aircraft or spacecraft originates from roughly the top 5 cm of the soil and is often obstructed by the water content in and on the plants. The spatial resolution of microwave observations of soil moisture is a function of the frequency, antenna size, and the antenna range. While aircraft-mounted radiometers can provide data with the resolution of about 1 km or better, national coverage requires satellite-based sensors. This translates into resolution on the order of 5 km (Entekhabi et al., 2004).

Methods of in-situ measurement of soil moisture take advantage of various physical phenomena (Raats, 2001). Perhaps the most practical method is Time Domain Reflectometry, in which the propagation velocity of an electromagnetic pulse, which depends on the water content, is measured. While these probes require careful calibration, they are inexpensive, safe, and easy to install. Any soil-moisture measurement network should also include soil-temperature sensors. These easy to make measurements would help predict surface runoff when rain falls on frozen soil, helping to mitigate effects of frequent spring flooding in parts of the country.

> **Recommendation: A national, real-time network of soil moisture and soil temperature observations should be deployed nationwide at approximately 3000 sites.**

This number corresponds to a characteristic spacing of approximately 50 km for a network that is spatially distributed across the continental United States. Although this spacing is insufficient to capture the full spectrum of short-term spatial variability of surface soil wetness, 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 numerical weather prediction, water resources management, flood control and forecasting, and forestry, rangeland, cropland, and ecosystems management. This characteristic spacing would also provide data at a resolution that complements historical and relevant datasets. Site selection should be biased toward existing networks, provided that the instrument exposure is acceptable and real-time communication is possible.

Although we argue for the deployment of a national network of soil moisture measurements to improve the prediction of water movement on the surface and below, precipitation remains the most significant variable that determines runoff. Currently two major sensors are used to monitor precipitation: rain gauge networks and weather radars. In principle, the combined use of these two systems should provide detailed and accurate depiction of rainfall across the country. Unfortunately, this is not the case, especially at the short time scale relevant to flash-flood prediction. Partly due to very high spatial and temporal variability of precipitation, and rainfall in particular, the accuracy of rainfall maps is not very high. Ciach et al. (2007) report random errors approaching 50 percent for hourly rainfall maps produced by the national network of WSR-88D weather radars, also known as NEXRAD. As the temporal scale of rainfall accumulation increases, the random errors decrease, and, as a result, seasonal maps of precipitation depict correct pictures of the process.

The major problem is sampling. Rain gauges are distributed too sparsely to capture the variability of rainfall patterns, in particular those of convective origin. Radar beams "look" slightly upwards and tend to overshoot clouds at a certain distance. Radars located on mountaintops in the West consistently miss precipitation originating in clouds at lower elevations. A solution is to place small, inexpensive radars that survey relatively small domains (~1000 km^2), such as urban areas or sections of mountainous terrain. We discuss such systems further in Chapter 4.

Another variable that is not observed as densely as it should be is the stream flow. The USGS monitors the nation's rivers in real time at some 1700 sites. Other agencies complement this at the sites they operate. This is not sufficient coverage, considering the complexity of water movement though the landscape and the primary role that water transport plays in other biogeochemical processes. Continuous observations of stream and river discharge provide a dual benefit for the general problem of forecasting and control of water resources. On the one hand they are directly relevant to flood forecasting and reservoir inflow prediction, and on the other hand they provide a constraint on the models used to forecast other elements of the water cycle that are critical for numerous applications. These include groundwater discharge, pollution transport in surface and ground water, and evapotranspiration.

Accurate monitoring of the major fluxes and storages of the water cycle is a prerequisite to improved prediction of many environmental problems affecting the nation. Transport of sediment originating in soil erosion is a result of agricultural practices and vegetation, erosive power of raindrops and wind, concentrated surface runoff, and transport along the river channel network. Sediment carries both nutrients and pollutants that are attached through cohesion and undergoes transformations while traveling. It affects many other quality aspects of the surface waters and their biological environment by changing the turbidity and acidity.

Current techniques for stream-flow estimation are expensive and labor intensive. Building the structure that houses the sensor that measures stage (depth) is the major expense. The relationship between stage and discharge is developed empirically by periodic and more direct measuring of the discharge, as a product of water velocity and channel cross-section. The empirical data collection has to be repeated over time so that a full range of variability is represented. For high flows this presents practical difficulties and risk to the crew.

Recent developments include advanced *contactless* technologies, and several are being tested and researched. The techniques range from optical sensors to active remote sensing using low-power radars. Other approaches involve computational fluid mechanics models to develop the rating curve and an inexpensive stage sensor for converting to discharge. Some of these techniques are inexpensive and could complement the core networks operated by the USGS and other agencies.

The observational limits of various aspects of our nation's water resources have been recognized by the research community. Hydrologists and environmental engineers argue for the development of a network of well-instrumented natural observatories to further our understanding of water movement in the environment. Comprehensive observations of water quantity and quality are required to improve our predictive capabilities to benefit society. Details of the arguments are provided in CUAHSI (2007) and WATERS (2008).

FOOD PRODUCTION

Importance to the National Economy

Food is grown in all regions of the United States, with each region taking advantage of local climate and soils to exploit its competitive advantage for specific food-related products. The relatively inexpensive transportation of the 20th century has reduced the incentive to raise a wide range of food crops, including some that are only marginally adapted to local soils and climate, in every region. With inevitable rises in transportation costs and increased interest in locally grown food, future weather and climate information needs for food production may be more extensive than in the past. Fruits and vegetables grown at the margins of their optimal ranges are more vulnerable to influences of drought, flood, water-logged soils, heat stress, cold stress, cloudiness, too high or too low humidity, diseases, insects, herbivores, growing season length, or other factors relating directly or indirectly to climate.

The commodity crops of corn, soybean, wheat, oats, barley, rye, etc. are grown on vast areas as monocultures. Food consumed by humans in the categories of fresh fruits, nuts, and vegetables, by contrast, are considered relatively high-value crops and are grown in smaller plots with higher income per unit area, more intense use of labor, more frequent use of irrigation, and higher costs of production per unit area. For various reasons, monitoring meteorological conditions on smaller spatial and temporal scales may be more important in regions growing specialty crops than those growing commodity crops. This will become increasingly so as specialty crops are raised more widely in climatically marginal regions or regions commonly devoted to commodity crops.

Animals are raised in every region of the United States for meat, milk, and egg production. But like commodity grains, commodity meat production (beef, pork, poultry, fish) tends to concentrate in certain areas where there is access to feed grains, abundant water, optimal temperature or precipitation regimes, and access to transportation or markets.

Animals used for meat, milk, and egg production may be raised in confined spaces (either indoor or outdoor) or in "free-range" environments. Confinement operations present additional environmental issues, such as high volumes of odor dust and waste, that call for additional environmental monitoring. Free-range (i.e., grazing) operations typically cover large areas where growth and productivity of grazing materials are factors to be monitored.

Extreme events such as heat waves, freezing rain, extreme cold, severe storms, excessive rain or snow, or high humidity can have serious impacts on animal productivity or even mortality. Weight gain in meat animals, egg production, milk production, and the success of animal breeding are all negatively impacted by extreme high temperatures. Cold rain followed by sub-freezing temperatures leads to sickness in beef animals raised without shelter. The monitoring of current conditions and access to reliable short-term forecasts would allow pre-emptive actions to minimize adverse weather effects on animals raised under confined conditions.

U.S. food production feeds a population of over 300 million people. In 2007, the United States exported about $82 billion in commodity crops, livestock, and horticultural products. In 2008, the total is expected to be $114 billion.[18]

Current Assets and Operational Requirements for Mesoscale Observations

Environmental conditions monitored for agricultural crops usually include standard surface meteorological variables but also include photosynthetically active radiation (PAR), evapotranspiration, soil temperature, and soil moisture. For some crops, leaf wetness (as a measured variable) is a critical factor for management decisions relating to pests and pathogens. Of these variables, the one least likely to be observed, and yet of critical importance for many regions, is soil moisture. The heterogeneity of soils and landscapes make representative observations of soil moisture a major challenge.

The increased education and sophistication of agricultural producers, coupled with the increased availability of weather and climate information

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[18] U.S. Department of Agriculture, available at *http://www.fas.usda.gov/cmp/outlook/2008/Aug-08/AES-08-28-2008.pdf*.

over the Internet, has intensified use of such information by producers and by agribusiness service providers for near-term management decisions, long-term plans for marketing, investments in conservation practices, and water management (irrigation, tile drainage, grass waterways). Modern farm machinery comes equipped with devices for measuring and recording planting rates, chemical application, and grain harvest yield, all as a function of the (high-resolution) position in the field. This high spatial detail, along with the high spatial detail of weather and soil conditions begins to reveal previously unavailable opportunities for maximizing yield and reducing adverse environmental impacts. Agribusiness service providers also must be knowledgeable of current and future weather conditions for maintaining material inventories, managing storage facilities, and generally anticipating weather-driven demands by producers for their goods and services. The crop insurance industry has a major interest in reliable and accurate weather and climate information, especially under potentially changing climate, and in extreme events such as high wind, tornadoes, drought, hail, and freeze occurrences.

Needs for the Future

Weather Data for Driving Decision-Support Tools

The increased use of decision-support tools in agriculture based on current or projected future conditions calls for a wider range of measurements, higher density of sensors, and higher frequency of observations. High-density surface wind observations go into the formula for estimating evapotranspiration and determine when conditions are favorable for applying pesticides or starting controlled burns in the fields. Models of growth for commodity crops use past, current, and future predicted weather and allow producers to plan management and marketing activities. Decision-support tools can be designed to alert producers of impending disease or insect outbreaks when future conditions favor such events. Examples of methods used to increase profitability or environmentally sustainable agriculture include decision-support tools and models for predicting soil erosion, nitrate leaching, soil moisture, soil temperature, irrigation scheduling, forage quality, sub-surface drainage tile flow, stream-flow, water quality, insect migration or infestation, fungal growth, milk production, and weight gain in meat animals. The storage of grain and transport of both grain and animals to market are vulnerable to weather-induced hazards or reduction in product quality.

Bio-Economy and Increased Needs for Weather Information

National mandates for the increased use of biomaterials to replace fossil fuels for mobile transportation have intensified the need for enhanced biomass production from agricultural lands. Future needs to raise increased amounts of both food crops and fuel crops from the same land area will heighten the role of weather and weather forecasting—especially seasonal forecasting—in decision making in the bio-economy. A wider variety of crops in regions now commonly dominated by monocultures of commodity crops will experience changed surface-atmosphere interactions, such as changed evapotranspiration, which in turn could alter the precipitation recycling ratio. Interannual variability in cropping choices therefore could contribute an anthropogenic component to the interannual variability in regional climate. Bringing marginal land into production because of the profit incentive of higher commodity prices for feed grains and biofuels may require special monitoring; such lands are marginal because they are highly erosive or are located at the margins of cropping regions due to their soil or climate conditions. Soil storage of carbon is emerging as a method of sequestering carbon from the atmosphere. Microbial processes in soil that regulate the conversion of labile carbon to carbon dioxide are highly temperature and moisture dependent, suggesting a need to monitor these conditions as a means of monitoring carbon storage. All these factors raise the urgency for higher density meteorological and soil measurements for the bio-economy.

Water Quality Observations Related to Food Production

Emerging issues of surface water quality (with negative contributions by chemical-laden runoff from agricultural lands), long-term sustainability of agricultural practices, and soil sequestration of carbon to meet the goals of reducing concentrations of atmospheric carbon dioxide likely will increase the demand for additional environmental measurements. Surface-water-based measurements of temperature, stream flow, dissolved oxygen, particulate loading, nitrate and phosphate concentrations, and pesticide concentrations are of most interest.

By following the analysis provided by Schlatter et al. (2005), we can estimate the spatial and temporal scales of influences of weather on food production (Table 3.3). We can also estimate the measurement resolution (instrument accuracy, spatial resolution, and temporal resolution) needed to meet the needs of the various food production areas (some are speculative and require validation).

TABLE 3.3 Spatial and temporal scales of several meteorological phenomena of consequence for agricultural industries, and the measurement resolution (instrument accuracy, spatial resolution, and temporal resolution) required to adequately observe those phenomena

Event/variable	Space	Time	Measurement Resolution
Heat wave (temperature)	500-1500 km	2 days-1 week	1°C , 10 km, 1 h
Drought (soil moisture)	500-1500 km	2 weeks to interannual	2 mm
Wind	1 km-2000 km	1 min-4 days	1 m s^{-1}, 1 km, 1 min
Precipitation	10 km-regional	hours to days seasonal to interannual	1 mm, 1 km, 1 h
Cloudiness	local to regional	daytime hrly to clim	1.1 sky, 10 km, 20 min
Temperature	500-1500 km	seasonal	1°F, 10 km, 1 h
Flood	0.1 km-100 km	2 days-2 weeks	sub-basin
Hail	0.1 km-20 km	5 min-5 h	100 m

SOURCE: Derived from an analysis provided by Schlatter et al. (2005).

4

Observing Systems and Technologies: Successes and Challenges

In this chapter we highlight current and emerging observing systems and technologies to address the observational needs discussed in Chapters 2 and 3. Systems and technologies are considered in two broad categories: those based on the surface and those based in space. In the spirit of considering the issue *From the Ground Up*, those based at the surface are given more emphasis and further categorized according to whether the technology provides in-situ or remotely sensed observations. Surface-based remote sensing systems are discussed according to whether the sensing technology is active or passive. We discuss systems that may be based at the surface but provide both in-situ and remotely sensed observations in the vertical dimension at heights well above near-surface. Some of these systems are mobile (e.g., aircraft). Others are designed to provide targeted observations.

Following the discussion of technologies and systems, we summarize several particular observational challenges, including those posed by the surface and the planetary boundary layer, and mountains, cities, and coasts. We conclude the chapter with a discussion of the global context within which U.S. mesoscale observations are embedded. The global context is important because, for many applications, the utility of limited-area mesoscale observations is highly dependent on larger domains of observations, for example, in the provision of initial and boundary conditions for mesoscale numerical weather prediction models.

SURFACE-BASED OBSERVING SYSTEMS

Mesoscale meteorology is closely identified with surface observing systems, perhaps because disruptive weather is intrinsically at the mesoscale, and impacts are most often experienced at or near the surface. The United States has enormous diversity and complexity within its inventory of surface-based observing assets, which are operated by federal, state, and local agencies, numerous segments of the private sector, universities, schools, and hobbyists and other enthusiasts. Surface-based observing systems employ both in-situ sensing as well as active and passive remote sensing technologies. A number of efforts have summarized observational capabilities in the United States. For the last decade and with funding from the Global Energy and Water Cycle Experiment (GEWEX) America's Prediction Project (GAPP), University Corporation for Atmospheric Research/National Center for Atmospheric Research (UCAR/NCAR) has developed a database that describes and maps what is available (*http://www.eol.ucar.edu/projects/hydrometnet*). The National Science Foundation (NSF) recently sponsored development of another database to serve the dual purpose of providing users with information about available resources and to identify future observational needs in atmospheric research (see *http://www.eol.ucar.edu/fadb/*). The National Oceanic and Atmospheric Administration (NOAA) is currently developing an Observing Systems Architecture website with a comprehensive list of NOAA networks at *http://www.nosa.noaa.gov* (check "Observing System Inventory" on the left side of the page). A summary table based on these websites appears in Appendix B. Other useful websites for such information include *http://madis.noaa.gov* and *http://www.met.utah.edu/cgi-bin/databbase/mnet_no.cgi*.

Networks for Surface Observations: Land-Based

Most commonly, "surface" measurements consist of temperature and relative humidity, wind, precipitation, and air pressure. World Meteorological Organization (WMO) standards prescribe wind measurements at a height of 10 m in open areas, and pressure, temperature, and humidity at about eye level (1.5 m), but many surface measurements deviate from these standards, often for good reason. For example, routine observations are made for applications in transportation, agriculture, the power industry, air quality, and public safety, nearly all of which have specific criteria that differ from WMO standards.

There are many thousands of surface sites gathering weather and related information. Based on the UCAR/NCAR and NSF surveys, approximately 500 surface networks operate in the United States and its coastal waters. Federal and state agencies as well as universities and the private sector take observations off the coasts of the lower 48 states, Alaska, and Hawaii. The federal government alone operates approximately 25,000 sites for numerous applications, including climate monitoring, weather forecasting, and monitoring conditions near fires; however, many sites do not report data in real time. Many state departments of transportation, working with private-sector transportation weather service providers, operate networks along highways, and at least one railroad collects observations along its tracks. States, cities, and universities maintain mesoscale networks for air quality monitoring, as part of their flash-flood warning procedures, for agriculture, research, and general weather information. A relatively recent development is urban networks for use in the case of deliberate or accidental toxic releases. Other groups that collect data are power companies, chemical processing plants, and television stations. Even private citizens have automated weather stations in their homes, some of which produce real-time data.

Although surface sites are numerous, abundance doesn't necessarily translate into utility. The sites are not evenly distributed: There are gaps in rural areas, areas with limited access, and in complex terrain. It is a major effort to keep information on multiple networks up to date, so some of networks included in Appendix Table B.1 may have languished due to lack of funds: The numbers are always changing. On the other hand, some smaller networks may not be documented.

Figure 4.1 maps the surface coverage for meteorological data over Washington State. The data are from NorthwestNet, which collects and integrates measurements made by multiple groups.

On the map, one can see areas of dense and sparse data coverage. The latter areas typically have low population density or are difficult to reach due to terrain or other factors. The densely covered areas have data from multiple sources, including weather hobbyists, air pollution networks, and road networks, as well as more conventional sources. Not all of observations are suitable for all applications. For example, roadside weather stations are installed along stretches of road with frequent hazardous weather, such as high winds or icing, so they are often not "representative" of synoptic conditions. However, such non-representativeness on the synoptic scale is strong evidence of value at the mesoscale and is the primary driver for such extensive private and public investment in surface stations nationwide.

Likewise, data from individual homes and schools may not meet the accuracy standards or exposure criteria that are required for numerical weather prediction or research. However, nearly all observations are suitable for some purposes, such as identifying the passage of a strong front with a well-defined wind and temperature change. It is possible that some specialized networks have sites with higher quality data than one would expect, but the supporting metadata are absent.

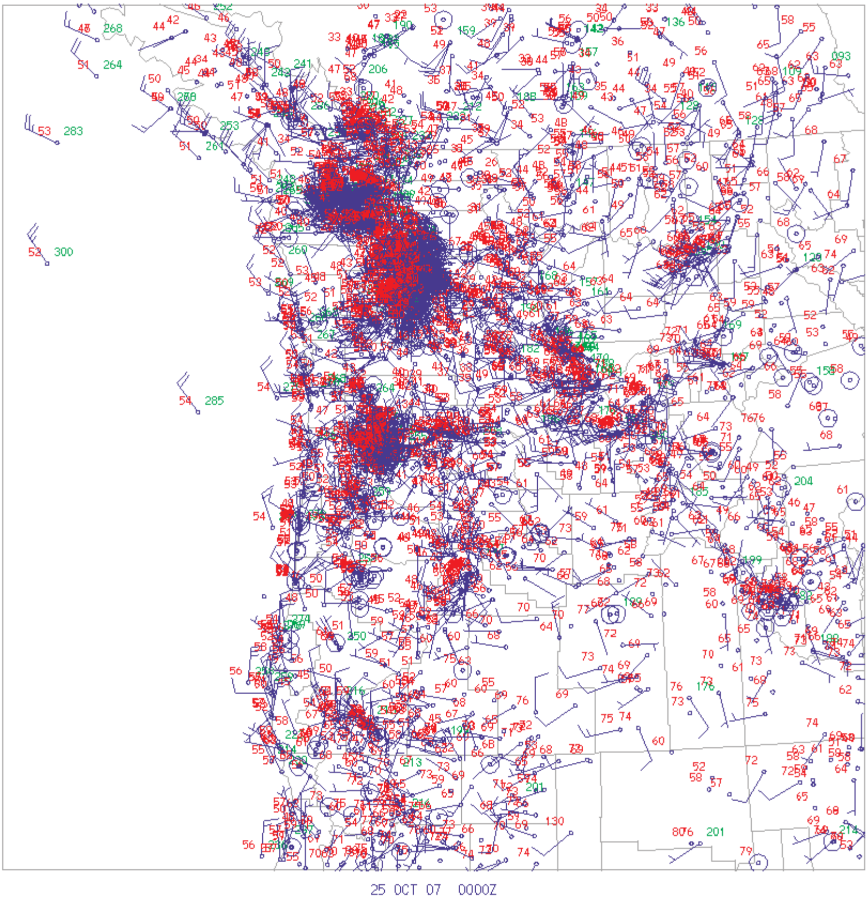

FIGURE 4.1 Sample map of NorthwestNet surface observations. SOURCE: Figure provided courtesy of Cliff Mass, University of Washington.

While the technology for many of the "weather" variables is mature, measurement of rainfall and especially surface snowfall and precipitation type remains a challenge. Rainfall measurements from gauges are reasonably accurate, but rainfall varies on scales smaller than the typical spacing between gauges; this problem has been alleviated to some degree by combining gauge and weather radar measurements. The Natural Resources Conservation Center operates the Snowpack Telemetry (Snotel) network of "snow pillows" that weigh the snow using pressure sensors to estimate the water supply. Data are routinely available daily but are accessed at higher rates for special needs. The type and amount of frozen precipitation is critical to keeping the roadways passable (NRC, 2004a). Precipitation type and snowfall rate are critical information at airports.

While networks that collect weather data can be dense, as illustrated in Figure 4.1, networks that collect soil moisture can seem sparse by comparison, as illustrated in Figure 4.2. A notable exception is the Oklahoma Mesonet (see Box 4.1). Soil-moisture estimates are relevant for numerical prediction and agricultural applications, among others. Automated techniques exploit, for example, the variation of the dielectric constant for soils (time-domain reflectometry), neutron scatter by water in the soil (neutron probes), and measuring how a ceramic block embedded in the soil reacts to heat pulse. The dearth of soil-moisture data is currently being addressed by running land-surface models that integrate precipitation, solar radiation, etc., for a period of time. Satellites, to be discussed in the next section, have potential to supply near-surface soil-moisture data, but estimates are limited by clouds and thick vegetation. Larson et al. (2008) have suggested a new technique for tracking soil-moisture fluctuations that is independent of

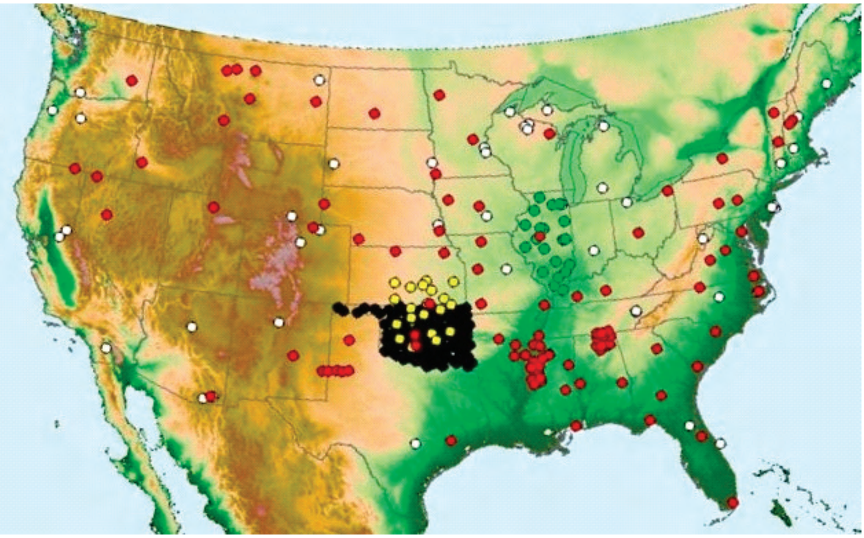

FIGURE 4.2 Soil-moisture networks in the United States documented at *http://www.eol.ucar.edu/fadb/*. NOTES: The black dots represent the Oklahoma Mesonet; green, the Illinois State Water Survey network; yellow, ARM/CART; white, AmeriFlux sites; red, United States Department of Agriculture/Natural Resources Conservation Service (USDA/NRCS) Soil Climate Analysis Network (SCAN). SOURCE: Courtesy of Scot Loehrer.

BOX 4.1
The Oklahoma Mesonet

The most prominent state mesonet is the Oklahoma mesonet (Figure 4.1.1), which is used for emergency response, agriculture, severe storms forecasting, research, and other applications (McPherson et al., 2007). The Oklahoma mesonet consists of 120 automated stations, with at least 1 station in each of Oklahoma's 77 counties. At each site, the environmental variables are measured by a set of instruments located on or near a 10-m-tall tower. The Oklahoma Climatological Survey (OCS) at the University of Oklahoma receives the observations, verifies the quality of the data, and provides the data to mesonet customers. It takes only 5 minutes to make measurements available to the public.

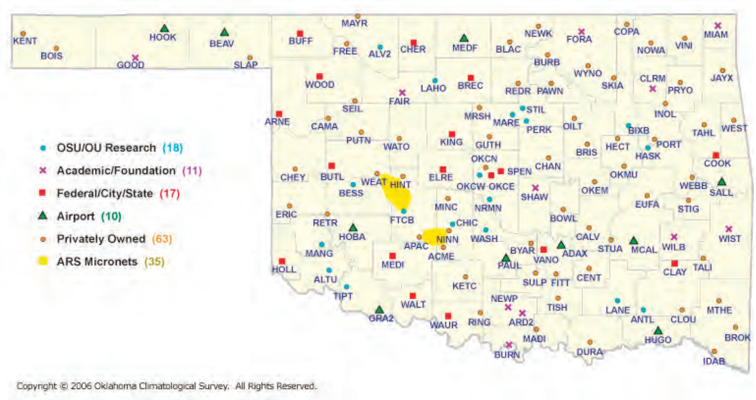

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FIGURE 4.1.1 Map of the Oklahoma mesonet.
NOTE: Multiple agencies are involved in the individual sites.

The standard measurements include temperature and humidity (1.5 m), wind (10 m), air pressure, precipitation, incoming solar radiation, and soil temperature at 10 cm either below natural cover or bare ground. Most sites also sample air temperature at 9 m above ground, wind speed at 2 and 9 m above ground, soil moisture at 5, 25, and, 60 cm below ground, soil temperatures at 5 and 30 cm below ground under the natural sod cover, and soil temperature at 5 cm below bare ground. At 10 sites, turbulence fluxes of heat, moisture, and momentum are sampled at half-hour intervals in addition to the soil and weather variables.

cloudiness; it exploits the effect of soil moisture on the reflection of Global Positioning System (GPS) radio waves. Currently, available remote sensing technologies cannot provide soil moisture below approximately 5 cm. In addition to numerical data, there is a growing network of web cameras monitoring the nation's streets and highways. While not especially useful for numerical weather prediction, cameras are highly useful for road transportation, providing drivers and road managers a check on road conditions (weather, traffic flow, state of the road due to precipitation), and for monitoring wind and weather changes in other applications, such as fighting forest fires or warning about the spread of noxious substances.

Coastal Ocean Networks

The Integrated Ocean Observing System (IOOS) provides real-time quality-controlled data for both the oceans and the Great Lakes, "from the global scale of ocean basins to local scales of coastal ecosystems."[1] IOOS is an end-to-end system that involves observations, data communications and management, and data-analysis and modeling, through its three interacting subsystems, Observation and Data Telemetry, Data Management and Communications, and Data Analysis and Modeling. These challenging tasks involve partnerships among federal and state agencies, the private sector, and universities. IOOS has a coastal component, which involves the U.S. Exclusive Economic Zone (EEZ, which extends 200 nautical miles or 370 km offshore) and the Great Lakes, and a global component.

Coastal and interior waters in the United States are monitored by a diverse network of buoys operated by both the public and private sectors. These diverse measurements are being incorporated into 11 Regional Coastal Ocean Observing Systems (RCOOSs), parts of which also participate in a National Backbone of coastal observations. Most of the RCOOS buoys measure meteorological variables. NOAA's National Data Buoy Center collects and quality-checks, and then distributes the data via the GTS in real time. The core variables measured by the National Backbone sites include ocean data on composition (salinity, dissolved nutrients, dissolved oxygen, chemical contaminants), life (fish species and abundance, zooplankton and phytoplankton species and abundance, waterborne pathogens), and other physical characteristics (temperature, sea level, surface waves and currents, heat flux, bathymetry and bottom character, sea ice, optical properties).

The RCOOSs (Figure 4.3) are being coordinated by regional associations that will in turn contribute to the evolving IOOS.

There are of the order of 700 coastal observation sites in approximately 50 networks. Since these sites must cover the Great Lakes and the

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[1] See *http://www.ocean.us/what_is_ios*.

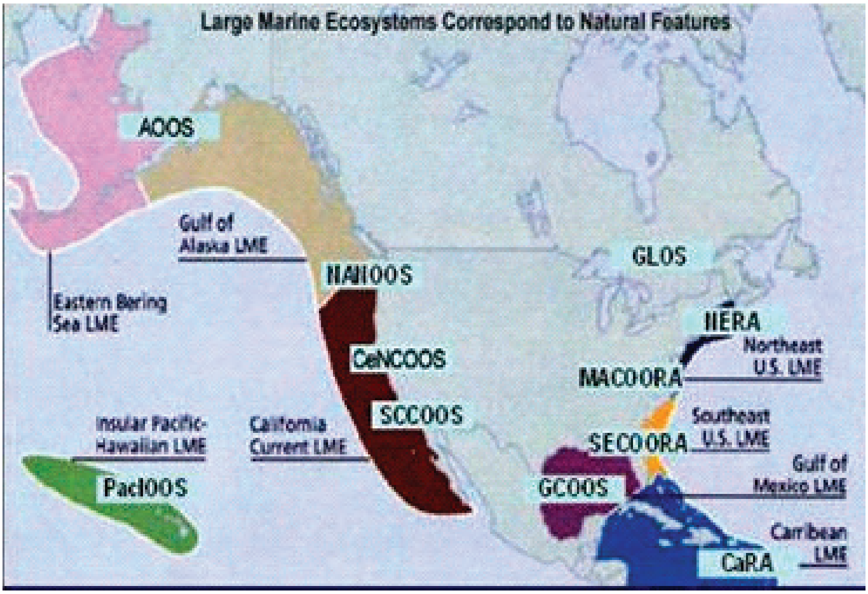
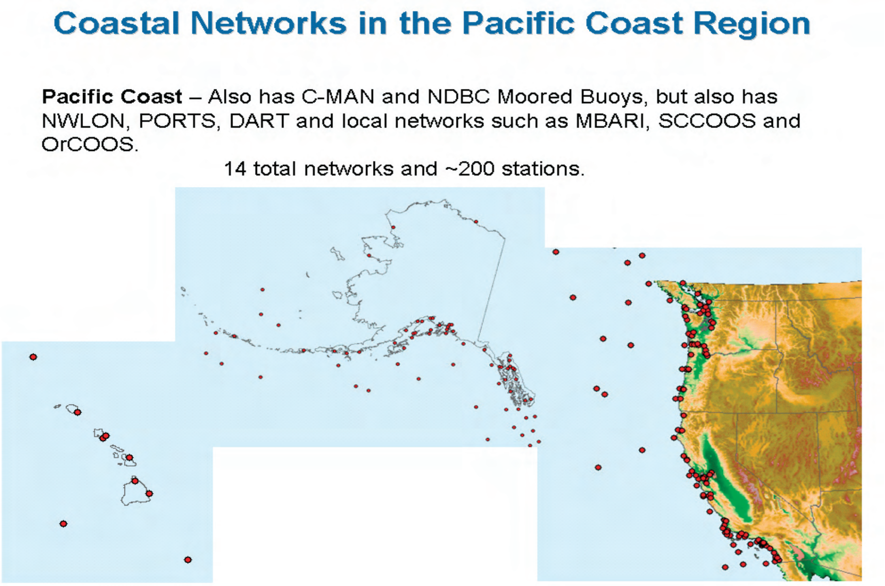


FIGURE 4.3 Regional Coastal Observing Systems. NOTE: LME = Large Marine Ecosystems. SOURCE: National Data Buoy Center, *http://www.ndbc.noaa.gov/*.

U.S. coastline plus the EEZ, the coverage is sparse compared to the land surface. To illustrate, the continental United States has a surface area of 7,700,000 km^2, while a conservative estimate of the EEZ is slightly less than one-third that value. As shown in Appendix Table B.1, the number of meteorological sites on land reporting in real time exceeds 10,000. Significant deficiencies exist over the coastal waters despite the fact that oceanic regions tend toward greater uniformity over larger regions. The 700 coastal ocean sites, which include Alaska and Hawaii, clearly do not resolve either the atmospheric or oceanic mesoscale (Figures 4.4 and 4.5).

To counter this large difference in the density of surface observations between land and sea, satellite scatterometer winds and sea-surface temperature estimates provide high-quality information at high resolution over the oceans. However, some of these measurements become problematic very close to the coasts, owing to strong gradients and land-contaminated satellite footprints. The low density of measurements immediately offshore is a matter of considerable concern, given that 50 percent of the U.S. population lives within 50 miles of the coast and the increased complexity and importance associated with coastal airflow near large cities.



Coastal Networks in the Pacific Coast Region

Pacific Coast – Also has C-MAN and NDBC Moored Buoys, but also has NWLON, PORTS, DART and local networks such as MBARI, SCCOOS and OrCOOS.

14 total networks and ~200 stations.

FIGURE 4.4 Coastal networks along U.S. Pacific coastlines.

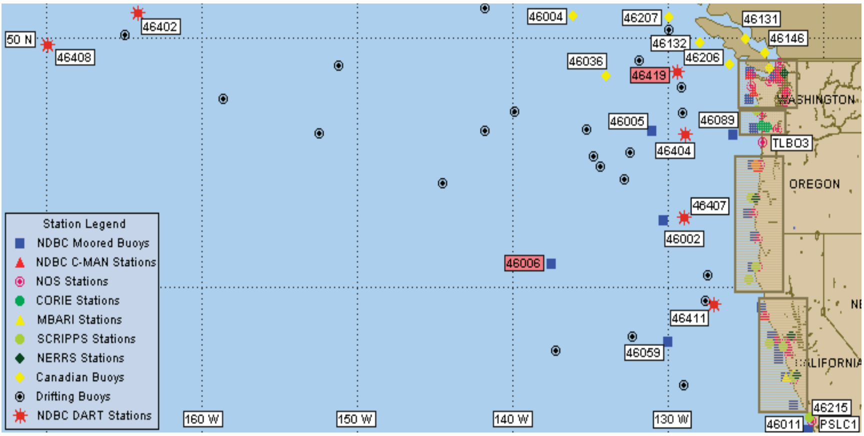


FIGURE 4.5 Sites in the Pacific Northwest. SOURCES: GAPP/NCAR Earth Observing Laboratory, *http://www.eol.ucar.edu/projects/hydrometnet*. Figure from National Data Buoy Center, *http://www.ndbc.noaa.gov/*.

The Vertical Dimension: Surface-Based In-Situ Technologies

The high cost of atmospheric measurements relative to surface measurements is the reason why the government bears the cost of many observations taken well above ground. The one major system, the radiosonde network, launched from the ground at fixed times to collect observations at various altitudes, is described below.

Radiosondes are balloon-borne instrument packages that measure temperature, relative humidity, and wind as a function of pressure, from near the surface to stratospheric altitudes (generally 10 hPa or higher). Radiosondes have been the standard for atmospheric measurements in the troposphere and lower stratosphere since World War II. The vertical resolution of the measurements is good, better than 10 hPa. The roughly 80 U.S. raob sites are widely spaced, several hundred kilometers apart. Balloons are usually launched twice a day at 0000 and 1200 UTC.

Thus, the sampling density of the radiosonde network is poorly matched to the large amplitudes and small scales of lower tropospheric variability. In 2000, the National Research Council (NRC) Panel on Geoscience, Environment, and Resources discussed improved temperature monitoring capabilities from this network (NRC, 2000). It found the radiosonde network to be in decline and insufficient even for global monitoring. The trend has persisted and is not likely to reverse.

In addition to the standard temperature, relative humidity, and wind radiosonde data, a subset of the U.S. network contributes to the WMO's Global Atmosphere Watch Ozone monitoring network. With ozonosondes launched in tandem with a modified radiosonde, telemetered ozone profiles are available at approximately 100 sites globally. These data are important for stratospheric ozone, but the slow sensor response limits the application of such profiles in lower tropospheric applications unless balloons with a slower rise rate are used or inexpensive fast-response sensors are developed.

Evolution of the technology associated with disposable sondes continues; the dollar cost per sounding has declined, and the quality of data continues to improve. Small disposable nanosensors are currently being tested, which may make more parameters (trace gases, for example) possible to measure from profiling sondes. Further development of sensor technology for carbon dioxide, ozone, and other priority pollutants is encouraged since the technology to profile these variables via remote sensing is not mature or sufficiently cost-effective. This need for obtaining profiles for "chemical weather" variables described in the "Decadal Survey" (NRC, 2007a) would suggest that the current network be maintained as a source for profiling information for additional variables.

The Vertical Dimension: Surface-Based Remote Sensing Technologies

Passive and active remotesensing techniques have been employed in up-looking configurations at the surface. As examples, several types of sensors are described below that utilize microwave, infrared, and visible parts of the electromagnetic spectrum.

Passive Sensors

Microwave radiometers. The microwave spectrum from a few to 180 GHz frequency contains a wealth of information on water and hydrometeors in the atmosphere. Outside of a broad O_2 absorption feature at 60 MHz, the spectrum is dominated by the pressure- and temperature-dependent spectrum of water vapor, liquid water, and ice. Up-looking microwave spectro-radiometry has been used to retrieve profiles of temperature, water vapor, and cloud liquid water (Solheim et al., 1998). The temporal resolution of the profiles is excellent—5 minutes—but the vertical resolution decreases quickly with altitude and is coarser than that for radiosondes.

Several Atmospheric Radiation Measurement/Clouds and Radiation Testbed (ARM/CART) sites operate microwave radiometer profilers (MWRP) that measure downwelling microwave radiation in two frequency ranges: 22-30 GHz and 51-59 GHz (Liljegren, 2007). The former range contains a weakly absorbing water vapor resonance band; measurements in five channels are used to infer water vapor profiles. The latter frequency range lies on one shoulder of the broad oxygen absorption band mentioned above. Measurements in seven channels are used to infer temperature profiles. The profiles, along with cloud liquid water path are derived at roughly 5-minute intervals.[2]

GPS Integrated Precipitable Water. An analysis of GPS signal delays that result from the radio refractive index profile leads to estimates of (columnar) Integrated Precipitable Water (IPW; Bevis et al., 1992). IPW indicates the depth of liquid water that would result if all water vapor in a vertical column were condensed. Except during maneuvers of GPS satellites, IPW estimates are stable, accurate except during intense rainfall, and do not need calibration. GPS/IPW measurements are thus used as a reference standard to calibrate rawinsondes There are 300 to 400 ground-based receivers in the United States that report hourly (Figure 4.6). Most of the GPS receiver sites in the United States were in place before it was recognized that water vapor, a nuisance for geodetic applications, was producing a useful signal for atmospheric applications. Both IPW and slant-path water vapor

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[2] For more information, see *http://www.arm.gov/instruments/instrument.php?id=mwrp*.

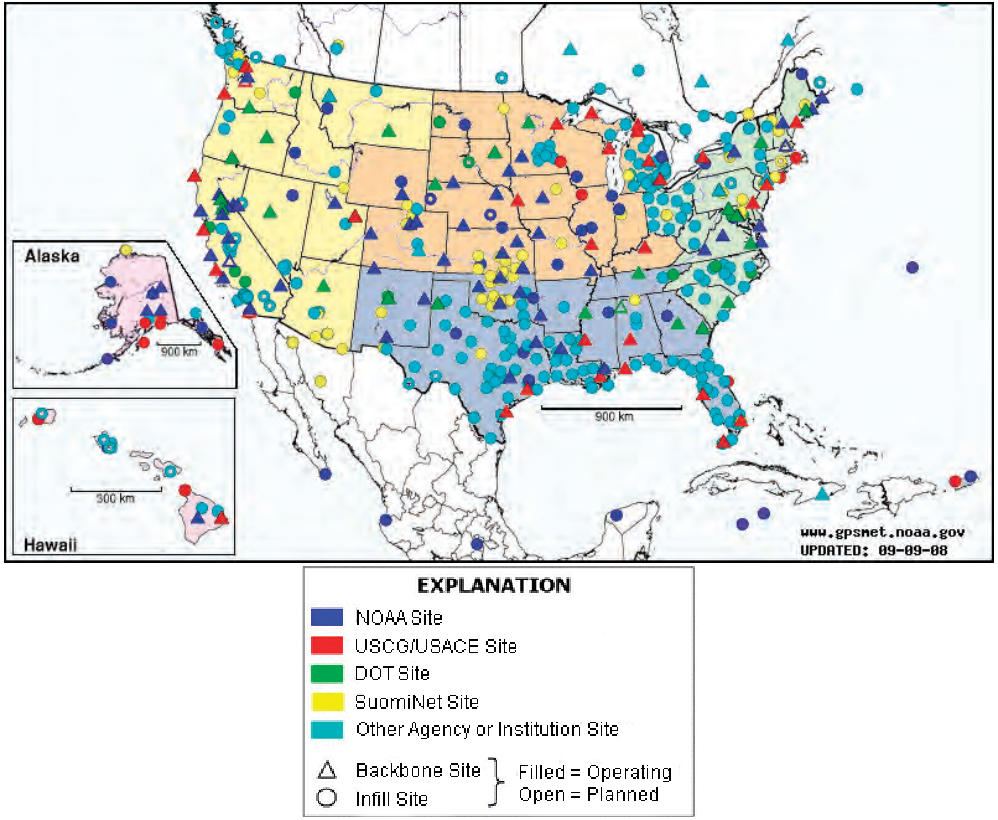

FIGURE 4.6 The surface-based GPS network in the United States.

measurements (Braun et al., 2003) have been found useful for analyzing atmospheric water vapor content. SuomiNet (Ware et al., 2000), an array of surface-based GPS receivers, includes a mesoscale (spacing 50-60 km) array in Oklahoma, where it can be ingested into experimental Numerical Weather Prediction (NWP) models used to predict severe storms.

Advanced Emitted Radiance Interferometer. In the infrared, many more gases (CO_2, CO, O_3, CH_4, NO, H_2O, etc) have spectral features that can be used for ground-based atmospheric profiling. The Atmospheric Emitted Radiance Interferometer (AERI) was developed at the University of Wisconsin and now has been more widely distributed in variants using commercial Fourier transform interferometers. The AERI has approximately 1 cm^{-1} spectral resolution across much of the infrared spectrum. Main products of the instrument are temperature and water vapor profiles that use an infrared retrieval of multiple wavelengths near 15 µm, 4.3 µm, and 6.6 µm.

Additionally, CO columns have been measured and have been used as indicators of biomass burning (He et al., 2001). Results for $O_{3,}$ NO_2, CH_4, and fluorocarbons by AERI radiances have been reported by Evans et al. (2002).

Sun photometry. A number of networks exist globally for the determination of aerosol optical depth using the attenuation of direct sunlight. At least three technologies are able to make these measurements at this time: (1) the Physikalisch-Meteorologisches Observatorium Davos (PMOD) instrument used in a series of remote observation sites in the Global Atmosphere Watch (GAW) aerosols network (Fröhlich et al., 1995); (2) the shadowband radiometer in a number of confederated networks (the United States Department of Agriculture UV-B network, the Michalsky Network, the NOAA Baseline Surface Radiation network, and the Surface Radiation network); and (3) the Cimel sunphotometer (CSPHOT) as part of the NASA Aerosol Robotic Network (AERONET; Holben et al., 2001) and the PHOTONS[3] network. A recent review of networks of aerosol optical depths has been presented by the WMO GAW (2004). Sun photometer networks used in conjunction with satellite optical depth measurements have been used for spatial and temporal extinction of ground-based particulate mass measurements (Engel-Cox et al., 2006).

Active Sensors

Scanning radars. When active remote sensors such as radars are able to perform scan sequences on time scales commensurate with mesoscale

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[3] PHysics, Optoelectronics, and Technology Of Novel Microresonator Structures.

atmospheric evolution, volumetric snapshots of atmospheric structure may be obtained. Volumetric structure is often key to identification of severe storms, rain changing to snow, hail versus rain, pollution plume rise versus fumigation, etc.

Weather radars are sensitive to precipitation and also insects, birds, and refractive-index gradients in clear air. The U.S. WSR-88D network of over 150 10-cm scanning Doppler radars (Figure 4.7) is essential for detecting and tracking storms of all kinds, including severe storms, and the related issuance of public warnings. The Federal Aviation Administration (FAA) operates 47 Terminal Doppler Weather Radars near major U.S. airports to detect and report hazardous weather around airports. In precipitation, the radial velocity data are useful to estimate the mesoscale wind field, especially embedded rotation or convergence. Clear-air echoes can be used to estimate the boundary-layer wind field through Velocity-Azimuth Display (VAD) techniques or echo tracking. Because backscatter from insects is significant in otherwise clear air, such information is typically available for the boundary layer when the temperature is above 10 °C. Soon, WSR-88D radars will be equipped with polarimetric capability, which will improve estimates of precipitation amount and type. Television stations in many markets operate Doppler radars in competition for viewership as part of their weather broadcasts; data are sometimes shared with local weather service offices for severe-storm nowcasting. Other radars (e.g., the CHILL radar operated by Colorado State University) and the S-Pol radar operated by the National Center for Atmospheric Research are used for research.

Even though the WSR-88D network is a core source of mesoscale meteorological information, its ability to give high-spatial and -temporal information has limitations, as discussed in an NRC report (NRC, 2002). One of the limitations is related to the spreading of the beam with increasing distance from the radar and the curvature of the Earth's surface. At 0° elevation angle, because of the Earth's curvature, the volume being probed at long ranges can be at several kilometers height and averaged over several kilometers depth (Figure 4.7). In winter, the 0° elevation beam overshoots shallow precipitating clouds that are producing snowfall, and, when radars are located on hilltops near the West Coast, clouds producing substantial "warm-rain" precipitation. For systems designed to probe boundary-layer phenomena, this limits the range of applicability of radar to 100 km or less. Given these simple geometric facts it comes as no surprise that WSR-88D coverage is discontinuous, having been designed to satisfy a 3 km (10,000 ft) constant altitude specification.

One possible solution to this deficiency is to deploy additional radars in much greater numbers. If such radars were of the WSR-88D (10 cm) type, the cost would be quite high, and the radar coverage would be excessively duplicative in other applications. The Collaborative Adaptive Sensing of

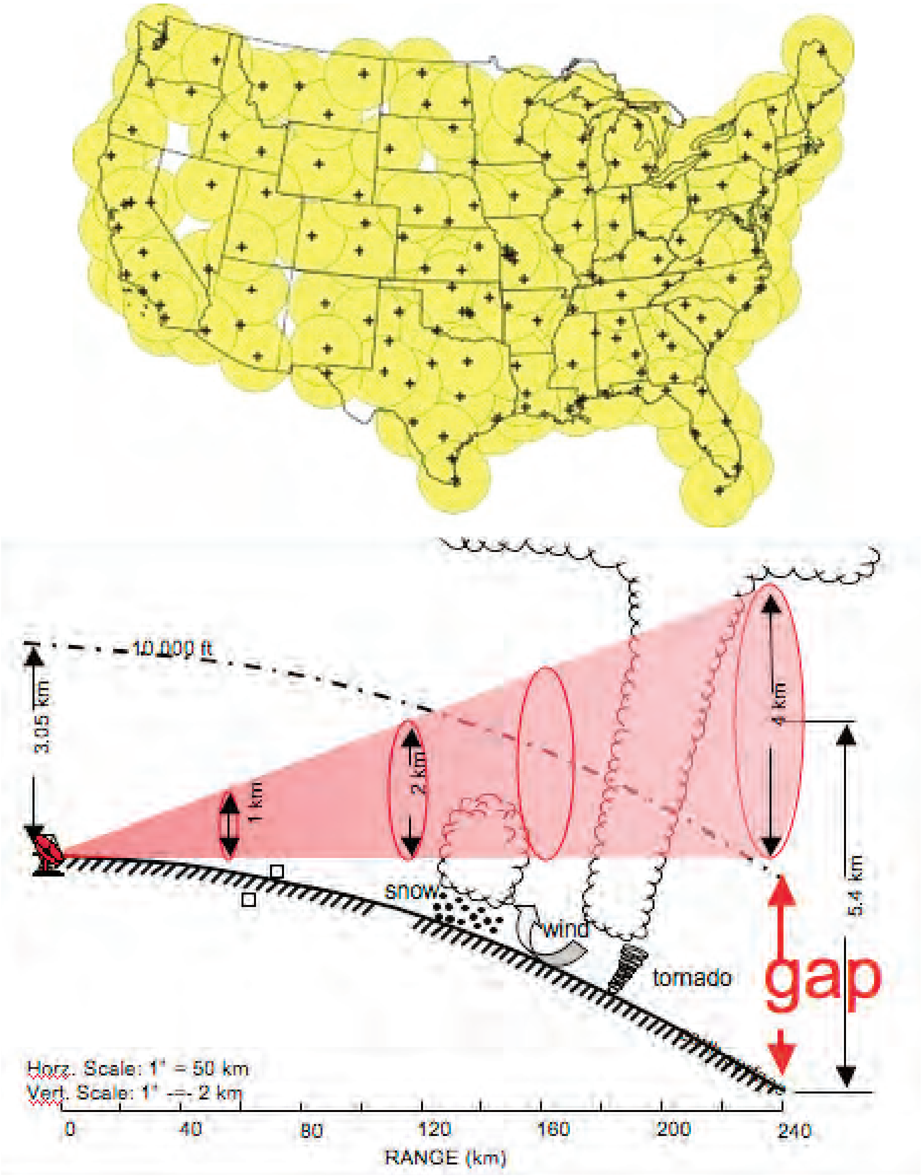

FIGURE 4.7 Current U.S. WSR-88D coverage and the gap in coverage generated by the Earth's curvature. SOURCE: McLaughlin (2005), figure from the Collaborative Adaptive Sensing of the Atmosphere 2007 briefing to the committee.

the Atmosphere (CASA) project has been developed at the initiative of the National Science Foundation. CASA is currently evaluating the effectiveness of small (3 cm) prototype radars in testbed mode, as if these were to be densely distributed across the United States (McLaughlin et al., 2005). Potentially thousands of such radars could be placed on buildings and cell phone towers. CASA has adaptive scanning technologies that are designed to intelligently seek targets of interest (mesovortices, for example) and to increase the sampling of these targets close to the surface.

A 2007 experiment with these types of systems was conducted in Oklahoma and provided a striking example of the need for this technology. On May 9, 2007, a shallow mesovortex developed into an F1 tornado near Lawton, Oklahoma.

The image (Figure 4.8) shows the hook echo prior to forming into a tornado, at very low altitude and high resolution—observations made possible with the CASA network. The same storm produced an F1 tornado that touched down near Minco, Oklahoma, at 0350 UTC that was not detected by the WSR-88D system but was detected by forecasters at the National Weather Service using targeted CASA observations. Damage surveys subsequently confirmed the tornado event. Caution must be exercised in consideration of such solutions since high-frequency radar signals attenuate rapidly in precipitation, and backscatter easily becomes non-Rayleigh, which introduces other complications. In principle, however, multiple view angles and polarimetric methods can mitigate these complications.

Other radar developments look at changes in radio refractivity of the atmosphere driven mainly by relative humidity (Fabry, 2004). This technology shows promise based on tests at National Center for Atmospheric Research and elsewhere (Weckwerth et al, 2005 (JAM 44(3)). These radar systems may aid in the mapping of moisture fields in a dense, highly distributed radar network. In combination with other passive technologies above in a testbed, vertical profile information on temperature and humidity should be widely available across the country.

Cloud radars. Cloud radars operate at shorter wavelengths, from millimeters to a centimeter or two. These radars paint a three-dimensional picture of multiple cloud layers, but attenuation by precipitation limits their useful range. Cloud radars are used to research clouds, tornadoes, and the clear-air boundary layer.

Radar wind profilers. The introduction of radar wind profilers, operating variously at 50, 404, 449, and 915 MHz frequency, has been an important development from NOAA's Earth Systems Research Laboratory. Horizontal and vertical winds are estimated from backscatter associated with radio refractive index gradients when measured at different beam pointing angles.

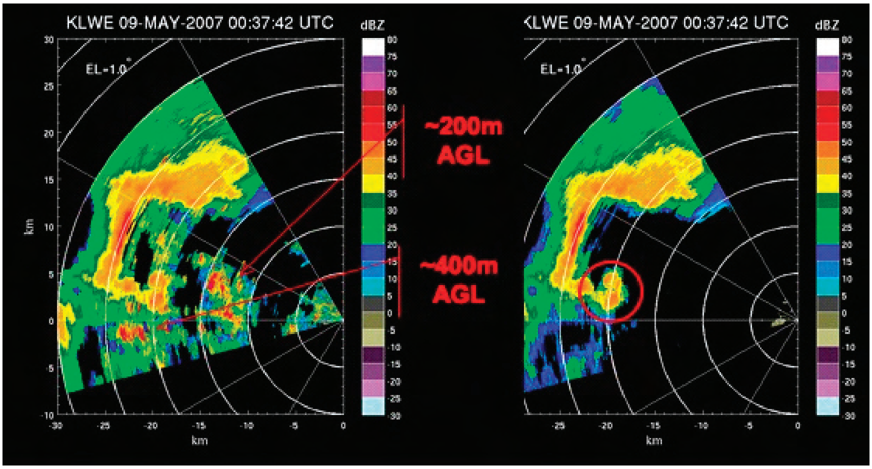

FIGURE 4.8 The Lawton tornado showing the hook echo (red circle, right panel) at an altitude of approximately 400 m above ground level. NOTE: The image on the right has been filtered to remove ground clutter. SOURCE: V. Chandrasakar, CSU/CASA.

The sharp drop in signal at the top of the convective boundary layer is used to estimate its depth; however, estimates of the depth of the night-time boundary layer are more difficult due to its shallowness. Boundary-layer depth is a major source of uncertainty in the predictive capability of current numerical chemical forecast models.

The National Profiler Network (NPN), with 32 sites in the central United States and 3 sites in Alaska,[4] delivers wind profiles up to 17 km. Sample data from an NPN site at Conway, Missouri, are shown in Figure 4.9. Wind speed and direction are retrievable throughout the troposphere at good temporal and vertical resolution.

At this time, data from approximately 100 Cooperative Agency Profiler (CAP) sites from over 35 different agencies from around the world are being acquired by Earth System Research Laboratory's (ESRL's) Global Systems Division. The CAP sites are home to boundary-layer profilers (BLPs), small, relatively low-cost ultra high frequency (UHF) Doppler radars used primarily to measure vertical profiles of horizontal winds. BLPs have a minimum range of approximately 100 m above ground level (AGL) and range resolutions selectable from 60-400 m. Depending on the configuration of the radar and the atmospheric conditions, BLPs are capable of measuring wind up to approximately 1-5 km AGL.

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[4] See *http://www.profiler.noaa.gov/npn/profiler.jsp*.

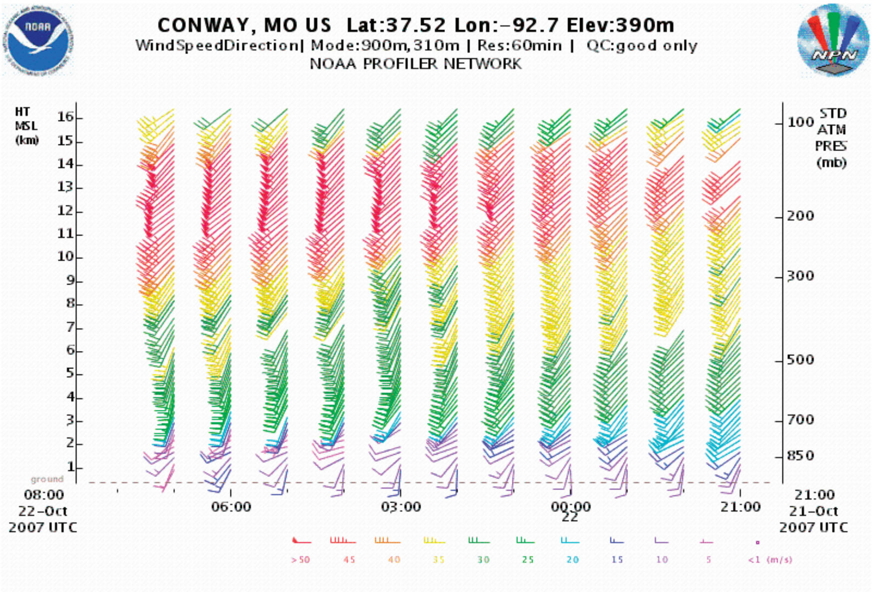

FIGURE 4.9 Eleven hours of wind data from the NPN profiler at Conway, Missouri. NOTE: The short wind barbs, long barbs, and flags stand for 5, 10, and 50 m s^{-1}, respectively.

The NPN is a nationally funded enterprise. The diverse agencies that fund the CAP are loosely affiliated, if at all; they are willing to be part of the collective that gathers the data into a single processing center. There are undoubtedly some profilers in the United States that do not belong to either network.

Sodars. Along with radar wind profiling, acoustic remote sensing or sodar technology is a way to determine boundary-layer height. In a sodar, pulses of sound are emitted vertically along a single axis (and sometimes additional axes at angles to the vertical) at a frequency near 1600 Hz. Sound waves in the atmosphere propagate at a known speed (a function of virtual temperature) and reflect from inhomogeneities in the density structure of the atmosphere, prevalent at temperature inversions. From the time of flight of the emitted pulse and the returned reflected sound, one can determine range to the height of the planetary boundary layer (PBL). Commercial sodars have been available since the 1970's. The power-aperture product of the sodar's transmitter and receiver determines the altitude to which the top of the PBL can be detected. Some systems can probe to several kilometers altitude, but they can be quite loud and annoying to nearby residents, which limits their use around populated sites.

Radio Acoustic Sounding System (RASS). Many NPN profilers are collocated with an acoustic transponder, hence the term Radio Acoustic Sounding System (Neiman et al., 1992). The transponder emits sound waves, whose propagation speed is detected by the Doppler radar at various ranges, thus enabling estimates of the virtual temperature profile. Eleven sites near the center of the NPN array have RASS capability to help with weather analysis and forecasting. Measurements typically extend up to 2-3 km, higher under light wind conditions. Many BLPs are also equipped with RASS. This technology has the potential to estimate PBL depth under some circumstances, but, like sodar, the noise it produces can be irritating.

Ceilometry. Another old technology is the use of light scattering at the base of clouds to determine ceiling heights. As early as the 1940s rotating mirror-lamp combinations were used to determine ceiling heights. Since the 1980s, small pulsed lasers have been used to determine these heights. In the light detection and ranging (lidar) configuration, a pulse of light is sent into the atmosphere. The interval of time between the emission and the detection of reflected light from the cloud determines the height of the cloud. A visible light analog to radar, lidar has been used for detecting not only cloud base but also atmospheric constituents in cloud-free air.

For clouds, the system need not have high power, because the signal from clouds is large. To measure ceiling height, commercial laser ceilometers use gallium-arsenide (Ga-As) diode lasers in the near infrared with telescopes with apertures of a few centimeters to send pulses of light into the air. For airport observations, ceiling heights of <10,000 ft are most important; thus early ceilometers focused on the measurement of lower clouds. Interest in the detection of higher clouds is growing, and the current Vaisala ceilometers can reach to 25,000 or 35,000 ft. Highly sensitive ceilometers are also able to detect aerosols at lower altitudes. Recent work has shown that ceilometers may give information about PBL structure (and PBL height) as an additional capability.

With nearly 180 ceilometers in the Automated Weather Observing System (AWOS), ceilometers may also allow derivation of aerosol profiles. To date, however, comparison of the diverse outputs of these systems has not been quality assured for aerosols or for PBL variables. Further work in this area is indicated.

Lidar. A visible- or infrared- wavelength analog to radar, lidar has been used for detecting aerosols and for using aerosol backscatter to estimate PBL depth. Lidars are also used to detect trace gases. Some infrared lidars are safe to the human eye, easily operated in heavily populated areas such as Washington D.C., and capable of detecting some types of pollution and other particulate matter. The first lidars were built nearly 40 years ago, yet the technology continues to mature rapidly and become increasingly useful. A review of lidar technology has been recently published (Weitkamp, 2005). The WMO is attempting to create the Global Aerosol Lidar Observation Network (Bösenberg and Hoff, 2008).

Lidar technology can be divided into elastic (i.e., systems that measure at the frequency of the emitted light) and non-elastic systems. In elastic systems, one fundamental difficulty is that the energy returned to the lidar is a function of the scattering coefficient of the scatterers (aerosols or gases) times the integrated two-way transmittance of the atmosphere out to the target and back. In radar, this attenuation is small and ignored, and the signal is proportional to the scattering cross-section of the targets. In lidar, the two-way transmittance cannot be ignored, even for clear air, since Rayleigh scattering in visible wavelengths is significant. This forms a problem of having one measured variable (the returned energy) and two unknowns (the backscatter coefficient and the two way transmittance). To rectify this problem, Rayleigh scattering is assumed to retrieve either backscatter or extinction profiles. Precise measurements of extinction profiles are dependent on an assumed microphysical model in elastic lidar.

Elastic lidars are simple to operate, and many networks that give profiles of aerosols exist worldwide. In the lowest power configuration, a very high repetition rate (>2000 Hz) Nd-YLF crystal lidar oscillator is used, in conjunction with a 10-20 cm aperture receiver, to form a "micropulse" lidar. The network configuration of these lidars is called the Micro-pulse Lidar Network (MPL-NET), and five such systems exist in the United States. In addition, another 10-20 higher power elastic lidars exist at universities and government research labs. These systems have been formed into an informal network called REALM (the Regional East Atmospheric Lidar Mesonet; Figure 4.10).

Next in complication in the lidar family is the non-elastic Raman lidar technique. In this technology, the outgoing pulse at the fundamental wavelength undergoes Raman scattering from gases in the atmosphere (N_2, H_2O are the most common Raman-shifted frequencies monitored). The ratio of the water vapor Raman signal to the nitrogen Raman signal gives the water vapor mixing ratio as a direct result. This allows determination of relative humidity profiles, if a temperature profile is available. Similarly, the ratio of the elastic aerosol channel signal to the Raman nitrogen signal gives the aerosol mixing ratio, and, by taking a derivative of this ratio with range, the extinction of the aerosol can be measured precisely with no assumptions about the aerosol (in contrast to the elastic systems discussed above). The Raman lidar technique has been widely used in Europe with a network called EARLINET (European Aerosol Research Lidar Network; Matthias et al., 2004) and nearly 100 journal publications have resulted from this work. In the United States, there are less than five such systems. However,

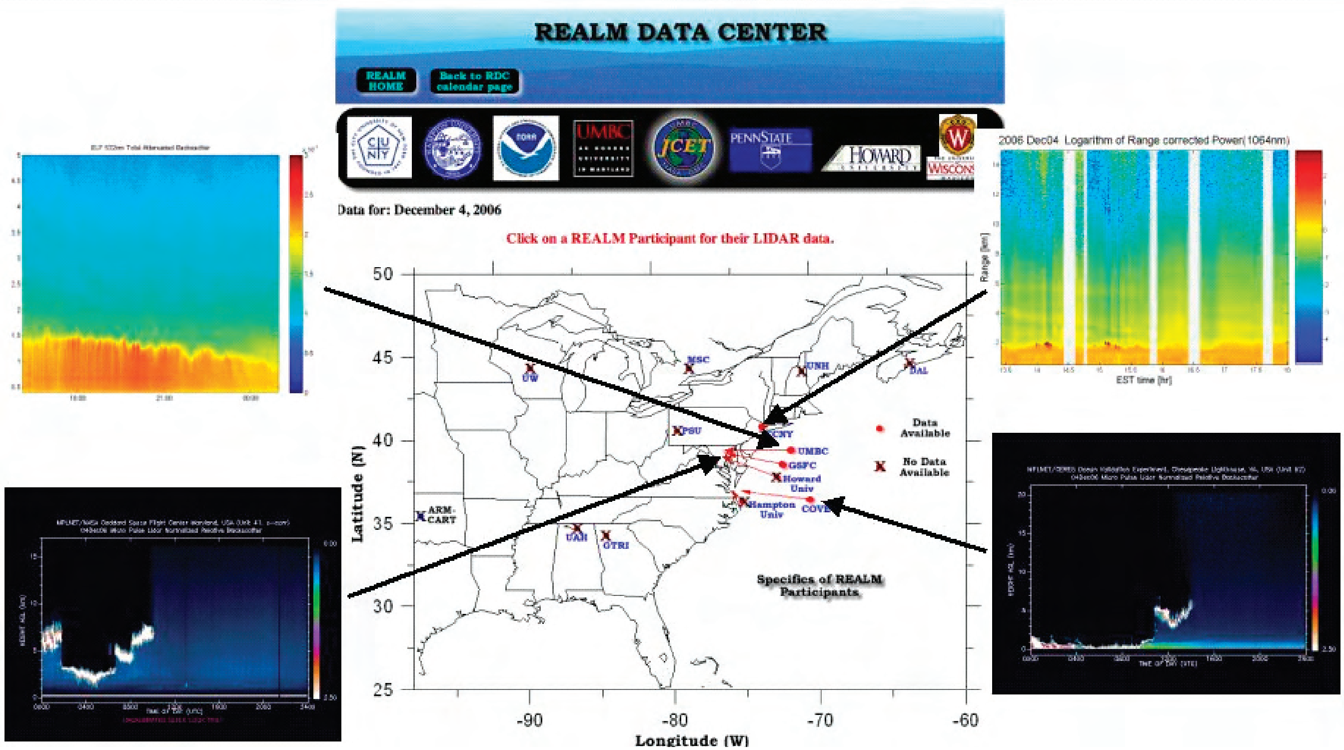

FIGURE 4.10 Simultaneous observations of lidar planetary boundary-layer heights from four REALM lidar stations from Virginia to New York City on December 4, 2006.

the United States has arguably the longest continuing record from such a system at the Department of Energy—ARM/CART Raman Lidar (Turner et al., 2002)

Other technologies with lidar include Doppler lidar for winds (Grund et al., 2001), differential absorption lidar (Ancellet and Ravetta, 2005) for ozone, water vapor, and nitrogen dioxide profiling; high spectral resolution lidar (Piironen and Eloranta, 1994); Rayleigh temperature profiling (McGee et al, 1995); and multi-wavelength lidar (Veselovskii et al., 2004) for aerosol microphysical characterization. Several companies (e.g., Halo, Leosphere, Coherent) are producing low-power, high-repetition-rate 1.55 μm fiber laser transmitter Doppler lidars, which can obtain wind information to heights of several hundred meters. However, relatively few types of lidars are currently used extensively in operations because of the expense and eye-safety issues.

Surface-Based Transportable and Mobile Observing Systems

Not all observational networks are at a fixed location. Increasingly, commercial aircraft are instrumented. Furthermore, a number of dedicated observational and research facilities in the United States are either transportable (typically shipped to a location for an observational field program) or mobile (i.e., easily movable to a new location in anticipation of an impending event such as hurricane landfall or major tornado outbreaks). These systems add a new dimension to our fixed observational assets by providing additional information where it is needed through targeted observations.

Automated Aircraft Reports

The ACARS (Aircraft Communications Addressing and Reporting System) program was initiated in the 1970s by NOAA and the FAA to put temperature and wind sensors on the shells of commercial aircraft. Current participating airlines include United, American, Delta, Northwest, Southwest, Federal Express, and the UPS. Most ACARS-equipped aircraft provide latitude, longitude, altitude, time, temperature, wind direction, and wind speed. Some aircraft also provide turbulence data in the form of either vertical acceleration or eddy dissipation rate. A small subset of aircraft, mostly UPS, also provide moisture data. A review of the precision of the data relative to radiosondes can be found in Schwartz and Benjamin (1995).

Today, more than 100,000 automated aircraft reports are available over the United States each day from domestic commercial flights, with more than half coming from ascents and descents below 20,000 ft. The main source of reports is the Aircraft Meteorological Data Relay (AMDAR) system, which collects wind and temperature reports from nearly 1500 U.S aircraft operated by major long haul carriers. Moisture measurements aboard a few aircraft (Water Vapor Sensing System, version 2—WVSS2) are being tested.

A program called TAMDAR (for Tropospheric AMDAR), started in 2003, collects information from short-hop carriers that generally fly in the mid-troposphere, below the flight levels of long haul carriers. The TAMDAR sensor is a lightweight (1.5 lb), low-drag (0.4 lb @ 200 knots), low-power device designed for easy installation and retrofit to any aircraft. The TAMDAR system measures temperature, relative humidity, winds, icing, turbulence, and position using GPS during ascents and descents (Moninger et al., 2008). When operating under typical high-resolution settings, ascent and descent observations are made at 10-hPa (100-m or 300-ft) pressure intervals up to 200 hPA (6000 ft) above ground level. Observations higher than 200 hPa above ground level are made at 25-hPa intervals. If an observation has not been made below 20,000 feet (465 hPa) for 3 minutes, then an observation is triggered by time default; if an observation has not been made at heights above 20,000 ft, then an observation is triggered by time default.

A program called Measurements of Ozone, Water Vapor, Carbon Monoxide, and Nitrogen Oxides by In-Service Airbus Aircraft (MOZAIC; Marenco et al., 1998; Zbinden et al., 2006) has been used to profile ozone, carbon monoxide, water vapor, and nitrogen oxides upon takeoffs and landings of commercial aircraft in Europe, Asia, and North America. The measurements have allowed determination of seasonal differences in the ozone column, detection of stratospheric air versus tropospheric sources, and some long-term trends in ozone measurements. Focusing on takeoffs and landings in New York City, the authors have determined that New York has a 10 percent higher contribution to tropospheric ozone than do the European or Asian cities studied. Adding other species to commercial aircraft profiles in U.S. airspace, including the lower troposphere, seems to be a promising new technology.

Role of Unmanned Aircraft Systems

The National Aeronautics and Space Administration (NASA) and NOAA have recently committed to significant development in unmanned aircraft systems (UAS; earlier called unmanned aerial vehicles or UAV). With the advent of these pilotless vehicles, a new class of airborne platforms is now available for targeted observations. A potentially useful adjunct to coastal weather radars, these vehicles hover over hurricanes and help to enable more precise predictions of ground track at landfall. Errors of order

10 km can cost millions of dollars in damage and risk human life if imprecise decisions are made. UAS have the ability to fly at 60,000-65,000 ft for up to 12 hours, and pilot fatigue is never an issue, no matter how long the mission. Current developments include the introduction of downward pointing radars, downward pointing lidar, imaging cameras in the visible and infrared, and dropsonde technology. Such developments will allow forecasters to better monitor eye-wall replacement, which can be a major factor in hurricane intensification or weakening.

These instruments also will have application in forest and brush fires in deriving plume heights and fire spread, fuel moisture characteristics, and smoke dispersion. In a recent UAS demonstration during the California fires of October 2007, NASA was able to advise the FAA and the U.S. Forest Service (USFS) about fire front behavior, which allowed the teams fighting the fires to target activities to control the blazes and to reroute air traffic around areas of hazardous smoke.

Finally, in cases of national emergency in urban areas, the ability of UAS to monitor plume dispersion for hours around an event would be hard to match with other observing systems.

Targeted Observations

Targeted observations are made on demand, as the problem dictates. They are used for both operations and research. Familiar examples of targeted observations are the NOAA and military aircraft missions that target hurricanes and, during the "off" season, take measurements in winter storms affecting the western and eastern U.S. coasts. Other examples are aircraft missions to release dropsondes around hurricanes to improve forecast accuracy, rapid-scan images programmed for Geostationary Observation Environmental Satellites (GOES; to be discussed later in this chapter), and extra radiosonde releases when severe storms threaten the U.S. mainland. UAS, large and small, are being considered both for targeted and routine observations, especially in remote oceanic and polar regions; and they have potential to "sniff" out toxic releases (NRC, 2003a). It might also be possible to move a fleet of mobile radar wind profilers into a region threatened by hurricanes.

Targeted observations have been used for research since aircraft penetrations of thunderstorms during the Thunderstorm Project in the 1940s. Prominent research-based systems include mobile Doppler radars and mesonets (e.g., Weckwerth et al., 2004, Bluestein et al., 2001). Mobile radars include, for example, the C-band SMART radars (Biggerstaff and Guynes, 2000), the X-Pol and X-band Dopplers on Wheels (Wurman, 2001), the University of Massachusetts millimeter radar (Bluestein and Pazmany 2000), and mobile radar wind profilers (e.g., the Mobile GPS/

Loran Atmospheric Sounding System [MGLASS] operated by the Earth Observing Laboratory [EOL]/NCAR, the Mobile Cross-Chain Loran Atmospheric Sounding System [MCLASS] operated by the National Severe Storms Laboratory [NSSL]). Radiosonde are also released from mobile platforms. Mobile Radiometers supplied by the Desert Research Institute were deployed during the International H_2O Experiment (Weckwerth et al., 2004).

Mobile mesonets are typically instrumented cars (e.g., Straka et al., 1996), or rapidly-deployable instrumented towers, such as the Texas Tech University Stick-Net,[5] which can be deployed in the time it takes to drive to the phenomenon of interest (installation time less than 3 minutes). Rapidly deployable surface stations are also available for supplemental observations during wildfires (mobile Remote Automated Weather Stations, RAWS) and many other emergency management and public safety applications, such as deployment after September 11, 2001 in New York City and during major sporting events such as the Super Bowl.

Airborne remote sensing has become important in operations and research. The P3 aircraft used to penetrate hurricanes are equipped with a horizontally scanning C-band radar and a vertically scanning X-band Doppler radar. A Navy P3, operated jointly with NCAR, also has an airborne Doppler radar. Both have been used extensively in field programs to investigate convective precipitation, including mountain precipitation, storm initiation, and hurricane landfall. Airborne Doppler lidars and differential absorption lidars have also been flown.

Surface-Based Network Collaborations

The desire to use data from multiple networks has led in recent years to "collectives," which combine the data from a number of networks, offering easier access to shared data and quality checking for the included groups. The two flagship collectives are the Meteorological Assimilation Data Ingest System (MADIS; Miller et al., 2005), which is based at ESRL/NOAA and is essentially NOAA's attempt to create a network of networks, and MesoWest (Horel et al., 2002), which is based at the University of Utah and is the primary source of surface mesonet data for many end users across the country.

NOAA's Hydrological Automated Data System (HADS)[6] provides real-time data from more than 13,000 river and weather sites. Another important collective is NorthwestNet, based at the University of Washington. More recently, the Federal Highway Administration has started to develop

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[5] See *http://www.atmo.ttu.edu/TTUHRT/WEMITE/sticknet.htm.*

[6] See *http://www.nws.noaa.gov/oh/hads/.*

the *Clarus* (Latin for "clear") System to integrate surface transportation weather observations over the United States, and data from many state departments of transportation have resided on MADIS for years. The Consortium of Universities Allied for Hydrological Sciences has been developing a Hydrologic Data Access System[7] that provides access to data not only from networks (e.g., Ameriflux and Long-Term Ecological Research Network [LTER] sites) but also from North American Regional Reanalysis. RAWS[8] are operated by multiple agencies for air quality and fire weather applications. AIRNOW links air quality data from multiple locations for air-pollution applications. On a smaller scale, the state climatologists in some states have begun efforts to form a collective among the networks within their states. (e.g., South Carolina and Iowa).

> **Finding: Surface network collaborations represent a significant step forward and serve to achieve improved quality-checking, more complete metadata, increased access to observations, and broader usage of data serving more than one locally driven need.**

SPACE-BASED OBSERVATIONS

Satellites are essentially tools for global observations, but part of their utility lies in setting the context for mesoscale surface-based observations. Satellites provide vital information on the evolution of severe storms, and remotely sensed soundings and water vapor imagery contribute to the interpretation of the severe storm environment. Satellites also provide information on surface characteristics such as vegetation and soil moisture, both of which have been shown to be important to storm initiation and the prediction of convective weather.

Satellite orbits can be divided into two types, geostationary orbits and low-Earth orbits. In a geostationary orbit, the satellite travels at the same rate as the Earth revolves, affording a constant view from a vantage point 40,000 km above the equator. The distance limits resolution and signal-to-noise ratio but affords a view of evolving storm systems on a routine basis, at intervals of 30 minutes or less. Low-Earth orbiting satellites do not provide a continuous view, but their lower altitude (100s of km above Earth's surface) enables higher-resolution images and stronger signals, opening up the opportunity to generate many remotely sensed products at intervals of twice a day. A common type of low-Earth orbiting satellite, the sun-synchronous polar-orbiting satellite, samples a point on the Earth at 12-hour intervals. Another low-Earth orbit is the less frequently used pro-

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[7] See *http://www.cuahsi.org/his.*

[8] See *http://www.fl.fed.us/rm/pubs/rmrs_grt119.pdf.*

grade orbit (faster than Earth's angular rotation), which enables sampling through the diurnal cycle over time (e.g., for tropical rainfall in the case of the Tropical Rainfall Measuring Mission [TRMM]), and specialized constellations that take advantage of other space-based assets such as GPS for radio-occultation measurements.

Satellite instruments use the microwave, infrared, visible, and ultraviolet (UV) parts of the electromagnetic spectrum to probe the atmosphere and the Earth's surface. Measurements of visual reflectance of sunlight from the surface are the easiest to comprehend for those uninitiated to satellite meteorology. Parameters to be retrieved generally relate to the diminution of sunlight before it reaches the surface (clouds, aerosols, absorbing gases) or reflectance quantities from the surface (albedo, land use, vegetation characteristics). Recently, techniques to retrieve aerosol optical depth over the ocean (which has a minimally varying reflectance over a dark surface) has been determined to be possible to about 20 percent precision (Remer et al., 2005). Many gases absorb in the ultraviolet and visible portions of the spectrum, and this provides the ability to do species-specific sampling. O_3, SO_2, NO_2, CHCO, H_2O, and aerosol size information have all been retrieved in the UV and visible spectral channels of space-borne measurements.

GOES can view large portions of a single hemisphere. GOES spatial resolution is about 1×1 km for visible and 4×4 km for infrared data. Measurements are at intervals of the order of ten to a few tens of minutes, providing the capability to follow cloud evolution. In "rapid-scan" mode, GOES provides valuable data for mesoscale analysis and nowcasting (Browning, 1982). In addition, cloud or water vapor features can be tracked to estimate winds, providing data between radiosonde or aircraft reports. Precipitation has been estimated from an infrared cloud-top algorithm. NOAA's next generation geostationary satellite, GOES-R, can deliver skin temperature over land and water but with limited spatial resolution and only in clear sky views, and also can be used to identify cloud top height. GOES-R is planned to have a multi-channel Advanced Baseline Imager that will view the United States at least every 5 minutes with a factor of four higher spatial resolution than the current generation of GOES.

The Moderate-resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua polar-orbiting satellites uses infrared radiation to retrieve vegetation characteristics, which are used as input into the land-surface models embedded in experimental numerical weather prediction models. Satellite images such as GOES, the Advanced Very High Resolution Radiometer (AVHRR), and MODIS, can deliver skin temperature with limited spatial radiation and only for clear skies. Future images for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and GOES-R will have greater spatial resolution and thus the potential for more clear fields of view. These satellites also have the "split window" channels that allow for low-level moisture corrections. The current GOES series of satellites eliminated the split window capability early in the series and replaced the 12.5-micron channel with one at 13.2 microns to help with cloud height assignment; thus in some areas the current GOES surface temperatures are compromised by moisture. Surface winds are problematic from space, except over the open ocean.

Microwave imagers such as the Advanced Microwave Scanning Radiometer (AMSR) (Njoku et al., 2003) and the Special Sensor Microwave Imager (SSM/I) (Jackson et al, 2001) can give surface water content (standing water and in a very shallow, ~1-cm layer below the surface), but cannot give information on subsurface water. AMSR's footprint is of the order of 25 km so the resolution in areas of varying topography, where runoff and streamflow may be most important, is problematic. Ground-penetrating radar such as RADARSAT (LeConte et al., 2004) has been used to probe soil moisture, but the instrument does not produce a routine product in this regard. The "Decadal Survey" (NRC, 2007a) has identified the L-Band (1-2 GHz, ~20 cm-wavelength) Soil Moisture Active-Passive radar-radiometer approach as a promising technology for soil-moisture retrieval and placed it in the top three missions for development by NASA, but also pointed out that the Hydros mission designed for this purpose was cancelled.

Spaceborne radars and lidars have been used to sense precipitation, clouds, and aerosols. Radar satellites such as RADARSAT, TRMM[9] and CloudSat are in orbit and are returning information with high vertical resolution from these pulsed measurements. In the visible regime, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission is returning very high vertical resolution images of clouds and aerosols. These active sensors promise to be able to retrieve data well down into the lower troposphere with high resolution, which is of value to the mesoscale observations of this study.

TRMM has demonstrated the use of space-based radar measurements to estimate rainfall rates over the ocean while also providing profiles of precipitation and observations of lightning using a high-speed, charge-coupled device detection array. TRMM's 13.8-GHz precipitation radar electronically scans a 280-km-wide swath with a spatial resolution of 4 km. Scientists at NASA's Goddard Space Flight Center used TRMM data as a baseline to calibrate polar-orbiting passive microwave sensors and geostationary infrared sensors to produce 3-hourly global precipitation maps.

The lidar on CALIPSO is a two-wavelength (532 and 1064 nm) polarization-sensitive lidar that provides 30-60 m vertical resolution profiles of aerosols and clouds within its 100-m field of view. CALIPSO was

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[9] See *http://trmm.gsfc.nasa.gov.*

launched in tandem with CloudSat, which carries a 94-GHz nadir-looking radar Cloud Profiling Radar (CPR) that measures the power backscattered by clouds as a function of distance from the radar. The CPR profiles clouds along the satellites ground track with a horizontal resolution of 2 km while providing information with 500-m vertical resolution on cloud water and ice concentrations, cloud thickness and cloud base and top height. CloudSat and CALIPSO are flying in a formation called the "A-Train" with Aqua, PARASOL,[10] and Aura. While satellites are mesoscale-resolving in the spatial domain, the infrequent time domain sampling suits them for climate statistics but severely limits their utility either for monitoring or predicting mesoscale events.

Space-Based Soundings

Satellites provide atmospheric soundings using both infrared and microwave remote sensing. The NOAA High Resolution Infrared Radiation Sounder (HIRS) and the GOES sounder provide vertical profiles of temperature and moisture, as well as other variables. The NOAA polar-orbiting satellites that fly Advanced Microwave Sounding Units (AMSU-A and AMSU-B) provide similar thermodynamic information. In both cases, sampling in the spectral region at the center of the absorption band yields radiation from the upper levels of the atmosphere (i.e., radiation from below has already been absorbed). Radiation signals at wavelengths increasingly distant from the center of the absorption bands are from successively lower levels of the atmosphere. This smears out the temperature and moisture, particularly in the lower atmosphere, limiting but not eliminating their utility at the mesoscale. Moreover, infrared soundings require clear skies.

More vertical resolution can be obtained using more portions of the spectrum. Hyperspectral infrared sounders, such as the Atmospheric Infrared Sounder (AIRS) on NASA's Aqua satellite, uses thousands of spectral bands in the infrared spectrum with greater accuracy and vertical resolution than before, although still not of radiosonde accuracy or vertical resolution, particularly in the lower atmosphere. The EUMETSAT's[11] Infrared Atmospheric Sounding Interferometer instrument measures atmospheric trace gases in over 8000 channels. The exploitation of such data for mesoscale applications is being investigated.

Earlier, we discussed the analysis of signals from GPS satellites to infer the amount of water vapor in a vertical column of air. The technique of radio occultation (RO) greatly expands the utility of GPS; it results in

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[10] Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar.

[11] Network of European Meteorological Services.

measurements of electron density in the ionosphere, temperature soundings in the stratosphere, and temperature and moisture soundings in the troposphere. Radio-occultation measurements from the Taiwan-U.S. COSMIC/FORMOSAT-3 mission[12] (Anthes et al., 2008) are providing real-time temperature soundings with roughly 500-m vertical resolution in all kinds of weather, since the radio waves are not affected by clouds or precipitation. However, the horizontal resolution is 150-200 km (Ware et al., 1996), a drawback for mesoscale applications.

From an altitude of 20,000 km, the GPS satellite sees the low-Earth orbiting satellite's rising or setting over the Earth's surface, hence the term "occultation." The speed of the radio waves between the two satellites is a function of the atmosphere's radio refractive index. Virtual temperature profiles can be calculated from a number of satellite-to-satellite paths, with excellent accuracy from the mid-troposphere upward, where there is little moisture. Sophisticated assimilation techniques that combine RO data with information from prediction models have been able to extract moisture information from the RO data in the lower troposphere, useful for global NWP.

Satellite-based sounding information of other quantities, such CO_2, CO, O_3, and CH_4, are of increasingly high quality, but they don't fully meet the requirements for this study, since many instruments derive only full-column quantities (column O_3, for example), and it is difficult, if not impossible, to untangle the planetary boundary-layer information from those profiles. Many sensors, designed to give many levels of vertical resolution, have not lived up to billing and give only one or two pieces of independent information, which tend to peak higher in the troposphere than would be useful for planetary boundary-layer application. Ultraviolet and infrared instruments may get such a large portion of their orbit level radiances from high in the atmosphere that they cannot even see the surface. And finally, clouds as an obscurant are a major limitation in making routine surface observations since approximately 70 percent of the pixels are contaminated by cloud on average.

OBSERVATIONAL CHALLENGES

The Surface Challenge

While much of the technology involved in surface meteorological measurements is reasonably mature, important challenges remain. Land-surface properties, especially soil moisture, are only measured in scattered areas,

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[12] Constellation Observing System for Meteorology, Ionosphere, and Climate/Formosa SATellite.

yet this has been identified as an important variable in numerical weather prediction, and for many agricultural applications. Likewise, measurements of precipitation type and amount, especially for frozen precipitation in real time, are important for aviation (de-icing aircraft, keeping airports open) and road transportation (informing decisions by road managers regarding plowing and road-treatment chemical application).

The Challenges of Geography and Urbanization

Although maps show an impressive number of meteorological observations, zooming in inevitably reveals extensive gaps in relation to known mesoscale variability. This is particularly true for soil-temperature, soil-moisture, and air-pollution measurements, as just mentioned. In addition, there are regional-scale surface station deficiencies for real-time reporting of standard meteorological data.

While mesoscale and convective-scale phenomena can occur anywhere in the United States, it is not necessary to measure all atmospheric variables at sub-kilometer scales at all locations in order to produce accurate and useful analyses and forecasts. However, there are three regions (urban areas, mountains, and coastal zones) for which nature and/or people have created structures of significance on such small spatial scales that special measurement and network strategies are needed. These structures can create very strong gradients in atmospheric (and chemical) variables across short distances that are of vital importance to life and property. Whereas measurements over homogeneous terrain are intrinsically representative of a broader area, data in small-scale three-dimensional environments are often representative of only a tiny volume.

Moreover, urban areas, mountains, and coastal zones all have special needs. All three create their own weather, which is often poorly resolved in synoptic NWP models. Considering the importance of water storage in the snowpack and reservoirs and hydroelectric power generation, and the danger of traveling in the winter or fighting forest fires in the summer, the needs for observations in the mountains go beyond those for weather forecasting alone. Coastlines and cities, both of which have high concentrations of people, also take on special importance, particularly when one considers the need for observations to respond to a release of toxic substances, to treat the roads in response to an ice storm or blizzard, or to evacuate people in advance of hurricane landfall.

Urban Areas

High-resolution weather information in urban areas is vital because of the greater population density coupled with the added complexity introduced by large buildings (and possibly terrain and coastal features as well). The impacts of typical weather phenomena are magnified in cities; for example, heavy rains can cause severe flooding, snow and freezing rain can disrupt transportation, and severe storms and accompanying lightning and high winds can cause power failures. Urban dwellers also are more susceptible to public health and safety issues such as heat stroke, heavy air pollution, and terrorism. Large urban areas also impact weather and atmospheric structure in various ways. Urban heat islands result from the combined effects of changed thermal and radiative properties of the surface, anthropogenic emissions of sensible heat, and changes in the exchange of water and the corresponding impact on the radiation budget. Changes in surface roughness in urban areas also affect the exchange of heat, mass, and momentum between the surface and the atmosphere, as well as the depth of the urban mixed layer. Hydrological processes also are altered to a significant degree as a result of buildings and pavement that affect runoff and stream flow. Large urban areas may influence the genesis, intensity, and movement of convective storms and frontal boundaries. There are unique issues related to air quality and terrorism, which were discussed in Chapter 3.

There is a pressing need to improve our ability to characterize and forecast urban weather. The increasing spatial resolution of NWP models allows for the opportunity to address urban meteorology and impacts to a greater degree. However, as pointed out by the 10th Prospectus Development Team of the U.S. Weather Research Program (Dabbert et al., 2000), improving short-term predictions of weather and air quality in urban forecast zones requires improvements in our measurement and modeling capabilities. Improving our capabilities requires special consideration of the urban environment and the "urbanization" of our meteorological measurement and modeling components. Recent studies are showing that improvements in NWP and air quality dispersion require better descriptions of urban surface fluxes and the vertical structure of the urban boundary layer (Baklanov et al., 2006). These improvements present new challenges for urban observing systems, which need to characterize flows and constrain models operating at scales of a few hundred meters. The measurement challenges include the following (Baklanov et al., 2008): (1) Availability of suitable and representative instrument sites, allowing for security, power, data transmissions, neighborhood convenience, public safety, accessibility, and planning permission; (2) Height and positioning of sensors to meet the needs of adequate reference height, so that the appropriate surface type is within the upwind fetch and observational footprint for sensors; and (3) Sufficient number of sensors to be deployed within the city area as well as at a number of reference rural sites so that influences due to the city can be differentiated from the day-to-day and diurnal changes under various prevailing meteorological situations.

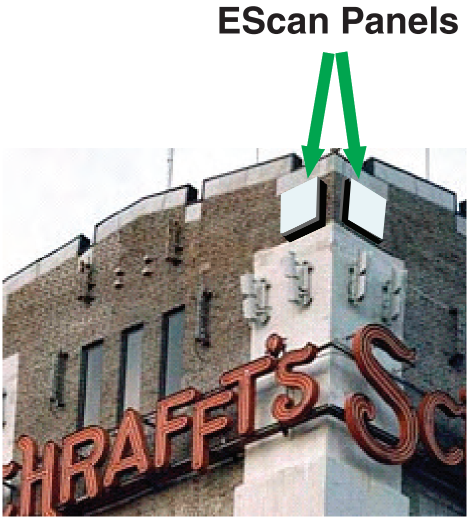

FIGURE 4.11 Conceptual design of microwave radar antenna panels mounted on the corner of a building (D. McLaughlin, UMass-Amherst/CASA).

These measurement issues are being studied in testbeds such as the Helsinki study discussed earlier, the Pentagon Shield program (Warner et al., 2007), and in urban field experiments.[13] Lessons learned here and elsewhere need to be factored into the urban component of the national mesoscale observing network. Urban networks provide unique challenges such as the need for three-dimensional measurements at dense scales and communications. In addition, the sensors cannot be deployed easily, and dealing with building architectural codes, real estate costs, and societal acceptance becomes very important. These challenges are already being addressed in other disciplines such as cell phone antenna deployments and in weather via a planned CASA project. Figure 4.11 shows a conceptual deployment scenario of low-cost microwave radar sensors in an urban environment where the radar antenna panels are attached to the edges of the taller buildings. The electronic-scanning sensors merge seamlessly with the background and have no moving parts (McLaughlin et al., 2007). Also shown in the figure are the communication antennas.

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[13] E.g., the December 2007 special issue of *Journal of Applied Meteorology and Climatology* on Joint Urban 2003.

Mountains

Mountains affect the weather by initiating convection and deep snowfalls, focusing water or wind into narrow valleys, and generating turbulence aloft and severe (≥100 mph) windstorms at the surface on their lee side. They present the danger of slick roads, high winds, poor visibility, and avalanches, rockfalls, and mudslides. They also cause significant downstream effects in weather and stream flow, the latter causing water resource management challenges up to 1000 km. Knowing the water content in the mountain snowpack is important to water managers and their customers. At the same time, mountains present special observational challenges. The weather conditions—temperature, winds, and precipitation—around mountains are so variable that the small number of measurement sites cannot capture the complexity. Radars and data transmission are both limited by blockage, and traditional flux measurements in complex terrain are difficult to interpret correctly. Measurement sites are difficult to install and maintain. Forest fires present a particular challenge, because wind and moisture measurements in remote terrain are critical.

Current observations in the mountains can be characterized as sampling sparse but sampling smart. Decades of experience have determined where Snowpack Telemetry measurements are sited, and methods are being developed to incorporate satellite information. Likewise, state DOTs know the weather-vulnerable portions of major roadways and the locations of site stations. The dangerous stretches of major roads are often equipped with web-cams to help travelers. Larger metropolitan areas have instrumented the watershed upstream to alert them of the possibility of flash floods.

At the mesoscale and smaller scales, challenges remain—particularly with respect to convective precipitation and wildfires. Because mountains block radar beams, many areas are without coverage. We have the tools to begin to address this, for example, gap-filling radars and lidars that operate in adaptive-collaborative modes with rain gauges, stream gauges, and satellites. As cell-phone towers proliferate, these offer platforms not only for radars and lidars but also for communication of data from remote sites.

High-resolution numerical models need to be part of the observational mix. Mountains provide strong forcing, making precipitation and wind patterns more predictable. The combination of good upstream conditions with some boundary-layer, surface, and radar data that the model can assimilate has the potential to provide the three-dimensional picture needed by fire meteorologists, snowpack and runoff analysts, and flash-flood or downslope windstorm forecasters. Thus the components needed for a "Mountain Net" are included in our architecture as proposed, the primary challenge being to address the severe under-sampling problem.

The Coastal Zone

Coastal regions have both natural and made-made features that create complex spatial and temporal variability in weather and sea-state conditions, much of which may go undetected. For example, prevailing offshore flow could be replaced by a sea breeze along one stretch of coast while adjacent stretches remain offshore, affecting forecasts of convective initiation and energy demand. Varying winds also can affect the destination of a hazardous chemical leak and the towing of ships and barges in a harbor. Coastal fronts can move onshore ahead of winter storms, affecting where different types of precipitation fall (solid, partly frozen, and unfrozen). Unmeasured air-sea interactions occur offshore, creating moisture and stability conditions that are ripe for severe weather outbreaks in the return flow regions.

The vulnerability of coastal zones is increasing annually, as more coastal regions become large population centers. Coastal counties are growing three times faster than other U.S. counties, and coastal and marine waters are an annual tourist destination for 90 million Americans. In addition, many coastal regions have significant topography, suggesting that their special observing and network needs are congruent with those of the Urban Net and Mountain Net described above. Additional requirements, though, exist for offshore weather and sea-state data, including profiling of winds, temperature and moisture above the surface, and temperature, current, and salinity at and below the surface. Thus the U.S. mesoscale network of networks should include a suite of additional buoys and land stations, and remote sensing capabilities extending 100-200 km from the coast.

The Planetary Boundary Layer Challenge

One of the most difficult to measure and yet one of the most important parameters is the height of the daytime and nighttime planetary boundary layer (PBL). Driven in the daytime by heating of the surface and convection and driven at night by winds and infrared radiative cooling of the surface, the PBL height is critically important in forecasting constituent concentrations in numerical models (since this is the height of the box into which constituents mix and react). It is now believed that the imprecision with which the PBL height is known is a major source of uncertainty in the predictive capability of current numerical chemical forecast models. It really is astounding after nearly sixty years of remote sensing observations in meteorology that such an important meteorological variable is not measured with regularity throughout its diurnal cycle.

The only area of relative strength relates to winds from ultra-high frequency (UHF) and very high frequency (VHF) wind profiles when combined with AMDAR and TAMDAR observations. This combination thoroughly captures the synoptic scale, and also some of the larger mesoscale circulations. However, the characteristic spacing of radar wind profilers is too large, often missing medium-sized mesoscale circulations that spawn disruptive and severe weather. The number of commercial airline observations has a large-amplitude diurnal cycle, which deprives the composite observing system of needed data for ~8 hours per day and leaves the system vulnerable during large storms (or terrorist attacks) when there are wholesale flight cancellations.

The national condition for thermodynamic, trace-gas, and aerosol profiling is one of significant inadequacy to address mesoscale prediction needs. A major improvement in thermodynamic profiling is needed. Radiosonde sites are several hundred kilometers apart and only address the synoptic scale. The vertically resolved water vapor field, especially in the

BOX 4.2
An Example Core Observing Site to Address the Planetary Boundary Layer Challenge

For the last 20 years, Howard University of Washington, D.C., has operated a research station at Beltsville, Maryland. Since 2001, when a NOAA Center for Atmospheric Sciences was founded at Howard as part of a NOAA Cooperative Agreement, the Beltsville facility has grown into a high-level core mesoscale observation site. A tall tower to measure CO_2 fluxes was installed by the University of Virginia, and a Raman lidar was constructed in cooperation with NASA. Radiosonde observations and ozonesonde releases have been carried out for validation of NASA's Tropospheric Emission Spectrometer and Ozone Monitoring Instrument. NOAA has contributed many of the radiosondes as part of its modernization program and the Pennsylvania State University has contributed the ozone soundings as part of the NASA INTEX Ozonesonde Network Study (IONS). Baron Meteorological Services has contributed a weather radar to the site. The EPA and the State of Maryland have contributed a radar wind profiler and a ground-based chemical monitoring capability (PM, O_3, NO_x) to the site. The U.S. Department of Agriculture (USDA) has contributed a shadowband radiometer to the site to measure aerosol optical depth, and NASA has contributed an AERONET site. Surface energy fluxes and subsurface temperature and moisture are measured at the site. Sonic anemometers measure turbulence at the site. Surface solar radiation fluxes (as in the Baseline Surface Radiation Network, NOAA) are being routinely made at the site.

Arguably, Beltsville is the type of station which can be expected to arise from the efforts recommended in this report. Multiple agencies, with disparate needs, can contribute to a single site and leverage resources. It is interesting that this site was founded and is operated by a Minority Serving Institution, which clearly lowest 1 km, is most critical, being essential for improved prediction of all high-impact weather. The needs of chemical weather predication are on a similar plane, requiring national-scale coverage of major pollutant species including aerosols, thereby enabling urban and regional pollutant forecasts. Some research stations have been established that include many of the core, ground-based remote sensing systems that supply these types of observations (see Box 4.2). Yet, there is no national coverage of sufficient scope to address the planetary boundary-layer challenge.

Recommendation: As a high infrastructure priority, federal agencies and their partners should deploy lidars and radio frequency profilers nationally at approximately 400 sites to continually monitor lower trospospheric conditions.

could not have accomplished a project of this scope without contributions from the federal and private sector.

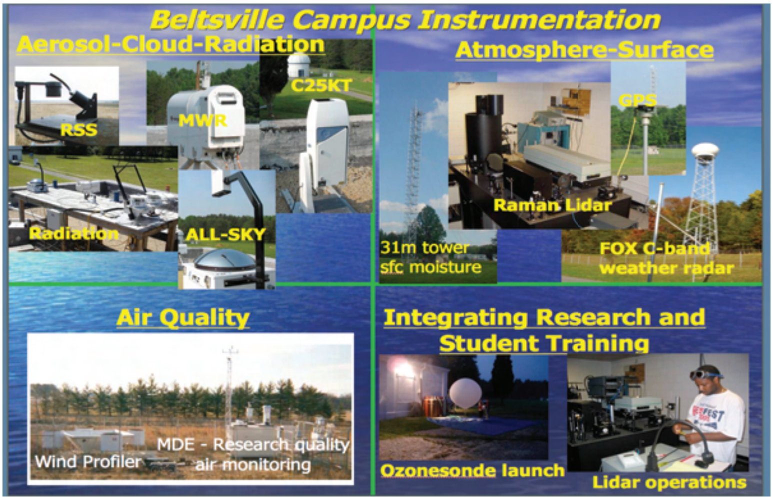

FIGURE 4.2.1 The Howard University Beltsville site showing the instrumentation component and training. SOURCE: Whiteman et al. (2006).

Wind, diurnal boundary-layer structure, and water vapor profiles are the highest priority for a network, the sites for which should have a characteristic spacing of approximately 150 km but could vary between 50 and 200 km based on regional considerations such as those just discussed for urban areas, mountains, and coastal zones. Such observations, while not mesoscale resolving, are essential to improved performance by high-resolution numerical weather prediction models and chemical weather prediction at the mesoscale. Through advanced data assimilation techniques, data from these 400 sites, when used in combination with geostationary satellite measurements, GPS constellation "wet delay" measurements, and commercial aviation soundings, could effectively fill many of the critical gaps in the national observing system.

Any sensors that measure air chemistry or aerosol properties above ground should be located with or near the meteorological profilers. Most chemical models use vertical grid spacing of 100-200 m in the lowest 3 km (finer near the surface), but chemical and aerosol measurements at even two or three levels within the lowest 3 km would be a marked improvement over present capability. Above 3 km, satellite measurements become increasingly effective at greater altitudes. Some of the measurements could be from towers, others from remote sensing by lidars or differential optical absorption spectroscopy.[14]

Challenges for Space-Based Observations

The "Decadal Survey" (NRC, 2007a) has identified a path forward for the next generation Earth observational satellite system for the United States. Measurements that are relevant to mesoscale applications include soil moisture using the L-band, soil composition and vegetation characterization from a hyperspectral spectrometer, columns of atmospheric trace gases to high horizontal resolution, aerosol and cloud profiles, land-surface topography, temperature and humidity soundings, tropospheric winds that don't depend on feature tracking (from Doppler lidar), and subsurface water.

The United States was expected to play a leading role in developing many of the space-based capabilities mentioned above, which in turn would have contributed substantially to mesoscale observations of the Earth, its ocean, and atmosphere. However, as pointed out in the "Decadal Survey's" preliminary report (NRC, 2005), "The national system of environmental satellites is at risk of collapse." Further deterioration in the U.S. plans led to an even more pessimistic assessment in the final report (NRC, 2007a): "Those concerns have greatly increased in the period since the interim

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[14] Described at *http://www.atmos.ucla.edu/~jochen/research/doas/DOAS.html.*

report was issued, because NASA had cancelled additional missions, and NOAA's polar and geostationary satellite programs have suffered major declines in planned capabilities."

The "Decadal Survey" links observations in solid earth, water, weather, climate, health, and ecosystem science areas to meeting societal challenges regarding water, food, and energy security, early warnings of hazardous weather, ecosystems services, and improvements in public health and environmental quality. Specific recommendations are made to both NOAA and NASA concerning GOES-R hyperspectral sounding capability, the elimination of climate monitoring sensors in NPOESS, deletion of the Conical image: Rain rate Scanning Microwave Imager/Sounder, and removal of key meteorological sensors from the early-morning orbiting satellite (0530 LST Equator crossing), and a series of other missions relevant to this study.

From a mesoscale perspective, the most disturbing finding was the elimination of hyperspectral infrared temperature and water vapor sounding capability from geostationary altitude. Support for the "Decadal Survey" conclusions is widespread. The National Weather Association, primarily representing operational forecasters, strongly advocates for "inclusion of a capable high spectral resolution atmospheric infrared sounder on the next generation of GOES-R series of spacecraft." The American Meteorological Society's Committee on Satellite Meteorology and Oceanography issued a consensus statement "On the Importance of Deploying a GEO Advanced Sounder without Delay." Further, a recent NRC workshop on "Ensuring the Climate Measurements from NPOESS and GOES-R" found strong advocacy for geostationary hyperspectral sounding, as did the coincident WMO "Workshop on the Re-design and Optimization of the Space-based Global Observing System."

In conclusion, satellites will play an increasingly important role in mesoscale observation, but limitations of frequency, resolution, and precision near the surface mean that satellite profiles will not replace ground-based observations in the near future.

> **Finding: It is a national imperative to sustain and improve operational geostationary satellite observations as a critical adjunct to the surface-based mesoscale network.**

Observations from geostationary orbit are unique and inherently Mesoscale, owing to the high rate of time domain sampling and excellent horizontal resolution. Visible and infrared imagery are invaluable to severe weather forecasts and warnings. Estimates of assimilation of radiances, cloud-drift winds, and free troposphere water vapor enable the initialization of global and mesoscale models. Over land, the vertical resolution of water vapor and temperature data normally obtained from geostationary orbit is not independently sufficient but absolutely essential. Continuous cloud layers prevent infrared soundings below cloud top; however, microwave imaging array technology (Lambrigtsen et al., 2006) offers a useful lower-resolution alternative under cloud cover. On the other hand, it is impractical to establish a stand-alone surface-based network with adequate horizontal resolution throughout the depth of atmospheric boundary layer and lower troposphere. Soundings obtained from ground-based profilers (including aircraft of opportunity) and geostationary satellites complement each other optimally, each of their strengths compensating for the other's relative weaknesses.

> **Recommendation: As a high satellite instrument priority, NASA and NOAA, in cooperation with foreign space agencies, should seek to improve the quality of geostationary satellite water vapor and temperature soundings within continental atmospheric boundary layers.**

Infrared hyperspectral soundings and soundings from microwave synthetic thinned aperture arrays, each in geostationary orbit, offer unique opportunities to improve mesoscale prediction. While potentially costly, the benefits from improved geostationary soundings would be large, likely enabling more skillful forecasts of convective rainfall and attendant severe weather and flooding. The geostationary platform is unique among satellites, offering the sampling frequency required in this application.

GLOBAL CONTEXT AND INFRASTRUCTURE

Much of the data collected are managed globally through the evolving Global Observing System (GOS),[15] which is coordinated by the WMO's World Weather Watch. Data from the the GOS are used for a variety of applications that span time scales from nowcasting to climate, and include land, ocean, atmosphere, and ecological applications. The GOS provides valuable examples of how a variety of user needs and requirements for various applications are addressed as well as how important areas such as data exchange are handled.

GOS is composed of two major subsystems, space- and ground-based. Each may be thought of as a system of systems. The ground-based subsystem provides observations from surface observing stations on land, upper air observing stations, ships at sea, moored and drifting buoys, and aircraft. While some of these systems are owned and operated by WMO members, the aircraft system is operated by various airlines and coordinated

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[15] Detailed information on the observing system component of the GOS can be found at *http://www.wmo.int/pages/prog/www/OSY/gos-components.html*.

within WMO through the AMDAR System Panel.[16] Some of the observing systems are coordinated with other international organizations (mainly the Global Ocean Observing System [GOOS], Global Terrestrial Observing System [GTOS], and Global Climate Observing System [GCOS]). Data from the space-based subsystem of the GOS[17] are provided by operational satellites in low-Earth and geostationary orbits and selected research satellites in low-Earth orbits. Those satellites are operated by various countries or consortia of countries with WMO activities through mechanisms such as Coordination Group for Meteorological Satellites (CGMS) and Committee of Earth Observing Satellites (CEOS).

The GOS Ground-Based Sub-System

Over land, a relatively sparse network of nearly 11,000 stations delivers observations of conventional meteorological parameters. About 4000 of those stations comprise the Regional Basic Synoptic Networks, whose data are exchanged globally in real time in compliance with WMO Regulation 40.[18] Over the oceans, ships and moored and drifting buoys also provide information for GOS. On any given day, about 2800 ships and 900 drifting buoys provide near-surface meteorological parameters as well as sea-surface temperature.[19] Solar radiation observations, surface lightning network observations, and tide-gauge measurements are also provided via the GOS, but in limited numbers. Upper air observations are provided mainly by land-based radiosonde and aircraft data, with a limited number of observations from ground-based wind profilers and radiosonde releases from ships at sea.

Close to 900 land-based upper air stations provide radiosonde soundings to the GOS twice a day: at 1200 and 0000 UTC. The AMDAR system provides observations of temperature and wind from commercial aircraft at flight level as well as soundings during ascent and descent. As noted by the 2007 WMO Expert Team on the Evolution of the GOS,[20] the global AMDAR program exchanges between 220,000 and 250,000 observations

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[16] "The goal of the Panel shall be to enhance the upper-air component of the Observing System of the World Weather Watch through cooperation among Members in the acquisition, exchange and quality control of meteorological observations from aircraft using automated reporting systems." The AMDR Panel's goals are found at *http://www.wmo.int/amdar/Goal_TOR.html*.

[17] Detailed information about the space-based component of the GOS can be obtained from the WMO Space Program web site: *http://www.wmo.int/pages/prog/sat/index_en.html*.

[18] Regulation 40 addresses the free exchange over the Global Telecommunications System of 6-hourly RBSN and all upper air, ocean, and satellite data (some Members provide surface observations on an hourly basis).

[19] See *http://www.wmo.int/pages/prog/www/OSY/gos-components.html*.

[20] See *http://www.wmo.int/pages/prog/www/OSY/Reports/ET-EGOS-3_Final-Report.pdf*.

per day over the WMO Global Telecommunications System. Most AMDAR observations are in the Northern Hemisphere, and programs like EUCOS (EUMETNET Composite Observing System) are working to optimize AMDAR ascent and descent data for use by EUCOS member countries. For example in 2006, EUMETNET-AMDAR provided approximately 750 soundings per day.[21] The RBSN observing stations and conventional upper air network do not all report on a routine basis, with the performance varying greatly by WMO region.[22] Reports from stations over the United States are very reliable.

In addition to the GOS, specialized observing networks such as the Global Atmospheric Watch for chemistry and the World Hydrological Cycle Observing System provide data that may or may not be in real time. Approximately one-fourth of the RBSN stations make up the Global Climate Observing System (GCOS) Surface Network,[23] and approximately 20 percent of the upper air sites make up the GCOS Upper Air Network. As with the GOS, performance of the GCOS sub-set of the GOS is not at 100 percent.

The GOS Space-Based Subsystem

The space-based subsystem of the GOS embraces the concept of a composite observing system with research and operational satellite data used in synergy.[24] Data are provided by both operational satellites and low-Earth orbit research satellites. Examples of the research products are hyperspectral sounding data from AIRS, altimetry measurements from JASON, precipitation measurements from TRMM, and sea-surface winds from ENVISAT. Much of the satellite data flowing into the GOS are used for routine analysis, nowcasting, and forecasting applications at the National Meteorological and Hydrological Services (NMHS) across the globe. Global NWP centers use the data for a variety of forecast guidance products.

How the GOS is expected to evolve over the coming decades was recently discussed in WMO Technical Document No. 1267, "Implementation Plan for Evolution of Space and Ground-based Subsystems of the

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[21] See *http://www.wmo.ch/pages/prog/www/OSY/Meetings/ET-EGOS_Geneva2006/Doc4-5.doc*.

[22] GOS performance is routinely monitored by major NWP centers (see for example *http://www.ecmwf.int/products/forecasts/d/charts/monitoring/coverage/*), however, the WMO formally evaluates GOS performance during special observing periods each year and the performance for various regions can be accessed from the reports of the Commission on Basic Systems reports on the following web site: *http://www.wmo.int/pages/prog/www/CBS-Reports/CBSsession-index.html*.

[23] See *http://www.wmo.int/pages/prog/gcos/documents/GSN_Stations_by_Region.pdf*.

[24] See *http://www.wmo.int/pages/prog/www/OSY/gos-components.html*.

GOS,"[25] which makes specific recommendations concerning the evolution of the space-based and surface-based subsystem of the GOS. Those recommendations were based on guidance from the Rolling Requirements Review process[26] as well as observing system experiments, and observing system simulation experiments performed by various NWP centers.

Results from these experiments are presented at WMO-sponsored workshops, such as the Fourth WMO Workshop on the Impact of Various Observing systems on NWP. Because of the long lead times for satellite systems, plans for the evolution of the space-based portion of the GOS have been based mainly on the long-term planning of both operational and research satellite operators. Future research missions will continue to contribute to the space-based component of the GOS while influencing its evolution. Those planned research missions include investigations of atmospheric chemistry and trace gases, the Earth's gravity field, soil moisture and ocean salinity, atmospheric winds using lidar, disaster and environmental monitoring, integrated atmospheric column water vapor, cloud ice content, cloud droplet properties and distribution, aerosols, and polar ice and snow water equivalent. Instrumentation under development to accomplish these measurements include space-borne lidar, high-resolution and hyperspectral imaging and sounding instrumentation, active and passive microwave sensors, cloud resolving radars, and L-band radars.

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[25] Information on WMO activities with respect to redesign of the GOS can be found at *http://www.wmo.int/pages/prog/www/OSY/GOS-redesign.html,* with a link to WMO Technical Document 1267 at *http://www.wmo.int/pages/prog/www/OSY/Documentation/Impl-Plan-GOS_Sept2004.pdf.*

[26] The Rolling Requirements Review (RRR) process is used to determine how well the GOS is meeting WMO user requirements in a variety of applications area. The RRR procedure consists of four steps: review of user requirements for observations; assessment of the capabilities of existing and planned observing systems; critical review (gap analysis), comparing the requirements with system capabilities, in terms of present and planned networks; and statement of guidance, which lists conclusions and identifies priorities for action. This information is made available to all users (WMO 2007).

5

Architecture for a Network of Networks

This report so far has described several aspects of the national-level mesoscale observation network including the vision, scope, needs and technologies. This chapter brings these aspects together in an architecture that can support all the functioning elements. The architecture recognizes that the national-level mesoscale network will be a network of networks (NoN), where the constituent networks embrace specific types of measurements or different geographical regions, many of which already exist.

MEASUREMENT NETWORKS

A new network of surface, above surface, and subsurface systems for mesoscale observing capability to meet multiple national needs should be defined ab initio, because very few systems have ever been planned and developed on the national scale. We have "national networks" such as ASOS, NEXRAD (WSR-88D), and the upper air rawinsondes, but they do not operate as true networks, because they (and most others) do not interact intelligently (i.e., adaptively and collaboratively) with other networks or even within their own network.

The current state of surface networks in the United States is an uncoordinated set of local or regional deployments. There is no systematic national-scale establishment of surface network systems that serves all mesoscale observing needs. However, regional networks can be linked and integrated to form national-scale networks. Such networks already exist in other disciplines. A classic example is the cell-phone network within the United States that is deployed on a national scale without regional differences in the system. The system partition may be according to business units rather than regions.

Current surface observation systems in the United States are quite numerous, as discussed in Chapter 2. Many of these networks result from some form of public enterprise, but the private-sector operates numerous networks as well. A well-known high-quality surface meteorological measurement system is the Oklahoma Mesonet (see Box 4.1). This network can be used as an example to denote the system technology (not necessarily the measurement technology) of such networks. The crucial communications component is handled by the Oklahoma Law Enforcement Telecommunication System (OLETS) communications infrastructure. Thus this system has attributes in terms of data bandwidth, space and time scales of observations, and the extent of observations (namely the State of Oklahoma). The Oklahoma Climatological Survey (OCS) receives the observations, verifies the quality of the data, and provides the data to mesonet customers. It only takes 5 to 10 minutes from the time the measurements are acquired until they become available to the public. It should be noted that this observation system consists of a suite of sensors that corresponds to specific technology that can be upgraded to future technologies.

Quality assurance and calibration are important aspects of this system and must be supported by extensive quality control software and a calibration laboratory. Thus this system has underlying technical and architectural aspects (McPherson et al., 2007).

With the Oklahoma Mesonet, the meteorological network and the communication infrastructure are public enterprises. An alternate paradigm was used to develop the Helsinki testbed, a mesoscale observational network in Southern Finland. This network was heterogeneous from inception, and the measurement infrastructure is built around anchor systems such as the Vaisala ultra-high frequency dual-polarization radar. This public-private partnership consists of the Finnish Meteorological Institute, the Vaisala meteorological measurements company, and the University of Helsinki. The testbed provides information on observing systems and strategies, mesoscale weather phenomena, and applications in a coastal high-latitude environment (60-61N, 24-26E). Interest in the Helsinki testbed focuses on meteorological observations and forecasting directed towards meso-gamma scale phenomena that typically last from a few minutes to several hours. These weather events are often too small to be detected by traditional networks. In coastal Finland, such weather events include temperature inversions, sea breeze, fog and low stratus, snow bands, urban heat islands, and convective storms. These and related phenomena such as lightning are often hazardous and cause substantial damage. For instance, fog causes considerable disruption of land, sea, and air traffic. The sea breeze and its phases of development play an important role in the dispersion of atmospheric constituents.

The Helsinki capitol area offers a representative study region for urban air quality research and boundary-layer modeling, especially in stable nocturnal conditions, which are dominant in the area. A key feature of the Helsinki testbed is the heterogeneous nature of the measurements and the emphasis on urban weather. Thus one of the main differences between most U.S. networks and the Helsinki testbed is the emphasis on multiple users and urban systems.

CONCEPTUAL ARCHITECTURE OF A NATIONAL MESOSCALE OBSERVING SYSTEM

The concept of surface and subsurface measurement networks has been developing ad hoc, and the prognosis suggests rapid growth, especially aided by communication technology, customer demand, and the thirst of mesoscale models for data. It is anticipated that a vertical planetary boundary layer (PBL) component that serves the mesoscale will be developed as part of this system. This enterprise can benefit extensively from standards and protocols just as the communication industry has benefited from them.

As described in Chapter 4, the technology of measurements is advancing at a steady pace; however, we note that this advancement is not nearly as rapid as that of the weather measurement networks themselves. The individual regional networks have evolved according to a variety of paradigms, driven by local needs such as measurements in complex terrain or urban environments, as well as by application drivers such as transportation, agriculture, or homeland security. Thus the most important structure to be developed in a national-scale mesoscale network is a fundamental architecture that can create a "network of networks." This concept is somewhat similar to that proposed for the National Ecological Observatory Network (NEON) project (*http://www.neoninc.org*) where the continent is divided into 20 regions. As emphasized in NEON, standards and architecture will form the most important aspects of a mesoscale network that satisfies multiple national needs.

A candidate national system serving multiple national needs will be one that can be considered a network of networks in an architectural sense. If current trends in technologies are a guide, many new instrumentation networks will be composed of intelligent sensors that can be tasked to take measurements in a collaborative manner. Therefore it is envisioned that these networked sensors will respond to some feedback based on input from users and the prevailing environment. As an example, the Collaborative Adaptive Sensing of the Atmosphere (CASA) system's network of sensors collaborates to jointly measure precipitation, and it adapts to the prevailing weather conditions (Zink et al., 2005). The mode of operation is changed as the intelligence in the system responds to user needs, the prevailing weather, and the fault status of a neighboring sensor.

The architecture describes the fundamental elements as well as the organizational and interfacial structures 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 user. The various attributes of the architecture such as the space-time domain of the environment, type of measurements to be made, the multiple types of users, and the observational needs were described in Chapters 3 and 4. For example, the fundamental space-time structure of the phenomena being observed determines the frequency, scale, and density of observations, whereas the type of measurements determines the type of sensors. Another important feature within the architecture is the link to data assimilation and numerical models that may produce atmospheric structure on scales considerably smaller than the observational density. The various user sectors are accommodated in the architecture by its ability to support multiple sectors such as energy security, health, transportation, and homeland security. In addition, the deployment challenges in coastal areas and complex terrain and the microscale needs in the urban environment are also important. Sensor tasking addresses the adaptive and collaborative nature of the sensors whereas architecture addresses the requirements of metadata, storage, and policy infusion.

Figure 5.1 provides a conceptual sketch of the candidate architecture of a national-scale mesoscale observing system.

The architecture supports many important attributes. First, it is a user-driven system with sensor tasking, instead of a passive data-push system. Second, metadata structure and resource management, based on policy, are central features of the architecture. In addition the network supports links to analysis algorithms, such as real-time products and data assimilation systems, and to storage, query, and decision-support systems. Above all, this is a closed loop architecture, where the users have a structure that can support responses based on the observations.

The architecture should provide a seamless ability to perform a Rolling Requirements Review (see Chapter 4), respond to the results of the review, and enable gap analysis to identify missing components of the system. It should also have the capability to support policy-based operation and to link to end users for decision making. The system attributes also include the ability to reconfigure itself to different modes of operation such as routine base operations, targeted modes, and event-driven modes. As an example, support of climate observations could result in systematic observations at very regular spatial and temporal intervals. In contrast, measurements could be targeted to monitor catchment areas of reservoirs or monitoring

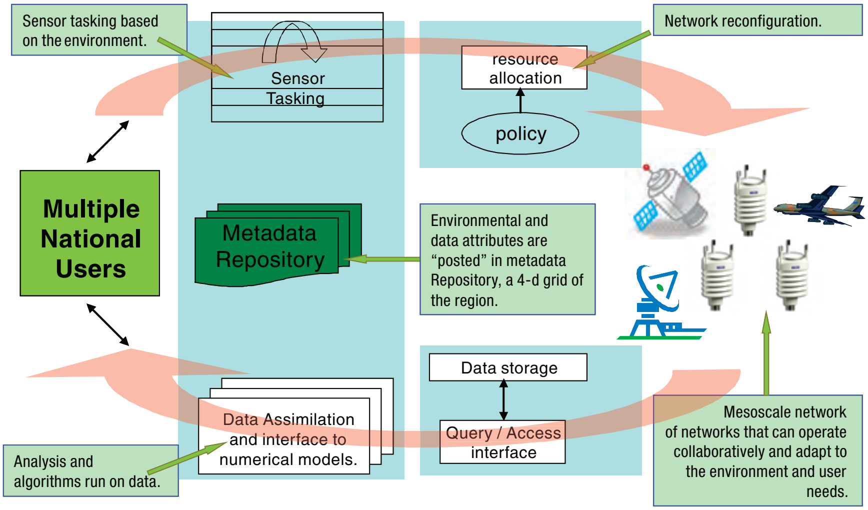

FIGURE 5.1 Candidate architecture for a national-scale mesoscale observing system. SOURCE: Figure supplied by V. Chandrasekar.

industrial releases. Event-driven modes of operation require the network to reconfigure itself, along with the associated models, to, for example, prepare for a tropical storm landfall or to assess the aftermath of an industrial accident or wildfires.

INTEGRATION OF DISPARATE NETWORKS, STANDARDS, AND PROTOCOLS

One of the main challenges to envision a network that serves multiple national needs is the concept of integrating networks and developing the necessary standards and protocols so that the private sector can manufacture cost-effective sensor and network solutions. As a reference, one could refer to existing system partitions such as those in the National Weather Service and the International Telecommunication Union (ITU) or those planned for NEON. The network architecture will also describe the lower-level attributes for the instruments, including communication and calibration protocols, siting standards, instrument metadata standards, and procedures for adding new instruments. Similarly, observations and customer needs will prescribe the requirements for data bandwidth and storage, whereas the architecture will prescribe the level of redundancy. The attributes of the storage system include a distributed archival system, while the attributes of the access system include capability for space, time, and application partitioning of the data. The information extraction subsystem includes the ability to incorporate quality control, data mining, visualization, and product generation capability while providing interface to data assimilation systems and mesoscale prediction models.

Since the national-level network is expected to be a network of networks, the architecture should support interoperability (the ability of diverse networks to work together), metadata across constituent networks, and the ability to add new networks and remove existing networks seamlessly, ensuring scalability.

Recommendation: A national design team should develop a well-articulated architecture that integrates existing and new mesoscale networks into a national "network of networks."

This architecture should 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 must also include a process that continually identifies critical gaps and the evolving requirements of end users.

The candidate architecture system encourages intelligent (collaborative and adaptive) sensors as well as responses to feedback from end users.

Recommendation: Emerging technologies for distributed-collaborative-adaptive sensing should be employed by observing networks, especially scanning remote sensors such as radars and lidars.

Some high-impact weather phenomena (e.g., tornadoes) of limited size and near-surface location can escape detection or be only poorly resolved by the current low-density network of weather radars. 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 and coastal and urban environments. Current state-of-the-art communication, computing, and remote sensing technologies facilitate this new paradigm for operation of networked instruments.

Short-range, low-power weather radars, scanning lidars and radiometers, and other sensors can provide earlier detection and increased sampling of hazardous weather phenomena if the sensors communicate with each other and adapt to the ever-changing situation. Consider, as an example, improved quantitative precipitation estimation in an urban setting. Several short-range radars with overlapping coverage can work in concert to follow a convective cell moving across an urban area that is causing potential for flash flooding. Limiting the range to 20-30 km will avoid a major short-coming of the current WSR-88D radar network, that is, intersecting the 0° C melting layer with beams and/or overshooting the low-level clouds, which lead to significant errors in rainfall estimation. Additionally, temporal resolution will increase when the need to scan everywhere is avoided when a small solid angle of scan will suffice. Increased spatial resolution is afforded by the short distances involved, substantial overlap between radars, reduction of random errors, and redundancy against instrument or communication failure. The above features should lead to improved accuracy of the fast-responding urban watershed by better locating heavy rainfall areas vis-a-vis the urban drainage patterns and infrastructure. Note that a new system would benefit from long-range surveillance capabilities, which are inherent to the current system. Given the capability for two-way communication with other sensors, radar and lidar information in the urban environment will influence the frequency, timing, and/or location of other observations and vice versa.

THE GLOBAL CONTEXT: GLOBAL EARTH OBSERVING SYSTEM OF SYSTEMS

Another example of an architectural challenge to organizing observational systems is the GEOSS or Global Earth Observation System of Systems. GEOSS is an international effort to integrate the observing systems of all nations into a comprehensive and sustainable system whose goal is to "provide the right information, in the right format, to the right people, at the right time, to make the right decisions."[1]

However, as the name implies, GEOSS is a distributed system of systems, building on current cooperative efforts among existing observing and processing systems worldwide, while accommodating new components.

Planning for GEOSS started in 2003 and is being developed by the intergovernmental Group on Earth Observations (GEO), which now consists of over 70 nations. The National Oceanic and Atmospheric Administration (NOAA) Administrator represents the United States and serves as a GEO co-chair along with representatives from South Africa, China, and the European Commission. The U.S. Group on Earth Observations (USGEO), a subcommittee of the President's National Science and Technology Council, coordinates U.S. government participation. USGEO is supported by 15 federal agencies and three White House offices.[2] The U.S. contribution to GEOSS is the Integrated Earth Observing System (IEOS), for which a strategic plan has been developed (see footnote for website). The goal is

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[1] From the GEOSS website at *http://www.noaa.gov/eos.html*; see also *http://earthobservations.org*.

[2] See *http://usgeo.gov.*

for GEOSS and IEOS to facilitate the sharing and applied usage of global, regional and local data from satellites, ocean buoys, weather stations and other surface and airborne Earth observing instruments.

There are many common themes in both programs. For example, a USGEO Working Group on Architecture and Data Management is developing a "Service Oriented Architecture" (SOA), an underlying structure that will support communications based upon loosely coupled connections among independent programs to create a scalable, extensible, interoperable, reliable, and secure framework.[3] These attributes are similar to those of the Mesobs architecture for a NoN outlined above, except that we propose a comprehensive closed loop architecture that enables user feedback to the observing system.

The national mesoscale NoN should be a vital component of GEOSS over the United States and could be thought of as one of the (very large) systems under its umbrella. This synergism will increase the value and possibly the cost-effectiveness of both efforts.

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[3] Link from *http://usgeo.gov/documents5dc2.html?s=docs.*

6

How to Get from Here to There: Steps to Ensure Progress

Several steps are required to evolve from the current circumstance of disparate networks to an integrated, coordinated network of networks (NoN). First, it is necessary to firmly establish a consensus among providers and users that a NoN will yield benefits in proportion to the effort required to establish it. This consensus-building step is essentially political, requiring agreement in principle at various levels of public and private participation, which leads to the collaborative development of an implementation plan. The new elements of a NoN are twofold: (1) the provision of services and facilities that enable individually owned and operated networks to function, more or less, as one virtual network, and (2) the provision of new observing systems or facilities to enable the national observational goals. The former is largely separable from the latter, since considerable benefit may be achieved from improved functionality with existing observational assets. In this chapter we identify a minimum set of essential core services and facilities that must be established in order to realize the dream of a NoN. We also discuss the need for augmentation of infrastructure, which is critical to a systematic evolution of the NoN. Chapter 7 will address the broader organizational implications of a NoN if it is to become a fully integrated observing system that meets multiple national needs.

PLANNING FOR THE FUTURE: CONVENING THE STAKEHOLDERS

Recommendation: Stakeholders, including all levels of government, various private-sector interests, and academia should collectively develop

and implement a plan for achieving and sustaining a mesoscale observing system to meet multiple national needs.

The plan should recognize and account for the complexity associated with the participants' differing roles, responsibilities, capabilities, objectives, and applications, as well as lessons learned from past experiences. To launch the planning process

- A mesoscale environment observing system summit should be convened to discuss and recommend the implementation of a NoN and to prescribe a process through which a plan will be developed. Participants from the private sector, federal executive branch, U.S. Congress, national organizations of governors and mayors, and key professional societies should attend.
- Forums to further discuss and recommend implementations of the mesoscale observing system should be organized by professional societies and associations such as the American Meteorological Society, National Council of Industrial Meteorologists, American Geophysical Union, Commercial Weather Services Association, National Weather Association, American Institute for Chemical Engineering, American Society for Civil Engineering, and American Association of State Highway and Transportation Officials. A leading role should be assumed by the Commission on the Weather and Climate Enterprise of the American Meteorological Society, the constitution of which is particularly well suited to this task.

IMPROVING THE USE AND VALUE OF EXISTING ASSETS: ESSENTIAL CORE SERVICES

Essential core services are defined as those services required to derive levels of function and benefit from a NoN that markedly exceed those currently realized from the assemblage of relatively independent networks. Essential core services include but are not limited to

- definition of standards for observations in all major applications,
- definition of metadata requirements for all observations,
- certification of data for all appropriate applications,
- periodic "rolling review" of network requirements and user expectations,
- definition and implementation of data communication pathways and protocols,
- design and implementation of a data repository for secure real-time access and a limited period for post-time access,

- generation of a limited set of products based upon the raw observations, most notably graphical presentations of data fields and analyses thereof,
- pointers to more sophisticated products generated externally, such as analyses produced from a short-term model prediction and multiple observation sources,
- pointers back to data providers, where more products and services are available,
- establishment of a link to National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) for archival of selected data, as deemed appropriate by NCDC,
- development and provision of software tools and internet connectivity for data searches, information mining, and bulk data transmissions,
- development and provision of a limited set of end-user applications software, which would enable selection of default network data configurations for major applications as well as tools for creation of custom network data configurations, and
- provision of a data quality control service with objective, statistically based error-checking for all major categories of data, including manual intervention and feedback to providers.

The premise for these services is to

- have expert assistance in establishing and maintaining standards for the data provided,
- know which additional data are available and suitable to one's own application,
- have compatibility with and ease of access to selected observations and analyses,
- ensure the archival of selected data commensurate with their useful lifetimes, and
- gain ease of access to the products and services of other providers.

The Primacy of Metadata

Metadata (information about the instruments themselves and how they are sited and used) should be required of every component in an integrated, multi-use observing system and should be kept up to date. Observational data have maximum value only if they are accompanied by comprehensive metadata. Examples follow:

- contact information for person or organization responsible for providing data

- type of data provided and parameters measured
- instrument type (e.g., liquid in glass thermometer, cup anemometer with vane, radar wind profiler, satellite radiometer; may need to include specifications such as beamwidth, operating wavelength or frequency, pulse repetition frequency, sampling time, etc.)
- instrument manufacturer and part numbers
- date of installation or most recent upgrade
- manufacturer specifications for accuracy and precision
- location of instruments (latitude, longitude, elevation); height above ground at which each parameter is measured
- site description (e.g., open, grassy field; roof of school; under a tree) or observation platform (e.g., satellite, balloon, aircraft)
- nearest obstacles preventing view of horizon; their distance and height (not applicable in all cases)
- frequency of maintenance
- time and frequency of measurement
- information about any on-site data processing (e.g., averaging, smoothing, thinning)
- frequency of data transmission
- data format (units and order of magnitude information)
- mode of transmission: land line, wireless communication, microwave, uplink to satellite
- data latency (length of time between the raw measurement and receipt of the report by a collection center
- documentation of any changes in instruments and their location or exposure since the site was established

Given this information, each instrument at each site in the network of networks can be continually monitored and evaluated regarding its utility in various categories of user application. Data access may then be streamlined to exhibit to the user a network configuration of greatest relevance to the particular application.

As discussed in previous chapters, today's metadata in support of mesoscale observations are incomplete at best and, in the case of surface observations, woefully inadequate for the great majority of them. The collection and maintenance of comprehensive metadata is necessary, tedious, time-consuming, and labor-intensive, but not nearly as costly as deploying new observing systems. Many mesonet data providers want to see their instruments perform up to specifications and serve the intended purposes. They are inclined to respond when end users or automated quality-checking software detect questionable data. The United States needs a program that informs the providers of mesoscale observations why metadata are so vital for quality-checking for use in multiple applications.

Provision of metadata should be mandatory for membership in the NoN. Incentives and assistance should be offered to the operators of networks who provide it. The contents of a metadata file should be carefully defined, and, once assembled, a national database of metadata should be frequently updated and accessible to all. If action is taken to improve metadata and to 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.

Standards for Instrument Sites and Exposures

In the case of surface observations, which are more numerous, diverse, and variable in quality than other observing systems, much useful guidance for traditional meteorological measurements has been compiled.

- Siting criteria for the Oklahoma Mesonet stations are available in Shafer et al. (1993). Examples of metadata for the instruments at these sites appear in McPherson et al. (2007).
- The World Meteorological Organization lists 20 principles in *GCOS Climate Monitoring Principles*.[1]
- Siting criteria for observations in urban areas are available in WMO (2006) and Oke (2007).
- Siting standards for Road Weather Information Systems are described in a report by Mandredi et al. (2005), which is available at *http://ops.fhwa.dot.gov/publications/ess05/ess05.pdf*.

Standards for data accuracy in specific applications vary widely. For example, the temperature at a climate monitoring site would normally be measured more accurately than the temperature in a school yard. In one case, climatologists would like to discern temperature trends of a fraction of a degree over a period of decades. In the other case, a teacher might decide whether it is safe for the children in her charge to go outside for recess.

Quality-Checking of Observational Data

Four methods of quality-checking are commonly employed: (1) Determine whether the measured value is physically plausible (“engineering” check). (2) Compare an observed value with nearby neighboring values (“buddy” check), either directly or by means of a more sophisticated analysis, under the assumption that conditions in the neighborhood are

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[1] *http://www.wmo.ch/pages/prog/gcos/Publications/GCOS_Climate_Monitoring_Principles.pdf*.

nearly uniform. This is often effective in uncovering the larger random errors. Usually, only like observations are compared, but there are exceptions. (3) Compare the observed value with a predicted value (for example, a value extracted from a 1-hour model forecast). Often called a "background" check, this comparison can uncover biases in an observing system. (4) Conduct periodic field checks of the sensors and their surroundings, and laboratory calibrations as necessary. See, for example, Shafer et al. (2000).

Rolling Requirements Review

Once every few years, the World Meteorological Organization (WMO) conducts a Rolling Requirements Review, first mentioned in Chapter 4, a survey of observing systems worldwide and their effectiveness in meeting needs in a number of application areas: global NWP, regional NWP, synoptic meteorology, nowcasting and very short-range forecasting, seasonal to inter-annual forecasting, aeronautical meteorology, atmospheric chemistry, agriculture, oceans and coastal regions, and hydrology. Each review concludes with recommendations for improving space-based, atmospheric in- situ, and surface-based components of the global observing system. The most recent WMO "Statements of Guidance" concerning observing systems in the above application areas may be found at *http://www.wmo.int/pages/prog/sat/documents/SOG.pdf*.

Similar rolling requirements reviews, of which this National Academies report could be considered the first, would serve the United States well. The U.S. focus in this instance would be on mesoscale applications in the short time frame of 2 days or so, particularly events hazardous to health and safety and/or affecting the economic sectors discussed in Chapter 3.

AUGMENTING EXISTING INFRASTRUCTURE

The previous section discussed ways in which the use and value of current data can be enhanced in the absence of new or improved observing systems. This section examines the augmentation of existing observational and computational infrastructure, including the establishment of new observing systems, diagnostic tools, and experimental facilities.

The Role of Observational Testbeds

Dabberdt et al. (2005b) describe a testbed in the following way:

> A testbed is a working relationship in a quasi-operational framework among measurement specialists, forecasters, researchers, the private sector, and

> government agencies aimed at solving operational and practical regional 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 substantial commitments and partnerships.

The main purpose of an observational testbed is to demonstrate that a particular collection of new observations improves regional weather predictions and all of the decisionsupport systems that affect life, property, and economic well-being. Testbeds enable the acquisition of knowledge on how best to sample atmospheric properties and phenomena, oftentimes resulting in improved knowledge of the observed phenomena and their statistical properties.

Effective testbeds have the following hallmarks:

- They require considerable advanced planning, resources, personnel, and time (often more than 1 year); hence, they are used sparingly and only when multiple purposes are served.
- Testbed planners enlist the support of stakeholders and involve them in planning.
- The program plan states expected outcomes and defines the measures of success.
- The program is flexible; it can adapt to changing conditions.
- By definition, the testbed is limited in scope, but it is clear how to generalize results to larger regions or to the solution of other problems.
- The testbed is end-to-end, starting with observations and ending with decisionmaking by stakeholders.
- Ideally, the testbed operates in real time in a quasi-operational setting.

The essence of a testbed is the test and refinement loop illustrated in Figure 6.1.

If the experimental observations or derived products stand up to rigorous tests of utility, accuracy, reliability, computational efficiency, cost-effectiveness, and repeated scrutiny by users, they can make the transition to operations. Otherwise, user feedback leads to modifications and another round of testing or to the elimination of the proposed observing system.

The testbed is but one step on the pathway from research and development to operations (routine, real-time application). The sequence of steps is

- Develop a concept for a new observing system.

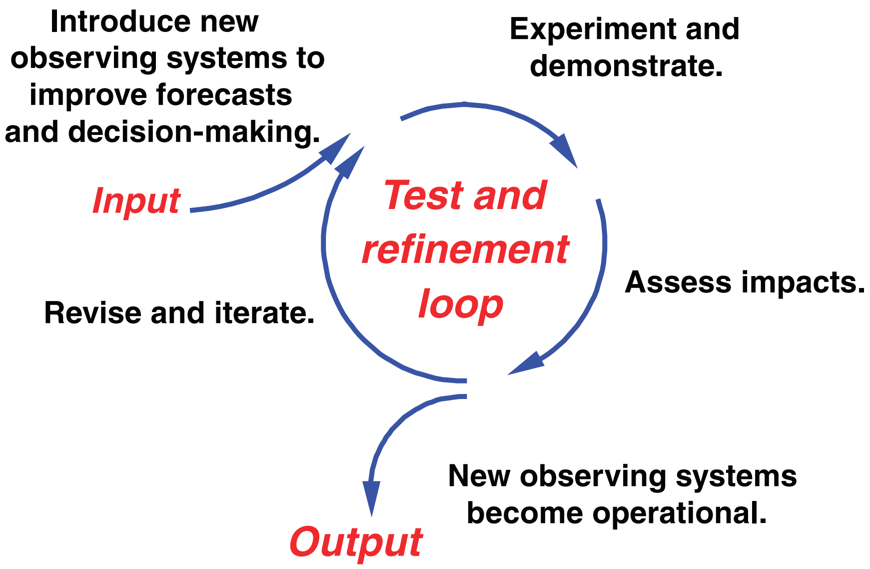

FIGURE 6.1 Conceptual schematic of a testbed refinement loop (Dabberdt et al., 2005). SOURCE: Reprinted with permission from the American Meteorological Society. © Copyright 2005 American Meteorological Society (AMS).

- Build a prototype.
- Calibrate the instrument in the laboratory; compare its measurements with those of similar instruments.
- Field test the observing system for performance, ruggedness, and reliability.
- Incorporate the system in a testbed; integrate it with other observing systems.
- Verify that the new observing system yields positive benefit for the intended application and collateral benefits for other applications *when used with existing systems*.
- Deploy the new observing system in an operational network.

An example of a working testbed is the Hydrometeorological Testbed (see *http://www.esrl.noaa.gov/psd/programs/2008/hmt/*), which deploys special observational assets in a quasi-operational environment to improve the prediction of winter storms that cause flooding along the West Coast.

That testbeds already exist is reason to include them in this section on "Augmenting Existing Infrastructure." Yet testbeds will evolve to serve broader needs. A spectrum of additional testbed applications related to network design is envisioned, including the application of observing system simulation experiments (OSSEs), the development of assimilation systems for chemical weather, and the addition of key sensors and their siting to facilitate the merging of in-situ and satellite observations to provide finer-resolution spatial distributions.

> **Recommendation: Federal agencies and partners should employ "testbeds" for applied research and development to evaluate and integrate national mesoscale observing systems, networks thereof, and attendant data assimilation systems. Among other issues, testbeds should address the unique requirements of urbanized areas, mountainous terrain, and coastal zones, which currently present especially formidable deficiencies and challenges.**

Diagnostic Studies

Closely akin to the notion of testbeds are various forms of diagnostic studies, both observationally and numerically based. In Numerical Weather Prediction (NWP), one can gauge the worth of specific observing systems in two ways.

First, for existing systems, one can include and then withhold specific observations from the initial analysis (e.g., eliminate all aircraft observations from the initial analysis) and see what happens to the forecast. One can also thin existing observations (e.g., cut the number of rawinsonde soundings in half) and examine the degradation in forecast accuracy. Alternatively, one may temporarily enhance the operational network with research-based systems to examine forecast accuracy improvement. These are called observing system experiments (OSEs). A few numerical weather prediction centers conduct OSEs annually. Such experiments help to determine which observing systems most affect forecast accuracy. On the basis of OSEs, one might conclude that fewer observations of a certain type might not harm the forecast but more observations of a different type would improve it.

Second, with regard to proposed or experimental observations, one can conduct an OSSE. An OSSE estimates the effect on forecasts of adding a new observation source (e.g., a Doppler wind lidar aboard a satellite). The major difference between OSEs and OSSEs is that *all* observations in the latter must be simulated: the new system that is being evaluated and all systems currently used in operational data assimilation, namely those systems that the new system will be competing against. A credible OSSE requires "calibration" from known observing systems, extensive computational resources similar to those used in operational numerical weather prediction, and careful execution.

Communication

Many observing systems produce voluminous information. For most applications, at least near real-time communication is essential. Ground-based remote sensors such as radars and lidars have intrinsically high data rates, necessitating an adequate communications bandwidth, which has increasingly become available and affordable. Rapid and flexible access to stored data is often a point of failure, requiring efficient data structures and applications software that are well matched to a wide range of user needs. A communications architecture that permits selective access to full resolution or general access to lower resolution data and analyses should be devised. Larger market forces governing the evolution of the data communications and data storage industries over the coming decade should easily accommodate these requirements.

User Interface

In order to screen mesoscale observations for specific applications, a sophisticated user interface is required. Behind this interface is a relational database that contains comprehensive metadata from each observing source, a pointer to the repository of each source, and high-bandwidth communication to each repository. These attributes will make it possible to retrieve information based upon highly selective criteria. In the future, given sufficiently detailed metadata for each observing source and specific enough criteria for the intended application, it should be possible to extract from geographically distributed repositories just the information that directly serves the application, no more and no less. Specific examples will more effectively make this point than generalizations:

- Search by application: "Show me highway pavement, temperature, and visibility conditions in north central Illinois."
- Search by application: "Show me regional chemical weather fields east of 85°W."
- Get information in the vertical: "Get me the best estimate of the current vertical profiles of temperature, moisture, and wind over Chicago's O'Hare Airport."
- Search for information that is sensor-, time-, and location-specific: "Show me precipitation data from tipping bucket rain gauges in Missouri between 1800 UTC 6 Aug and 0600 UTC 07 Aug 2007."
- Search for information from a specific network: "Show me all temperature data from the AWS (WeatherBug) surface network at 1200 UTC 06 Apr 2007."

- Search for observations of a specific variable, imposing criteria for instrument exposure: "Show me all winds measured in the last hour between 8 and 20 m above the surface where no obstacles higher than 20 m exist within 50 m of the anemometer."
- Search a historical archive: "Show me where no precipitation has fallen in the past 30 days."
- Search according to a designated threshold: "Show me where the wind speed currently exceeds 30 knots."

Clearly, the user interface capable of fulfilling these requests must be versatile, and the database must be quickly accessible. No interface with this sophistication currently exists.

IDENTIFYING A CENTRALIZED AUTHORITY

> **Recommendation: To ensure progress, a centralized authority should be identified to provide or to enable essential core services for the network of networks.**

Initially, the focus of such activities should be on markedly improved use and value of data from existing observing systems. As new observational, computational, and communications infrastructure is added, the focus should shift to the prompt and seamless accommodation of these new elements and their related objectives. The provision of core services is essential for adequate access to and the utility of mesoscale observations as applied to multiple national needs.

What the Centralized Authority is Not

The recommendation for a modest degree of centralization is tightly focused on essential core services. It specifically excludes centralization for the purpose of acquisition and operation of observing systems, which are owned and operated by agencies, corporations, and other organization to serve their specific missions. The centralized authority is an enabling element of the broader enterprise that comes into play only insofar as it is necessary to derive added utility and functionality from the network of networks. It does not speak to the ownership, operation, upgrading, or maintenance of the individual networks themselves. It follows that the centralized authority is envisioned as a relatively small but vital fraction of the entire NoN enterprise.

7

Organizational Attributes and Options for a Fully Integrated NoN that Meets Multiple National Needs

Organizational models in use today for existing mesoscale networks have evolved to meet relatively specific needs associated with the mission and goals of sponsoring entities, such as the National Weather Service (NWS), California Air Resources Board, Illinois State Water Survey, and Duke Energy Corporation. Regardless of the enterprise involved, there are common technical, logistical, and financial challenges associated with the operation of mesoscale networks. Numerous successful networks, both public and private, have surmounted such barriers, especially at local and regional levels, and also within federal agencies to some considerable degree.

Mesoscale observing networks exist to serve the needs of both owners and users of the data, who may or may not be one and the same. Because of diversity in the owner-provider combinations, there are a wide variety of organizational models in use. Successful networks continue to expand and grow, and their organizational structures evolve with those changes. This kind of flexibility is a hallmark of successful organizations in many applications.

As described in Chapter 6, a cohesive network of networks requires organization and leadership that is consistent and communicative with the full breadth of its membership in order to serve the varied interests. That is to say, almost no provider or user of mesoscale observations is too small or too large, or too simplistic or too technically sophisticated, to be served at some useful level. It follows that a NoN of the sort proposed here may require an organizational model different from those employed today, owing to its national scope and multi-sector participation, which implies the accommodation of some added complexity.

ORGANIZATIONAL MODELS OF EXISTING MESOSCALE NETWORKS

While it is tempting to divide the current organizational models into two categories (public and private), the reality is somewhat more complicated. A survey of the mesoscale networks in place today shows many different organizational models. Table 7.1 provides a rough breakdown that considers ownership of the network and related data distribution. These can be broken down into three broad categories (Table 7.2).

Organizational Strengths of Today's Mesoscale Networks

When these networks are taken as a whole and examined from a national needs standpoint, several characteristic strengths emerge:

- **They satisfy the needs of the owners/operators.** None of the example networks has become obsolete or no longer serves a purpose.
- **They have a regional or local focus.** Network operators working at a local level are often aware of observing systems or networks that escape notice at a higher level. One of the keys to success for networks such as Northwest Net has been their ability to tap into networks and systems that were previously unknown to a much broader constituency.
- **They are flexible and evolutionary.** Many networks start out with a single purpose, but then demonstrate value in new applications and evolve to meet those needs. They are able to demonstrate support and to command funding and/or subscription revenue. The key to success for hybrid networks is their ability to evolve and expand their scope of applications as they grow.

TABLE 7.1 Models distinguished by ownership and data distribution

Type of Network	Examples	Description
Publicly owned, Public data	ASOS, NEXRAD, RAWS	Typically thought of as the backbone of public meteorological networks
Publicly owned, Private data	DoD, HS	Public networks where information is not shared for a variety of reasons
Academically owned, IP defined	LIDAR, Ag networks, NEON	R&D networks where the intellectual property defines the data ownership
Privately owned, Private data	AWS, NLDN, TV Radar	Privately owned proprietary data
Privately owned, Public data	CWOP, MDCRS, CoCoRaHS	Privately owned networks that share data voluntarily

TABLE 7.2 Models distinguished by funding source, purpose, and cost of data access

Model	Government Funded	Privately Funded	Hybrid
Purpose	Publicly owned and operated networks installed to meet specific mission requirements	Privately owned and operated networks intended to generate revenue and/or to facilitate operations	Network of networks intended to assimilate observations from as many sources as possible
Ownership/ operating costs	Publicly owned and funded	Privately owned, with private and (often) some public funding	Multiple ownership
Cost of data access	Marginal cost of redistribution	Subscription fees	Provider dependent
Examples	• ASOS • AWOS (FAA) • NOAA Profilers	• AWS Weatherbug • Weatherflow • NLDN	• MADIS (ESRL) • MesoWest (Utah) • Northwest Net • MDCRS (aircraft observations • Clarus (FHWA)

NOTE: NLDN – National Lightning Detection Network

- **They have been able to bootstrap themselves into existence.** Using the energy and enthusiasm of the participants, these networks don't require a pre-existing hierarchy or organization to start or to grow.
- **They encourage voluntary participation.** Many of the hybrid networks include observations or networks from organizations or individuals who have funded systems themselves and want nothing more than to see the information used more widely. Many of these observations would be expensive to fund otherwise, so this kind of leveraged participation is a big multiplier.

It is important to note that these characteristic strengths share a "grass roots" theme, and, to be successful, existing networks have incorporated many of these characteristics. What could, and probably should, be viewed as a weakness is that many networks are principally composed of surface meteorological observations, often lacking a vertical dimension component.

KEY ATTRIBUTES OF AN IDEALIZED NETWORK OF NETWORKS

A NoN requires an organizational model with qualities and characteristics of the successful networks mentioned above, but goes further to encompass a national, multi-purpose scope. These attributes include:

- Have enough stability to maintain continuity.
- Provide incentives to existing and new networks to share data.
- Establish metadata standards and provide incentives to collect and maintain these data.
- Provide benefits to members, including ease of access to more and better data.
- Establish and protect data/ intellectual property rights.
- Establish a process to continually perform a rolling review of gaps and requirements.
- Remain flexible and evolve to meet changing conditions across sectors.
- Maintain a local presence for regular contact with providers and users.

LOCAL ISSUES VERSUS NATIONAL NoN OPPORTUNITIES

Most existing networks inadvertently create or otherwise experience impediments that are inconsistent with overarching national needs for a mesoscale observing system. Many of these can be solved in a straightforward manner if prevailing thought can be shifted from a strictly local reward system to a more global one.

Incentives for Metadata

The case for metadata was discussed in Chapter 6. Suffice it to say here that, given the need to serve multiple national needs, some powerful incentives will be required to generate and collect metadata. *A viable business practice would be for a national coordinating organization to pay providers for metadata, according to strict specifications, in order to achieve a uniformly high standard of compliance.* For example, the Federal Highway Administrations' Clarus program has a system in place to compensate state transportation departments for the labor involved in assembling metadata for the observations they provide to Clarus. This is a good example of what could be achieved on a broader scale of applications. The cost of incentives for metadata compliance would be a small fraction of the ongoing costs associated with acquisition, operation, and maintenance of observing systems, the majority of which will be borne by agencies, corporations, and other organizations that conduct "business as usual" to serve their specific missions.

Filling Gaps and Avoiding Redundancies

There are several examples of locations with multiple separate surface observing stations within a few meters of each other, all owned and operated by different organizations. Sometimes this redundancy enables comparison of measurements from different networks. However, different agencies or entities may install duplicative systems, because they lack access to data from the other network, or do not trust data from sources other than their own.

Another example is that of separate mesoscale networks that cover an intersecting geographic area with different sites. Often these situations result from an unawareness of existing networks. This leads to a condition of "false sparsity" when the reality in some instances may be a richly observed domain, provided the assets from multiple sources are coordinated. Since expense is always a barrier, this type of organizational duplication is usually unnecessary and always undesirable.

Most surface networks are implemented to meet a specific set of local requirements, without consideration of national needs. However, the effect of gaps in the weather forecast system is usually experienced remotely. For example, forecast errors may be experienced hundreds of kilometers downwind of mountains, because the sparsity of observations in the mountains, consistent with low population density, handicaps the initial conditions in the forecast, and the effect propagates downwind. *A viable business practice would be to provide incentives for investment in remotely located observing stations to improve local forecast skill.* Often this will require the participation of provider organizations that are only peripherally or indirectly served.

Consistent Data Collection and Archives

Each network has evolved its own data collection and archive capabilities to meet its own needs. While hybrids such as MesoWest, Meteorological Assimilation Data Ingest System, Northwest Net and others have greatly improved upon the base condition at regional scales for weather applications, these generally fall short of an accessible useable database on a national scale for all major applications. *A viable business practice would set standards for and maintain a genuinely accessible and useable national database for all major applications.*

Core versus Context of Partner Organizations

Certain organizations view mesoscale weather networks as an essential part of their "core" business or competency. Other organizations require similar information for "context" in decisionmaking, but view it as much less important to their overall mission. This difference in priority is often a barrier to coordination and sharing of information. *A viable business practice would offer incentives to "context providers" for meet-*

ing appropriate standards, thereby contributing to the broader utility of their data.

Intellectual Property Rights and Data Ownership

"Ownership" of the data collected by a mesoscale network can often be a barrier to its use. Prospective users may be unwilling to live with restrictions placed on redistribution or may not understand the rationale for such restrictions. On the other hand, some organizations may assume that provider "ownership" implies legal liability if data are shared or used outside their organization and then found to be missing or inaccurate. One way to finesse such objections is to release station data in real time, but only for assimilation into NoN analyses. Raw station data would remain proprietary to the provider and available on a fee-for-service basis for point-specific subscriber applications. The fabric of society is very complex in these respects, and such circumstances require individual attention. *A viable business model should include legal empowerment to negotiate data access and to facilitate data restrictions on a case-by-case basis. Legal empowerment should include advocacy for and being the beneficiary of "hold harmless" legislation in the case of liability concerns.*

Multiple Funding Sources and Creative Solutions

A common barrier likely shared by every mesoscale network is the generation and application of resources adequate to the task. This applies equally to the acquisition of new networks and/or observation systems and to the maintenance and operation of existing networks. On a federal scale, there are institutional (e.g., congressional appropriation) barriers to cost sharing or cost transfers from one agency to another and rigidly enforced restrictions associated with funding mechanisms to non-federal and non-governmental providers and users. *A viable business model should have significant flexibility to effect the transfer of funds and to exchange in-kind resources with alacrity among different types of organizations.*

Proposed Roles of Partners

The Committee has noted the wide dynamic range in the scale and sophistication of providers and users, ranging from individuals to federal agencies and Fortune 500 corporations. Somewhat independent of the overarching organization (business) model, it is useful to define four broad tiers of NoN participation (Table 7.3). While each tier is heterogeneous in its makeup, the tiers each define a typical level of technical expertise and/or mission similarity in the operation of mesonets and in the treat-

TABLE 7.3 Characteristic tiers for participation in the NoN

Tier 1	Tier 2	Tier 3	Tier 4
Federal Agencies	State and Local Government Agencies Publicly and Privately Operated Authorities, and Districts	Corporations in Weather-Sensitive Providing Weather Information Services	Cooperative Observers Weather Hobbyists, Enthusiasts
For the public good Serves federal missions National backbone including the most costly infrastructure 3-D atmospheric observations Reasonably well maintained and systematically operated networks High-quality accessible archives	Mainly for public good Serves regional and local missions Regional backbones contribute piecewise to enhance national mesoscale resolution Primarily surface, soil, water, and air quality Some upper air obs Operation, maintenance, data access and archives are highly variable	Mainly enables or serves business and industry Local, regional, national Mainly surface meteorology and atmospheric composition Distribution of special observations often limited in real time Operation, maintenance, data access, and archives are highly variable	Mainly for public good, education, and self satisfaction Surface meteorology plus some soil observation only, with minor exceptions A shaky backbone for local climate records Very high density mainly in urbanized areas Data often contributed to hybrid networks Operation, etc. highly variable

ment and communication of datasets collected from them. This generalization doesn't work in all aspects of all cases. For example, there are many instances of high technical expertise in lower-tier groupings that share related missions.

Tier I: Federal Agencies

Federal agencies are tasked with serving specific missions, the scope of which determine and limit a given agency's infrastructure and services. Collectively, the federal agencies are at a high level of technical expertise and contribute a sizeable fraction of mesoscale meteorological and other atmospheric observations. However, the scope of the combined federal agency missions and the implied observational infrastructure fall well short of the national mesoscale constituency as currently vested. A summary of federal agency infrastructure is provided in Chapter 4 and Appendix B. In the case of National Oceanic and Atmospheric Administration, its mission is focused on a suite of weather forecasts and warnings, climate monitoring at regional to global scales, and oceanic forecasts and monitoring. In so doing, NOAA cuts a broad and deep swath across the enterprise.

As tier 1 participants, federal agencies could provide a national technical and operational backbone for the NoN. NOAA is particularly well-suited to lead this effort. Where consistent with their missions, several federal agencies could provide guidance and training, and operate major observational and computational infrastructure. Especially prominent in this group are those surface-based remote sensing instruments necessary to map and profile lower tropospheric conditions with lidars, radars, and radiometric-spectroscopic systems. Each agency's contribution would be targeted, fully consistent with its particular mission, and non-duplicative of infrastructure and services provided by other member organizations. Collectively, the agencies would benefit from infrastructure and services provided by other organizations and the benefit derived from an enhanced level of cooperation and coordination among themselves.

Tier II: State and Local Government Agencies, Publicly and Privately Operated Authorities, and Districts

State and local organizations make extensive use of mesoscale data. This information is critical to routine decisions for law enforcement, surface transportation, roadway safety, flood hazards, water and air quality monitoring and warnings, flood control, operation of dams and spillways, fire weather monitoring and prediction, avalanche control, debris flow forecasts, drought monitoring, agricultural outlooks and warnings, etc. Most of these "public good" entities, whether operated publicly or privately, currently own, operate, and maintain mesoscale observing assets. Some are highly vested in sophisticated equipment and communications systems, such as statewide networks of surface stations, profiling systems, stream and floodway gauges, and urban scale monitoring of atmospheric pollutants, toxins, and other constituents. Usage of this information is typically local or regional, often with little or no co-benefit among various applications sharing common domains. While federal agencies cast a broad net of advanced monitoring systems, state-based and local-based systems collectively are far more numerous, providing spatial and temporal detail and atmospheric composition information, which is essential to many applications. The stove-piped nature of this circumstance has the effect of creating an environment of "false sparsity." That is to say, each application may operate with datasets of questionable adequacy, density, domain size, and temporal resolution amidst many other data sources, which could contribute to their objectives and to the benefit of many.

State and local agencies, authorities, and districts, both public and privately operated, currently serve as regional backbones for mesoscale and urbanized area observations. The in-situ component of these assets in populated areas is truly mesoscale in its spatial density, unlike the synoptic scale focus of federally supported systems. However, large gaps in mesoscale coverage exist in less populated regions, especially in regions of complex terrain, where the heterogeneity of conditions is both prevalent and most likely introduces uncertainty in decision making. Federal incentives in the form of cost sharing should be provided to state and local organizations, which could fill critical gaps and enhance the overall quality and consistency of mesoscale monitoring. Such cost sharing, together with non-remunerative enablement services, is a critical pathway toward a national mesoscale monitoring capability.

Tier III: Corporations in Weather-Sensitive Sectors and/or Providing Weather Information Services

A sizeable fraction of corporate America is weather sensitive and therefore requires weather and climate information either to remain competitive or to gain an edge on the competition. Corporations making intense use of weather data whose needs are not met from publicly available sources fall into three categories: (1) those that require specialized information and choose to build the observational and computational infrastructure to serve their exclusive purposes, (2) those who need similar information and contract for it from private weather service providers, and (3) the private weather service providers. The preponderance of applications is intrinsically microscale (e.g., vineyards and orchards), urban-scale, mesoscale, or mesoclimatological, though some applications are continental in scope.

The existence of a national network of networks would clearly be of net benefit to this "community" despite the fact that datasets from corporate sources often have highly specialized exposures and are associated with restricted access. We believe that a carefully crafted risk-reward structure could enable the private sector to better serve its own needs, stimulate private investment, lessen restrictions on data access to others, and improve the utility and profitability of weather and climate information for all.

The exploration and implementation of a structure that stimulates both public and private investment, maximizes access to mesoscale data, and adequately shields legitimate proprietary interests is squarely in the national interest. Therefore the Committee views this aspect of the weather-climate enterprise as a compelling case for a hybrid organization approach.

Tier IV: Cooperative Observers, and Weather Hobbyists and Enthusiasts

NOAA maintains a Cooperative Observer Program, which is an important part of the climate record and therefore important to a NoN. It is dense enough to contain significant information at the mesoscale. However, most data have not been available in real time, and the observations are taken only daily, thus minimizing their utility in operational meteorology. This contrasts with the thousands of weather hobbyists and enthusiasts who operate their own professional-grade surface weather stations, often to a reasonably high standard, and report these data in real time or near real time. As reported in Chapter 2, citizen participation at group and individual levels is rapidly expanding with regional and quasi-national network coverage, and is usually provided free in exchange for nothing more than the ability to see their observations included in a larger program. Historically such data have been dismissed or viewed with skepticism. However, with the advent of inexpensive digital electronics, solid state sensors, and Internet communications, such observations are known to have real value in limited applications, especially where organized professional observations are sparse, applications can accept large uncertainty, or where especially fine spatial resolution is desired, such as urbanized areas.

In an environment of nationally defined standards and accurate and complete metadata, observations of many hobbyists and enthusiasts can play an important role in serving multiple national needs at the mesoscale. Recreational activity may benefit most given the exceptional spatial density, a good frequency of such observations, and the less stringent requirements for accuracy and precision. Such observations can also serve a confirmatory role for quantitative analyses and likely would contribute to data numerically assimilated for surface analyses of broader utility. Therefore, incorporation of Tier IV data should be beneficial for limited network applications, provided that appropriate quality-checking is performed.

ORGANIZATIONAL MODEL OPTIONS

The preceding sections of this chapter present a somewhat abstract view of the organizational requirements for a successful new national mesoscale network. In the Committee's judgment, none of the existing networks or their organizational models were envisioned to meet the needs of a multitude of national providers and users having diverse interests and requirements. Below we discuss some desired organizational characteristics that could facilitate the functions previously described in Chapter 6 and the preceding sections. Subsequently we examine a spectrum of potentially applicable models and offer some qualitative judgments on them.

Desired Characteristics

In order to successfully meet the national needs identified in this report, the organization should be capable of certain desired characteristics.

1. Effecting partnerships
   - The organization should be adept at coordinating, enabling, and fairly representing the full dynamic range of public and private contributions, large and small.
   - Issues such as ownership of data, cost and pricing of datasets, and redistribution rights need to be addressed in a flexible, consistent and equitable manner.
   - National strategies on building networks versus buying datasets need to be evaluated across the full spectrum of potential solutions.
2. Economic scale
   - The organization needs to be large enough to make economic sense and to achieve certain economies of scale (e.g, large enough to coordinate and to provide core essential services), but small enough that it can remain flexible and adaptive to both users and providers needs.
3. Sustainability
   - The organization must be stable and have a basis for longevity in order to attract both users and providers.
   - The organization needs to offer incentives of various types, including but not limited to remunerative incentives, to shape an optimal and efficient NoN.
   - The organization must offer added value to users, who may face costs for conditioning and ease of access to certain datasets. User-valued services include consolidated datasets, uniform and complete metadata, and data quality-checking measures.

Categories of Models Considered

At least eight broad categories of organizational models may be considered for a NoN. When we refer to these models the frame of reference is *focused on those facilities and services that are required to implement the added value of the NoN,* not the facilities and services currently provided by hundreds of organizations to support the current collection of largely independent networks. Implicit in this assumption is that all members will continue to serve their specific mission needs with individual networks and related infrastructure in a manner similar to current practice, but subject to new standards and practices, as previously described, to derive the collective benefit. Only the infrastructure and services unique to NoN would be provided by a new organization (e.g, the essential core NoN services). Over time, additional responsibilities and authority could be assigned to the new organization by the NoN as deemed appropriate by the membership. The eight categories for organization considered are as follows:

- **Lead Federal Agency.** One agency would provide and coordinate essential core services for a NoN, having received and secured a commitment from other agencies that have mission requirements.
- **Confederation of Federal Agencies.** The federal government would both implement and serve a new management unit that would be governed by a confederation of agencies. The management unit might have multiple duties spread across agencies or be staffed by the agencies and seconded to the supervision of a designated lead agency.
- **Multi-level Government Confederation.** Similar to the above but directly involving state and/or local government leadership, staffing, and funding. Owing to the large number of confederated entities, some form of representative governance would be invoked.
- **Government-Industry Confederation.** Similar to the above differing only in the mix of partners and governance structure.
- **Publicly Chartered, Private Non Profit Corporation**. Similar to the Corporation for Public Broadcasting, National Public Radio, and the U.S. Postal Service, this organization would be chartered and funded by the U.S. Congress for defined aspects of the broader enterprise. It would be able to receive and provide funds to public and private organizations as appropriate to effect the NoN mission.
- **Privately Chartered Non Profit Corporation.** Similar to the above without a broad public mandate, but able to provide services to and receive services from publicly and privately funded organizations together with appropriate transfers of funds.
- **Private For-Profit Corporation.** Services, such as the essential core services, provided on a for-profit contractual basis, individually and collectively, with both public and private customers.
- **Seeded Viral NoN.** Essentially an extension of the current collection of networks, with the added impetus to mitigate deficiencies through a consensus-building process with a standing committee. Targeted incentives would be provided by federal agencies to derive greater benefits in national-scale applications from local and regional networks.

Each of these models, if adequately implemented, could improve the current state of mesoscale observations to meet multiple national needs. In principle, each has mechanisms available to it to stand a chance of improving coordination and information exchange. The issue boils down to one of efficiency, effectiveness, and inclusiveness with respect to the NoN enterprise and its operations. We asked these questions:

- What degree of centralization is needed to achieve a balance?
- Is a standing committee and consensus building enough?
- Can a federal agency afford or be permitted to interact responsively and effectively with such a large dynamic range of public and private providers and users (most of whom have applications unrelated to the mission of the federal agency)?
- Can or should a for-profit corporation provide the essential facilities and services for critical national-scale "public good" needs?
- Given the mixed history of federal agency collaboration, is it likely a comprehensive confederation could be assembled and function in the absence of centralized budget authority?
- How many agencies and other organizations is it practical to confederate for the purpose of leading and providing essential core services of the NoN?

On the basis of information previously presented in this report concerning (1) the current breadth of investment in the mesoscale observations enterprise, (2) the changes required to markedly increase the utility of existing observations, and (3) the establishment of pathways toward improved observing capabilities through diversity of investment, the Committee has reached the following judgments about which organizational options should be dismissed and which are worthy of due consideration.

Organization Options Dismissed

Lead Federal Agency

A single federal agency has a congressionally authorized mission that is quite narrow with respect to the mesoscale observations enterprise. To obtain authorization to perform the work of a centralized authority for the NoN would be controversial at best, peripheral to core programs of the agency, and possibly prohibited by statute, and it presents difficulties with respect to the transfer of funds and other resources among many types of public and private organizations.

Multi-level Government Confederation, Government-Industry Confederation

Confederation at multiple levels of government is judged to be impractical to implement, involving hundreds if not thousands of provider-users who would somehow have to organize through representative means, such as a governing board, to lead and perform the centralized effort. A government-industry confederation, while appealing, has similar drawbacks, since industry has relatively few large players involved in mesoscale observations per se, the field being dominated by large numbers of small to medium corporations and companies with needs tailored to niche markets. In effect, this adds complexity to the multi-level government confederation.

For-Profit Private Corporation

The for-profit private option is judged to be an inappropriate framework to serve the whole of essential facilities and services related to national-scale "public good" needs. For-profit participation is highly valued and should be targeted where appropriate.

Options Worthy of Due Consideration

Confederation of Federal Agencies

Approximately 10 agencies could have a significant stake in the NoN. The concatenated agency missions cut a broad swath through the NoN constituency. Agency representatives could form an effective joint management team, though historically agencies have had difficulty with decentralized funding authority beyond partnerships of two or three agencies. There remain difficulties associated with the transfer of funds and other resources among the many types of public and private organizations in a NoN.

While many possible implementations of confederation governance can be envisioned, one example could be a board, overseeing and relying on a lead agency for day-to-day centralized services. In this example, the governing board could be similar to the Committee of Earth Observing Satellites (CEOS), and the federal agency responsible for day-to-day operations could be NOAA/NWS. CEOS successfully arbitrates the various requirements of both users and providers of weather satellites and helps to provide guidance in both operations and acquisition of satellite systems.

NOAA would be an obvious choice for lead agency responsibilities in this confederation. NOAA/NWS successfully operates several programs including the NEXRAD radar network and the Automated Surface Observing Systems (ASOS), even though these programs are jointly owned by three federal agencies (NOAA, Federal Aviation Administration, and Department of Defense).

Strengths of a confederated federal agency organization include economic scalability and the relative stability associated with exclusive or an extremely high fraction of federal funding by co-sponsoring agencies. The attractiveness of this model is that federal agencies are capable of providing the continuity and longevity that successful networks require. On the other hand, recent experiences associated with Earth system observations (e.g the "Decadal Survey") suggest questions about the stability of this model, which usually is wholly dependent on both the funding and the organizational support provided by the federal agencies. Mesoscale observations have a more diverse set of funding sources, which could be used either as an argument for or against the federal confederation model.

The major weakness of the confederation model lies in the likely deficiency of public-private partnerships, which are required for success, where success is defined as meeting the needs of the broader enterprise, not just the concatenation of the federal missions. An organization led by large agencies tends to respond best to partners of like scale. Smaller organizations and individuals, which are an essential part of the broader mesoscale enterprise, could become disenfranchised and systematically withdraw from participation in the NoN.

Providing a true partnership between federal agencies and state governments, academia, and the commercial sector that will make up a large part of the user/provider base is a huge challenge for this model. The organizational culture of public and private entities is so different that friction is often inevitable. Examples do exist of successful partnerships, but these have generally been limited in scope and longevity. This model will succeed only if it can overcome the cultural inertia that makes it difficult to achieve true investment in both the private and public sectors. Nonetheless, despite the debate over NOAA's current Public/Private Partnership Policy, the National Research Council report titled *Fair Weather* (2003) called for more partnerships of just this sort.

Seeded Viral Model (SV)

The viral or organic-Wiki model is a continuation of the current patchwork of organizations and networks that make up the mesoscale observation system in place today. Instead of a central entity to operate and administer to the needs of a NoN, the SV model would have networks which would come and go and rely on the community of users and operators to figure out how to collect data centrally, set standards for metadata, etc. Users would go to different organizations to look for data, much as they do today. The risk/reward ratio for such networks is high since costs are low but the data may be of uncertain value. Like Wiki encyclopedias, the model exists because there is a demand for the service, there is a lack of a (financially) competitive model to provide that service, and there is willingness to contribute to make it occur. This model is anarchic in structure and has little centralized control or assurance of its continued existence.

The "seeded" aspect of the SV model are resources of federal origin to augment dominant local forces (that establish most sites) by adding motivation in the national interest and the broader public good. For example, incentives could be offered to encourage development in data-sparse regions in order to strengthen "remote impact" properties of the network, especially as warranted by numerical weather prediction.

It is easy to envision data providers voluntarily putting together a Wiki-type library of data resources to enable users to find the data they would like. Such a model would have low administrative costs. In fact, the World Meteorological Organization's Global Atmosphere Watch has recently endorsed a European data center on this model that provides "one-stop shopping" for satellite data but without significant input of intellectual property. Considerable architecture is being developed that automates the search process for data and the delivery of components from various providers.

Public-private partnerships are the key strength of the current system, and would be the core strength of the SV model. If one entity or organization wants data, and another has data to provide, they can usually work out a mutually agreeable arrangement. Indeed, this is the key to the successful mesoscale networks in operation today, and also the key to their continued growth.

Most prospective organizations do not have the economic scale or sufficient funding to independently meet all of the requirements for NoN membership identified in this report. The lack of stable funding, combined with the ad-hoc nature of many of the existing networks, will make it difficult for this model to provide for long-term stability. The organic nature of such a network parallels the life cycle of living systems that are born, thrive, founder, and die, which has advantages and also risks, especially regarding stability.

Statistically speaking, a modest evolution of the current condition is among the more likely outcomes for a NoN. The SV model is suited to that description, so it behooves the mesoscale observations enterprise to consider an evolutionary path along such lines, especially as a temporary means to improve the utility of existing data and the encouragement of network gap-filling. As has been said earlier in this report, the system we have today works at a certain level, but it lacks consistent quality, cohesion, coordination, and adequate investment to meet national scale needs, which intersect but also are additive to local-scale infrastructure investments.

Preferred Options

Private Non Profit Corporations, Either Publicly or Privately Chartered

After careful consideration of many options, the Committee is of the belief that some form of hybrid non profit corporation is the best organizational match to the NoN circumstance. Hybrid non profits are capable of broad reach, considerable flexibility, and minimal statutory restrictions regarding interactions with a wide array of vested interests. Hybrid public-private organizations offer the best chance to establish and cement a true partnership among all levels of government and many species and sizes of organizations in the private sector. Privately chartered non profits often prosper under the rules governing 501(c) 3 organizations. This is a federal code that governs exemption from certain taxes for scientific and educational activities, among many others.

Several organizations related to geophysical observations and research have been created under the management of 501(c) 3 corporations. Among these organizations is the Earth Science Information Partnership (ESIP), which is sponsored by NOAA, National Aeronautics and Space Administration and United States Geological Survey (*http://www.esipfed.org*). Since its inception it has grown through the contributions of data and sources both from the agencies as well as from other voluntary contributors. ESIP is governed by a parent 501(c) 3 corporation, the Foundation for Earth Science, which was established in 2001 to support scientific programs and organizations that collect, process, and analyze science-based Earth science information for a broad range of users. It is dedicated to bringing the most current and reliable data and data products to bear on the environmental, economic, and social challenges. The corporation is governed by a board of directors from academia, government, and industry.

Another example of a 501(c) 3 corporation is the University Corporation for Atmospheric Research (UCAR), which operates several technical and scientific programs. Among these is Unidata (*http://www.unidata.ucar.edu*), which has been a force in atmospheric data distribution development and services. Some of the developments and services have been related to mesoscale data distribution and related networking issues. Through the UCAR 501(c) 3, Unidata was initially launched by the National Science Foundation for university-based atmospheric research applications, but now also draws support from several public agencies and some private sources for various applications, some of which are in operational meteorology. UCAR also operates the National Center for Atmospheric Research, which is a Federally Funded Research and Development Center (FFRDC). FFRDCs are often the principal motivation for establishment of 501(c) 3 corporations.

Privately chartered non profits, such as 501(c) 3 corporations, must rely on the strength and influence of their governing board and the motivation of the sponsoring agencies themselves to succeed in satisfying a national-scale mandate that spans various public and private sectors. This is a fundamental distinction between privately and publicly chartered non profits, the latter having a clear national mandate and direct access to congressional funding.

Corporation for Environmental Monitoring (CEM)

In this model, a congressionally chartered, non profit corporation would be created to manage and operate a NoN. For the sake of example, this hypothetical corporation will be referred to as CEM. CEM would be modeled after existing publicly chartered corporations such as National Public Radio (NPR), the Corporation for Public Broadcasting (CPB), or the U.S. Postal Service. In the case of CPB, a board of directors sets policy and establishes programming priorities. The President of the United States appoints each member, who, after confirmation by the Senate, serves a 6 year term. The board, in turn, appoints the president and chief executive officer, who then names the other corporate officers. CPB governance includes both users and providers.

As a publicly chartered corporation, CEM would collect revenue from users of a NoN and apply these to offset operational expenses. Federal funds would be used to facilitate the establishment and provision of essential core services and to support performance incentives associated with the NoN, for example in the generation of metadata. Additional activities may be supported as required, including NoN design studies, evolving implementation strategies, and enablement services to new networks as created by the agencies and other providers.

The CEM role described is analogous to the CPB model. The CPB is allocated money from Congress and then uses that money to fund its member stations and organizations for a variety of purposes, including the production of content, upgrades to existing facilities, and development of new technologies.

Another example is NPR, which performs functions strongly related to CPB and directly serves a national network of radio stations. NPR operates as a non profit business that produces both news and entertainment products for its member stations and charges the stations fees that support the operation. Thus, with a limited federal subsidy, NPR is able to operate independently of the federal government and still serve its member organizations. NPR does not build or operate radio stations. Similarly, under this proposal, CEM would not build or operate observing networks.

A strength of a publicly chartered non profit corporation is that the organization is ideally positioned to effect a true public-private partnership. In principle, it can be responsive to user/provider organizations of all types and sizes. It has a federal government mandate, but it is not tightly bound by statutes, regulations, or relatively narrow agency missions in the breadth or the sectors of the community served. It constitutes a vehicle of convenience, through which the federal agencies can better accomplish some of their goals and objectives for the greater public good.

An organization such as CEM would be at least partly self-supporting, and as such it should have the stability required to endure. However, as a publicly chartered corporation, some federal subsidy to CEM would be required on an annual basis. If this subsidy were ever eliminated, it could have a detrimental effect on the organization. For example, the U.S. Postal Service could not survive without a federal subsidy, even though it raises a considerable amount of revenue.

The hypothetical CEM model provides all the necessary characteristics needed. It is easy to envision this hybrid non profit corporation, formed for the expressed purpose of coordinating the operation of environmental monitoring networks, collecting data, charging users of those observations for their use, and using the fees to fund the data collection. Federal, state, and local governmental initiatives could expand the NoN and offer incentives to others for the provision of additional observations that are carefully targeted to fill critical national needs.

A RECOMMENDED ORGANIZATIONAL MODEL

Recommendation: The United States should establish a robust and economically viable organizational structure to effect the national implementation of a multi-purpose environmental observing network at the mesoscale. It may be preferable for this organization to take the form of a publicly chartered, private non profit corporation. A hybrid public-private organizational model would stimulate both public and private participation over a wide, dynamic range of investment and applications; maximize access to mesoscale data; and effect a synergism between the public good and proprietary interests.

8

Concluding Thoughts

In previous chapters, we have offered several specific recommendations targeted to the private, public, and academic stakeholders of a national multi-purpose mesoscale observing system. These recommendations range in scope from specific applications of data to the particular types of observations and infrastructure that should comprise a national network of networks. In this chapter we address some human dimensions associated with the selection and provision of mesoscale information and we enumerate the highest observing system priorities associated with the critical gaps identified elsewhere in the report.

PRESERVING AND ENHANCING THE DIVERSITY OF INVESTMENT

A major implementation challenge is to retain the energy, enthusiasm, and diverse investments that have led to our current condition, while also introducing an appropriate degree of centralization for the purposes of coordination and integration to maximize the national benefit. This is easier said than done. However, the United States has been faced with analogous challenges in the past, and it has succeeded. The U.S. Congress has chartered private non profit corporations (e.g., National Public Radio) in situations where the scope of activity is truly national, yet major components of the effort are cooperatively resourced federally and locally through both governmental and private resources.

Providers and users of mesoscale data include individuals; water, energy utility, and air quality and transportation districts; agriculture-related organizations; municipalities, state governments, and federal agencies; and small businesses and Fortune 500 corporations. While each of these entities is important to the enterprise, all have a limited mission and therefore a mission-limited role where provision of infrastructure and services is concerned. A hybrid public-private organization would encourage the leadership and prominence of federal agencies such as National Oceanic and Atmospheric Administration, while also protecting, facilitating, and enabling the role of other interests, which are essential to the success of the collaborative enterprise.

While the mesoscale observational enterprise extends far and wide throughout the nation's commerce, industry, academia, and all levels of government, the federal role is pivotal. This is especially important in the case of costly three-dimensional observations, which enable short-range numerical weather prediction, the nowcasting of high impact weather, and chemical weather predictions.

THE EVOLVING HUMAN DIMENSION

The societal uses of mesoscale information are evolving rapidly, and these are increasingly interactive with the technical enterprise of weather prediction and climate monitoring. The need for information is sometimes driven by the increased importance of specific physical, dynamical, and chemical processes to new applications in an expanding user base. However, other needs are driven by behavioral change, evolving social values, and changing demographics. This aspect of mesoscale network design and evolving requirements must be viewed as a two-way process that includes integrated feedback mechanisms.

> **Recommendation: The stakeholders should commission an independent team of social and physical scientists to conduct an end-user assessment for selected sectors. The assessment should 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 the implementation and utilization of improved observations, periodic assessments should 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 should capture user comments from blogs and webpage feedback. Such a survey would actively seek out comments from people who are registered or who regularly access the data. The broad objectives of a survey would be to

- identify priority areas where training and outreach can be developed to broaden the number and types of users and uses of network data;
- develop ways to acknowledge and broaden the uses of environmental monitoring information, beyond weather, to include examination of societal vulnerability and resilience to a broader range of hazards;
- examine whether and how one state, group, or region's applications and partnership agreements can be used elsewhere;
- discover metrics that measure how well current initiatives meet the data needs of the citizenry, e.g., teachers, students, hospital administrators, golfers, homeowners, and individuals of all ages; and
- identify novel ways to build capacity for using environmental monitoring data in society.

HIGHEST PRIORITIES STEMMING FROM COMMON THREADS

While this report recognizes longer-term, larger-scale, full tropospheric/stratospheric applications, it is the first report to focus specifically on observational needs for high-impact mesoscale meteorological and chemical weather events. The Committee has surveyed needs for mesoscale observations in six application areas: weather and climate, energy, public health and safety, transportation, water resources and food production, and research. Commensurate with the Committee's charge, our surveys have emphasized regional and urban short-term applications, paying special attention to the atmospheric boundary layer within the continental U.S. and adjacent coastal areas.

A baseline need is to do those things necessary to enable broader and more effective use of existing observations. While an important first step, these remedial actions alone are insufficient to meet all the requirements for any of the applications surveyed. The major findings resulting from Chapters 2, 3, and 4 are distilled in Table 8.1. An "X" in the box means that the observational capability was considered for the application. Red means that the observational capability is primitive or that the techniques and/or the infrastructure to make the observations do not exist. Where the box is empty, the type of observation for a specific application area was not discussed or is not relevant.

The most sorely needed observations stand out in this table as two or more red entries in a single row:

- **Height of the planetary boundary layer**
- **Soil-moisture and soil-temperature profiles**
- **High-resolution vertical profiles of humidity**
- **Measurements of air quality and atmospheric composition above the surface layer**

TABLE 8.1 Application sector gaps for various parameters

Sector/ Variable	Weather and Climate	Energy	Public Health and Safety	Transportation	Food and Water
Surface wind speed and direction	X	X	X	X	X
Surface temperature	X	X	X	X	X
Surface relative humidity	X	X	X	X	X
Surface pressure	X		X	X	
Visibility	X		X	X	
Precipitation rate	X		X	X	X
Snow cover and depth	X			X	X
Precipitation amount	X	X	X	X	X
Precipitation type	X	X		X	X
sea-surface temperature	X				
Lightning	X		X	X	
planetary boundary layer height	X	X	X	X	
Soil-moisture and soil-temperature profiles	X	X	X	X	X
Direct and diffuse radiation	X	X	X	X	
Vertical wind profiles	X	X	X	X	
Vertical temperature profiles	X	X	X	X	
Vertical humidity profiles	X	X	X	X	
Hydrometeor mixing ratios	X				
Reservoir temperature/ water temperature		X			X
Stream flow		X		X	X
Ag climate variables		X			X
Icing near surface		X		X	
Air quality—surface	X	X	X		
Air quality—aloft	X		X		
Cloud cover/ sky view		X	X	X	
Surface turbulence parameters		X	X	X	

continued

TABLE 8.1 Continued

Sector/ Variable	Weather and Climate	Energy	Public Health and Safety	Transportation	Food and Water
Roadway temperature				X	
Subsurface temperatures				X	🟥 X
Low-level shear	X	X		X	
Marine swell heights/water depth/currents/air gaps				X	
Evapotranspiration					🟥 X
Water quality					X

NOTE: An “X” indicates that the measurement has been discussed under the topic listed in the column heading. An “X” with no red indicates that some network measurements are being taken, though spatial and temporal gaps may exist. An “X” with red indicates that measurements are so inadequate that no network can be said to exist, and the problem must be addressed.

In the next category are variables that have one red entry and at least one additional “X”:

- Direct and diffuse radiation
- Vertical profiles of wind
- Sub surface temperature profiles (e.g., under pavement)
- Icing near the surface
- Vertical profiles of temperature
- Surface turbulence parameters

If one wants to know where multiple, cross-cutting needs can be met through an investment in new or improved observing systems, Table 8.1 provides fairly specific guidelines.

Observations drive all environmental monitoring and prediction systems. Raw, calibrated, and checked observations can meet a few very short-term applications, that is, those requiring a response or decision within minutes to an hour. For all other applications, however, a system for assimilating disparate observations into a coherent analysis of present conditions is essential, as is the insertion of this analysis into a prediction model. Probably beyond 12 hours—certainly beyond 24 hours—the needs of all user communities converge: they must have prediction models. But without the observations to specify the initial conditions, the models are impotent.

National Needs

Meteorological and related environmental observations are needed at spatial and temporal resolutions much finer than widely available today. The priority uses and applications include tracking atmospheric dispersion of chemical, biological, and nuclear contaminants from industrial accidents and terrorist activities as well as smoke dispersion monitoring and predictions related to wildfires, prescribed burns, and seasonal agricultural fires; providing information for air quality forecasting, high-resolution nowcasting, and short-range forecasting of high-impact weather; providing high-resolution weather information for aviation, surface transportation, and coastal waterways; and providing support to regional climate monitoring.

The Vertical Dimension

The vertical component of U.S. mesoscale observations is inadequate. Assets required to profile the lower troposphere above the near-surface layer (first 10) are too limited in what they measure, too sparsely or unevenly distributed, sometimes too coarse in vertical resolution, sometimes limited to regional areal coverage, and clearly do not qualify as a mesoscale network of national dimensions. Likewise, vertical profiles below the Earth's surface are inadequately measured in both space and time. The solutions to these particular deficiencies require leadership and infrastructure investments from each of the pivotal federal agencies.

Metadata and Exposure

A NoN cannot deliver net benefit to users unless comprehensive metadata are supplied by all operators. Though provision of good metadata is an exacting task; metadata are key to the effective accommodation of diverse data sources and the widest possible utility of such information. The Committee repeatedly discussed conformance to World Meteorological Organization exposure standards, which is desirable in many instances but unnecessarily restrictive and sub-optimal in others. For example, restriction of sensors to WMO exposure settings and heights clearly would be counterproductive in the road and rail applications, yet non-standard exposures, provided these are known, will be potentially useful in multiple applications. Comprehensive metadata, including all aspects of exposure and observing system performance, enable network configurations to best meet customized needs as specified by the users themselves. Metadata enables one to ask questions across multiple networks and seek answers from the whole NoN.

Given that proper exposure is often application dependent, the Committee believes that low power wireless communication is an important and underused pathway for the mitigation of competing exposure requirements. A single surface station may economically achieve optimal exposures in a local area for winds, precipitation, radiation, and properties of soil, road and water surfaces, etc., as long as data rates and distances are compatible with low power wireless communications.

Geography and Demography

The Committee repeatedly returned to concerns about urban, coastal, and mountainous regions as these affect the mix of surface-based mesoscale observing systems. Mountains, coastlines, and cities have greater importance than their surface areas would imply. Ironically, these are consistently undersampled relative to their needs. All three create their own weather, which is often poorly resolved in synoptic Numerical Weather Prediction models. Considering the danger of traveling in the winter or fighting forest fires in the summer, the need for observations in the mountains goes beyond that for weather forecasting alone. Coastlines and cities, both of which have high concentrations of people, also take on special importance, particularly when one considers the need for observations to response to a release of toxic substances, treating the roads in respond to an ice storm or blizzard, or evacuate people in advance of hurricane landfall.

The effect of these considerations on priorities is somewhat uncertain. Cities have special needs at the mesoscale owing to population density and high exposure to a very wide range of human activity over very short distances. However, coastlines and mountains harbor considerable meteorological and environmental complexity often not experienced in other regions. While sections of coastline are often densely populated, mountains are not, suggesting fewer observations in mountainous regions, which is consistent with past practice. However mountains are where surface observations are by far the least representative of the surrounding area, harboring large gradients of atmospheric properties; they are often suspected of being the major source of error in numerical prediction for regions downstream, such as cities and coastlines. There is no easy way out of this conundrum except to rely on testbeds, observing system experiments, and observing system simulation experiment for guidance in mesoscale observation design; and to gain additional skill as computational capacity increases along with our ability to better resolve and understand atmospheric structure.

THE CHALLENGE FOR THE FUTURE

Today we are faced with a complex collection of mesoscale networks that are clearly driven by market forces. The condition is both energetic and chaotic and possesses local strengths, national gaps, and operational weaknesses. Local strengths are heralded by the proliferation of surface meteorological stations, which are often tailored to satisfy the monitoring needs of a particular application. The national gaps result from weaknesses in the federal government's observational infrastructure as they pertain to mesoscale numerical weather prediction and chemical weather prediction. Observational deficiencies in the mountains, at the coasts, and near urbanized areas require specialized attention. With respect to mesoscale numerical and chemical weather prediction and chemical weather forecasts, three-dimensional observations are paramount and involve heavy infrastructure to which federal agencies must be major contributors.

Nearly every dimension of participation in mesoscale observation is important and worthy of cultivation. The challenge is to harness the strengths of our current condition while creating an organizational circumstance that can stimulate and coordinate diverse assets to serve similarly diverse interests. The Committee believes that it has offered constructive and sometimes novel alternatives toward that end while avoiding prematurely prescriptive or excessively centralized solutions. Much work remains, especially with regard to the elaboration of architecture, the design of networks, and the forging of new relationships among all levels of government, industry, and the earnest contributions of our citizenry.

References

Aberson, S. D. 2003. Targeted observations to improve operational tropical cyclone track forecast guidance. *Monthly Weather Review* 131:1613-1628.

Ancellet, G and F. Ravetta. 2005. Analysis and validation of ozone variability observed by lidar during the ESCOMPTE-2001 campaign. *Atmospheric Research* 74(1-4):435-459.

Anthes, R. A., P. A. Bernhardt, Y. Chen, L. Cucurull, K. F. Dymond, D. Ector, S. B. Healy, S.-P. Ho, D. C. Hunt, Y.-H. Kuo, H. Liu, K. Manning, C. McCormick, T. K. Meehan, W. J. Randel, C. Rocken, W. S. Schreiner, S. V. Sokolovskiy, S. Syndergaard, D. C. Thompson, K. E. Trenberth, T.-K. Wee, N. L. Yen, and Z. Zeng. 2008. The COSMIC/FORMOSAT-3 Mission: Early results. *Buletin of the American Meteorological Society* 89:313-333.

Baklanov, A., O. Hänninen, L. H. Slørdal, J. Kukkonen, J. H. Sørensen, N. Bjergene, B. Fay, S. Finardi, S. C. Hoe, M. Jantunen, A. Karppinen, A. Rasmussen, A. Skouloudis, R. S. Sokhi, and V. Ødegaard. 2006. Integrated systems for forecasting urban meteorology, air pollution and population exposure. *Atmospheric Chemistry and Physics* 7:855-874.

Baklanov, A., P. G. Mestayer, A. Clappier, S. Zilitinkevich, S. Joffre, A. Mahura, and N. W. Nielsen. 2008. Towards improving the simulation of meteorological fields in urban areas through updated/advanced surface fluxes description. *Atmospheric Chemistry and Physics* 8:523-543.

Bevis, M., S. Businger, T. A. Herring, C. Rocken, R. A. Anthes, and R. H. Ware. 1992. GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *Journal of Geophysical Research* 97(D14):15,787-15,801.

Biggerstaff, M.I., and J. Guynes. 2000. A new tool for atmospheric research. Preprints, 20th Conference on Severe Local Storms, American Meteorological Society, Orlando, Florida, pp. 277-280.

Bluestein, H. B., B. A. Albrecht, R. M. Hardesty, W. D. Rust, D. Parsons, R. Wakimoto, and R. M. Rauber. 2001. Ground-Based Mobile Instrument Workshop summary, 23-24 February 2000, Boulder, Colorado. *Bulletin of the American Meteorological Society* 82:681-694.

Bösenberg, J., and R. M. Hoff. 2008. GALION, the GAW atmospheric lidar observation network. WMO GAW Report. Geneva, Switzerland: World Meterological Organization/Global Atmosphere Watch.

Braun, J. J., C. Rocken, and J. Liljegren. 2003. Comparisons of line-of-sight water vapor observations using the global positioning system and a pointing microwave radiometer. *Journal of Atmospheric and Oceanic Technology* 20:606-612.

Browning, K. A., ed. 1982. *Nowcasting*. London: Academic Press. 256 pp.

Burke, P. C., and D. M. Schultz. 2004. A 4-yr climatology of cold-season bow echoes over the continental United States. *Weather and Forecasting* 19:1061-1074.

Byers H. R., and R. R. Braham. 1949. The Thunderstorm Project. Washington, DC: U.S. Government Printing Office. 287 pp.

Caracena, F., R. L. Holle, and C. A. Doswell III. 1989. *Microbursts. A Handbook for Visual Identification*. Boulder: National Oceanic and Atmospheric Adminsitration, National Severe Storms Laboratory.

Carmichael, G. R., A. Sandu, T. Chai, D. N. Daescu, E. M. Constantinescu, and Y. Tang. 2008. Predicting air quality: Improvements through advanced methods to integrate models and measurements. *Journal of Computational Physics* 227:3540-3571.

CEC (Commission for Environmental Cooperation). 1997. Background Document on Air Quality Data Compatibility. Prepared for the North American Monitoring and Modeling Project of the CEC, August 1997.

Changnon, S. A. 1999. Data and approaches for determining hail risk in the contiguous United States. *Journal of Applied Meteorology* 38:1730-1739.

Changnon, S. A. 2001. *Thunderstorms across the Nation: An Atlas of Storms, Hail and Their Damages in the 20th Century.* Mahomet, IL: Changnon Climatologist.

Changnon, S. A. 2003. Characteristics of ice storms in the United States. *Journal of Applied Meteorology* 42:630-639.

Ciach, G. J., W. F. Krajewski, and G. Villarini. 2007. Product-error-driven uncertainty model for probabilistic quantitative precipitation estimation with NEXRAD data. *Journal of Hydrometeorology* 8:1325-1347.

Cifuentes, L., V. H. Borja-Aburto, N. Gouveia, G. Thurston, and D. L. Davis. 2001. Assessing the health benefits of urban air pollution reductions associated with climate change mitigation (2000-2020): Santiago, Sao Paulo, Mexico City and New York City. *Environmental Health Perspectives* 109(Suppl 3):419-425.

Concannon, P. R., H. E. Brooks, and C. A. Doswell III. 2000. Climatological risk of strong and violent tornadoes in the United States. Second Conference of Environmental Applications, American Meteorological Society, Long Beach, CA, January 8-12, 2000. 9 pp.

Coniglio, M. C., and D. J. Stensrud. 2004. Interpreting the climatology of derechos. *Weather and Forecasting* 19:595-605.

CUAHSI (Consortium of Universities for the Advancement of Hydrologic Sciences), 2007. *Hydrology of a Dynamic Earth. A Decadal Research Plan for Hydrologic Science.* Washington, DC: CUAHSI.

Dabberdt,W., J. Hales, S. Zubrick, A. Crook, W. Krajewski, J. C. Doran, C. Mueller, C. King, R. N. Keener, R. Bornstein, D. Rodenhuis, P. Kocin, M. A. Rossetti, F. Sharrocks, and E. M. Stanley Sr. 2000. Forecast issues in the urban zone: Report of the 10th Prospectus Development Team of the U. S. Weather Research Program. *Bulletin of the American Meteorological Society* 81(9):247-264.

Dabberdt, W. F., M. A. Carroll, D. Baumgardner, G. Carmichael, R. Cohen, T. Dye, J. Ellis, G. Grell, S. Grimmond, S. Hanna, J. Irwin, B. Lamb, S. Madronich, J. McQueen, J. Meagher, T. Odman, J. Pleim, H. P. Schmid, and D. L. Westphal. 2004. Meteorological research needs for improved air quality forecasting: Report of the 11th Prospectus Development Team for the U.S. Weather Research Program. *Bulletin of the American Meteorological Society* 85:563-586.

Dabberdt, W. F., T. W. Schlatter, F. H. Carr, E. W. J. Friday, D. Jorgensen, S. Koch, M. Pirone, F. M. Ralph, J. Sun, P. Welsh, J. W. Wilson, and W. Zou. 2005a. Multifunctional mesoscale observing networks. *Bulletin of the American Meteorological Society* 86:961-982.

Dabberdt, W., J. Koistinen, J. Poutiainen, E. Saltikoff, and H. Turtiainen. 2005b. The Helsinki Mesoscale Testbed: An invitation to use a new 3-D observation network. *Bulletin of the American Meteorological Society* 86:906-907. DOI:10. 1175/BAMS-86-7-906

Daley, R. 1991. *Atmospheric Data Analysis*. New York: Cambridge University Press. 457 pp.

Davis, R. S. 2001. Flash flood forecast and detection methods. Pp. 481-525 in *Severe Convective Storms*, C. A. Doswell III, ed. Boston: American Meteorological Society.

Durran, D. R. 2003a. Downslope winds. Pp. 644-650 in *Encyclopedia of Atmospheric Sciences*, J. R. Holton, J. A. Curry, and J. A. Pyle, eds. New York: Academic Press.

Durran, D. R. 2003b. Lee waves and mountain waves. Pp. 1161-1169 in *Encyclopedia of Atmospheric Sciences*, J. R. Holton, J. A. Curry, and J. A. Pyle, eds. New York: Academic Press.

Engel-Cox, J. A., R. M. Hoff, R. Rogers, F. Dimmick, A. C. Rush, J. J. Szykman, J. Al-Saadi, D. A. Chu, and E. R. Zell. 2006. Integrating lidar and satellite optical depth with ambient monitoring for 3-dimensional particulate characterization. *Atmospheric Environment* 40:8056-8067.

Entekhabi, D., E. Njoku, P. Houser, M. Spencer, T. Doiron, J. Smith, R. Girard, S. Belair, W. Crow, T. Jackson, Y. Kerr, J. Kimball, R. Koster, K. McDonald, P. O'Neill, T. Pultz, S. Running, J. C. Shi, E. Wood, and J. van Zyl. 2004. The Hydrosphere State (HYDROS) mission concept: An Earth system pathfinder for global mapping of soil moisture and land freeze/thaw. *IEEE Transactions on Geoscience and Remote Sensing* 42:2184-2195.

Evans, W. F. J., E. Puckrin, and T. P. Ackerman. 2002. Comparison of ARM AERI with Trent FTS Spectra for the Measurement of Greenhouse Radiative Fluxes. Twelfth ARM Science Team Meeting, St. Petersburg, FL, April 8-12, 2002.

Fabry, F. 2004. Meteorological value of ground target measurements by radar. *Journal of Atmospheric and Oceanic Technology* 21:560-573.

FEMA (Federal Emergency Management Agency). 2000. *Evaluation of Erosion Hazards*. Report prepared by the H. John Heinz Center for Science, Economics, and the Environment under Contract EMW-97-CO-0305. Available online at http://www. heinzctr. org/publications/PDF/erosnrpt.pdf, accessed September 5, 2008. 252 pp.

Fröhlich, C., R. Philipona, J. Romero, and C. Wehrli. 1995. Radiometry at the Physikalisch-Meteorologisches Observatorium Davos and the World Radiation Center. *Optical Engineering* 34:2757-2766.

Georgakakos, K., N. Graham, and A. Georgakakos. 2000. Can forecasts accrue benefits for reservoir management? The Folsom Lake Case Study. *The Climate Report* 1:7-10.

Glickman, T., Ed. 2000. *Glossary of Meteorology.* 2d ed. Boston: American Meteorological Society.

Grund, C. J., R. M. Banta, J. L. George, J. N. Howell, M. J. Post, R. A. Richter, A. M. Weickmann. 2001. High-resolution doppler lidar for boundary layer and cloud research. *Journal of Atmospheric and Oceanic Technology* 18:376-393.

He, H., W. W. McMillan, R. O. Knuteson, and W. F. Feltz. 2001. Tropospheric carbon monoxide column density retrieval during pre-launch MOPITT validation exercise. *Atmospheric Environment* 35:509-514.

Holben, B. N., D. Tanre, A. Smirnov, T. F. Eck, I. Slutsker, N. Abuhassan, W. W. Newcomb, J. Schafer, B. Chatenet, F. Lavenue, Y. J. Kaufman, J. Vande Castle, A. Setzer, B. Markham, D. Clark, R. Frouin, R. Halthore, A. Karnieli, N. T. O'Neill, C. Pietras, R. T. Pinker, K. Voss, and G. Zibordi. 2001. An emerging ground-based aerosol climatology: Aerosol Optical Depth from AERONET. *Journal of Geophysical Research* 106:12,067-12,097.

Horel, J., M. Splitt, L. Dunn, J. Pechmann, B. White, C. Ciolilberti, S. Lazarus, J. Slemmer, D. Zaff, and J. Burks. 2002. MesoWest: Cooperative mesonets in the western United States. *Bulletin of the American Meteorological Society* 83:211-226.

Illton, B. G., J. B. Basara, D. K. Fisher, R. Elliott, C. A. Fiebrich, K. C. Crawford, K. Humes, and E. Hunt. 2008. Mesoscale monitoring of soil moisture across a statewide network. *Journal of Atmospheric and Oceanic Technology* 25:167-181.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis*. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon and D. Qin, eds. New York: Cambridge University Press. 996 pp.

Jackson, T. J., A. Y. Hsu, P. E. O'Neill. 2001. Surface soil moisture retrieval and mapping using high-frequency microwave satellite observations in the southern Great Plains. *Journal of Hydrometeorology* 3:94.

Jones, S. C., P. A. Harr, J. Abraham, L. F. Bosart, P. J. Bowyer, J. L. Evans, D. E. Hanley, B. N. Hanstrum, R. E. Hart, F. Lalaurette, M. R. Sinclair, R. K. Smith, and C. Thorncroft. 2003. The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Weather and Forecasting* 18:1052-1092.

Kalnay, E., 2003: *Atmospheric Modeling, Data Assimilation and Predictability*. New York: Cambridge University Press. 341 pp.

Kaiser, J. 2005. Mounting evidence indicts fine-particle pollution. *Science* 307:1858-1861.

Knight, C. A., and N. C. Knight. 2001. Hailstorms. Pp. 223-254 in *Severe Convective Storms*, C. A. Doswell III, ed. Boston: American Meteorological Society.

Kocin, P. J., and L. W. Uccellini. 2004. *Northeast Snowstorms. Vol. 1: Overview; Vol. 2: The Cases*. Meteorological Monographs, 32, No. 54. Boston: American Meteorological Society. 818 pp.

Koster, R. D., P. A. Dirmeyer, Z. Guo, G. Bonan, E. Chan, P. Cox, C. T. Gordon, S. Kanae, E. Kowalczyk, D. Lawrence, P. Liu, C. -H. Lu, S. Malyshev, B. McAvaney, K. Mitchell, D. Mocko, T. Oki, K. Oleson, A. Pitman, Y. C. Sud, C. M. Taylor, D. Verseghy, R. Vasic, Y. Xue, and T. Yamada. 2004. Regions of strong coupling between soil moisture and precipitation. *Science* 305:1138-1140. DOI: 10. 1126/science. 1100217.

Larson, K. M., E. E. Small, E. Gutmann, A. Bilich, P. Axelrad, and J. Braun, 2008: Using GPS multipath to measure soil moisture fluctuations: Initial results. *GPS Solutions* 12:173-177.

Lambrigtsen, B. H., A. Tanner, T. Gaier, P. Kangaslahti, and S. Brown. 2006. A Microwave Sounder for GOES-R: Developing the GeoSTAR Mission. Proceedings of . IEEE International Geoscience and Remote Sensing Symposium, Denver, CO, July 31-August 4, 2006.

Lawrence, M., O. Hov, M. Beekmann, J. Brandt, H. Elbern, H. Eskes, H. Feichter, and M. Takigawa. 2005. The chemical weather. *Environmental Chemistry* 2:6-8.

Leconte, R., F. Brissette, M. Galarneau, and J. Rousselle. 2004. Mapping near-surface soil moisture with RADARSAT-1 synthetic aperture radar data. *Water Resources Research* 40:W01515. DOI:10. 1029/2003WR002312.

Liljegren, J. C. 2007. *Evaluation of a New Multi-Frequency Microwave Radiometer for Measuring the Vertical Distribution of Temperature, Water Vapor, and Cloud Liquid Water.* DOE Atmospheric Radiation Program Publication. Available online at http://www. arm. gov/publications/tech_reports/handbooks/mwrp_handbook. pdf, accessed September 4, 2008.

Linder, J. C. 2007. AIRNow: EPA mavericks shows that good air quality has grass roots. Chapter 8 in *Spiral Up and Other Management Secrets Behind Wildly Successful Initiatives*. New York: AMACOM Books.

Mailhot, J., and C. Chouinard. 1989. Numerical forecasts of explosive winter storms: Sensitivity experiments with a Meso-α scale model. *Monthly Weather Review* 117:1311-1343.

Manfredi, J., T. Walters, G. Wilke, L. Osborne, R. Hart, T. Incrocci, and T. Schmitt. 2005. Road weather information system environmental sensor station siting guidelines. Report No. FHWA-HOP-05-026, Federal Highway Administration, U.S. Department of Transportation. 46 pp.

Marenco, A., V. Thouret, P. Nédélec, H. Smit, M. Helten, D. Kley, F. Karcher, P. Simon, K. Law, J. Pyle, G. Poschmann, R. Von Wrede, C. Hume, and T. Cook. 1998. Measurement of ozone and water vapor by Airbus in-service aircraft: The MOZAIC airborne program, an overview. *Journal of Geophysical Research* 103(D19):25631-25642.

Matthias V., J. Bösenberg, V. Freudenthaler, A. Amodeo, D. Balis, A. Chaikovsky, G. Chourdakis, A. Comeron, A. Delaval, F. de Tomasi, R. Eixmann, A. Hågård, L. Komguem, S. Kreipl, R. Matthey, I. Mattis, V. Rizi, J. A. Rodriguez, V. Simeonov, X. Wang. 2004. Aerosol lidar intercomparison in the framework of the EARLINET project. 1. Instruments. *Applied Optics* 43(4):961-976.

McLaughlin, D. J., V. Chandrasekar, K. Droegemeier, S. Frasier, J. Kurose, F. Junyent, B. Philips, S. Cruz-Pol, and J. Colom. 2005. Distributed Collaborative Adaptive Sensing (DCAS) for improved detection, understanding, and predicting of Atmospheric hazards. In Proceedings of the 85th Annual Meeting of the American Meteorological Society, San Diego, California, January 9-13, 2005.

McLaughlin, D. J., E. Knapp, Y. Wang, and V. Chandrasekar. 2007. Distributed weather radar using X band active arrays. Proceedings, IEEE Radar Conference, Waltham, MA, April 17-20, 2007.

McPherson, R. A., C. A. Fiebrich, K. C. Crawford, R. L. Elliott, J. R. Kilby, D. L. Grimsley, J. E. Martinez, J. B. Basara, B. G. Illston, D. A. Morris, K. A. Kloesel, S. J. Stadler, A. D. Melvin, A. J. Sutherland, H. Shrivastava, J. D. Carlson, J. M. Wolfinbarger, J. P. Bostic, and D. B. Demko. 2007. Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet. *Journal of Atmospheric and Oceanic Technology* 24:301-321.

Miller, P.A., F. Barth, L.A. Benjamin, R. S. Artz, and W. R. Pendergrass, 2005: The Meteorological Assimilation and Data Ingest System (MADIS): Providing value-added observations to the meteorological community. 21st Conference on Weather Analysis and Forecasting, American Meteorological Society, Washington, DC, July 31-August 5, 2005.

Mitchell, K. E., D. Lohmann, P. R. Houser, E. F. Wood, J. C. Schaake, A. Robock, B. A. Cosgrove, J. Sheffield, Q. Duan, L. Luo, R. W. Higgins, R. T. Pinker, J. D. Tarpley, D. P. Lettenmaier, C. H. Marshall, J. K. Entin, M. Pan, W. Shi, V. Koren, J. Meng, B. H. Ramsay, and A. A. Bailey. 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *Journal of Geophysical Research* 109:D07S90. DOI:10. 1029/2003JD003823.

Moninger, W., S. G. Benjamin, B. D. Jamison, T. W. Schlatter, T. L. Smith, and E. J. Szoke. 2008. New TAMDAR fleets and their impact on Rapid Update Cycle (RUC) forecasts. 13th Conference on Aviation, Range, and Aerospace Meteorology, American Meteorological Society, New Orleans, LA, January 21-24, 2008. Available online at *http://ams.confex.com/ams/pdfpapers/134128.pdf*, accessed September 8, 2008.

Neiman, P. J., R. M. Hardesty, M. A. Shapiro, and R. E. Cupp. 1988. Doppler lidar observations of a downslope windstorm. *Monthly Weather Review* 116:2265-2275.

Neiman, P. J., P. T. May, and M. A. Shapiro. 1992. Radio Acoustic Sounding System (RASS) and wind profiler observations of lower- and mid-tropospheric weather systems. *Monthly Weather Review* 129:2298-2313.

Njoku, E. G., T. L. Jackson, V. Lakshmi, T. Chan, and S. V. Nghiem. 2003. Soil moisture retrieval from AMSR-E. *IEEE Transactions on Geoscience and Remote Sensing* 41(2):215-229.

NAS/NRC (National Academy of Science/National Research Council). 1958. Research and Education in Meteorology: Interim Report of the Committee on Meteorology. Washington, DC: NAS/NRC.

NRC (National Research Council). 1995. Assessment of NEXRAD Coverage and Associated Weather Services. Washington, DC: National Academy Press.

NRC. 1998. *The Atmospheric Sciences Entering the Twenty-First Century*. Washington, DC: National Academy Press.

NRC. 1999. *A Vision for the National Weather Service: Road Map for the Future*. Washington, DC: National Academy Press.

NRC. 2000. *Improving Atmospheric Temperature Monitoring Capabilities: Letter Report*. Washington, DC: National Academy Press.

NRC. 2002. *Weather Radar Technology Beyond NEXRAD*. Washington, DC: National Academy Press.

NRC. 2003a. *Tracking and Predicting the Atmospheric Dispersion of Hazardous Material Releases: Implications for Homeland Security*. Washington, DC: The National Academies Press.

NRC. 2003b. *Fair Weather: Effective Partnerships in Weather and Climate Services*. Washington, DC: The National Academies Press.

NRC. 2004. *Where the Weather Meets the Road: A Research Agenda for Improving Road Weather Services*. Washington, DC: The National Academies Press.

NRC. 2005. *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*. Washington, DC: The National Academies Press.

NRC. 2007a. *Integrating Multiscale Observations of U.S. Waters*. Washington, DC: The National Academies Press.

NRC. 2007a. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. Washington, DC: The National Academies Press.

NRC. 2007b. *Environmental Data Management at NOAA: Archiving, Stewardship, and Access*. Washington, DC: The National Academies Press.

Oke, T. R. 2007. Siting and exposure of meteorological instruments at urban sites. Pp. 615-631 (Chapter 6) in *Air Pollution Modeling and Its Application XVII,* C. Borrego and A.-L. Norman, eds. New York: Springer.

Orville, R. E., and G. R. Huffines. 2001. Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989-1998. *Monthly Weather Review* 129:1179-1193.

Petersen, R. A., and J. T. McQueen, eds. 2001. *An Assessment of NCEP/Eta Model Performance for the December 30, 2000 Snowstorm*. Silver Spring, Maryland: National Oceanic and Atmospheric Administration, National Centers for Environmental Prediction. Available online at *http://www.nws.noaa.gov/ost/eta.pdf*, accessed September 5, 2008.

Petty, K. R., and C. D. J. Floyd. 2004. A statistical review of aviation airframe icing accidents in the U. S. 11th Conference on Aviation Range and Aerospace Meteorology, American Meteorological Society, Hyannis, MA, October 4-8. 6 pp.

Pisano, P. 2007. Briefing to the NRC Committee on Mesoscale Observations for Multiple National Needs, January 3, 2007.

Raats, P. A. C. 2001. Developments in soil-water physics since the mid 1960s. *Geoderma* 100:355-387.

Rabier, F., H. Järvinen, E. Klinker, J.-F. Mahfouf, and A. Simmons, 2000: The ECMWF operational implementation of four-dimensional variational assimilation. I: Experimental results with simplified physics. *Quarterly Journal of the Royal Meteorological Society* 126:1143–1170.

Remer, L. A., Y. J. Kaufman, D. Tanré, S. Mattoo, D. A. Chu, J. V. Martins, R-R. Li, C. Ichoku, R. C. Levy, R. G. Kleidman, T. F. Eck, E. Vermote, and B. N. Holben. 2005. The MODIS aerosol algorithm, products and validation. *Journal of the Atmospheric Sciences* 62:947-973.

Saunders, S., C. Montgomery, T. Easley, and T. Spencer. 2008. The West's Changed Climate. Washington, DC: Natural Resources Defense Council. Available online at *http://www.nrdc.org/globalWarming/west/west.pdf*, accessed November 26, 2008.

Scheffe, R. 2007. Evolving interface between atmospheric characterizations and air quality assessments: Merging space, time, chemistry and environmental media—monitoring and assessment challenges. U.S. EPA, Office of Air Quality Planning and Standards. Meeting of the American Geophysical Union, San Francisco, CA, December 14, 2007.

Schlatter, T. W., D. Helms, D. Reynolds, and A. B. White. 2005. A phenomenological approach to the specification of observational requirements. A report to the Office of Science and Technology, National Weather Service, NOAA.

Schwartz, B. E., and S. C. Benjamin. 1995. A comparison of temperature and wind measurements from ACARS-equipped aircraft and rawinsondes. *Weather and Forecasting* 10:528-544.

Shafer, M. A., T. Hughes, and J. D. Carlson. 1993. The Oklahoma Mesonet: Site selection and layout. Pp. 231-236 in Preprints, 8th Symposium on Meteorological Observations and Instrumentation, American Meteorological Society, Anaheim, CA, January 17-22, 1993.

Solheim, F., J. R. Godwin, E. R. Westwater, Y. Han, S. J. Keihm, K. Marsh, and R. Ware. 1998. Radiometric profiling of temperature, water vapor and cloud liquid water using various inversion methods. *Radio Science* 33:393-404.

Straka, J. M., E. N. Rasmussen, and S. E. Fredrickson. 1996. A mobile mesonet for finescale meteorological observations. *Journal of Atmospheric and Oceanic Technology* 13:921-936.

Sun, J. Z., and N. A. Crook. 2001. Real-time low-level wind and temperature analysis using single WSR-88D data. *Weather and Forecasting* 16(1):117-132.

Turner, D. D., R. A. Ferrare, L. A. H. Brasseur, W. F. Feltz, and T. P. Tooman. 2002. Automated retrievals of water vapor and aerosol profiles from an operational raman lidar. *Journal of Atmospheric and Oceanic Technology* 19:37-50.

Veselovskii, I., A. Kolgotin, V. Griaznov, D. Müller, K. Franke, and D. N. Whiteman. 2004. Inversion of multiwavelength Raman lidar data for retrieval of bimodal aerosol size distribution. *Applied Optics* 43:1180-1195.

Wakimoto, R. M. 1985. Forecasting dry microburst activity over the High Plains. *Monthly Weather Review* 113:1131-1143.

Wakimoto, R. M., and J. W. Wilson. 1989. Non-supercell tornadoes. *Monthly Weather Review* 117:1113-1140.

Wang, C. -C., and J. C. Rogers. 2001. A composite study of explosive cyclogenesis in different sectors of the North Atlantic. Part I: Cyclone structure and evolution. *Monthly Weather Review* 129:1481-1499.

Ware, R. H., M. Exner, D. Feng, M. Gorbunov, K. Hardy, B. Herman, Y. Kuo, T. Meehan, W. Melbourne, C. Rocken, W. Schreiner, S. Sokolovskiy, F. Solheim, X. Zou, R. Anthes, S. Businger, and K. Trenberth. 1996. GPS sounding of the atmosphere from low earth orbit: preliminary results. *Bulletin of the American Meteorological Society* 77:19-40.

Ware, R.H., D. W. Fulker, S. A. Stein, D. N. Anderson, S. K. Avery, R. D. Clark, K. K. Droegemeier, J. P. Kuettner, J. B. Minster, and S. Sorooshian. 2000. SuomiNet: A real-time national GPS network for atmospheric research and education. *Bulletin of the American Meteorological Society* 81:677-694.

Warner, T., P. Benda, S. Swerdlin, J. Knievel, E. Argenta, B. Aronian, B. Balsley, J. Bowers, R. Carter, P. Clark, K. Clawson, J. Copeland, A. Crook, R. Frehlich, M. Jensen, Y. Liu, S. Mayor, Y. Meillier, B. Morley, R. Sharman, S. Spuler, D. Storwold, J. Sun, J. Weil, M. Xu, A. Yates, and Y. Zhang. 2007. The Pentagon Shield Field Program: Toward critical infrastructure protection. *Bulletin of the American Meteorological Society* 88:167-176. Available online at *http://www.rap.ucar.edu/staff/knievel/pubs/warner_et_al_bams_2007.pdf*, accessed September 8, 2008.

Weckwerth, T. M. 2000. The effect of small-scale moisture variability on thunderstorm initiation. *Monthly Weather Review* 128:4017-4030.

Weckwerth, T. M., D. B. Parsons, S. E. Koch, J. A. Moore, M. A. LeMone, B. B. Demoz, C. Flamant, B. Geerts, J. Wang, and W. F. Feltz. 2004. An overview of the International H2O project (IHOP 2002) and some preliminary highlights. *Bulletin of the American Meteorological Society* 85:253–277.

Weisman, M. L., and J. B. Klemp. 1984. The structure and classification of numerically simulated convective storms in directionally varying wind shears. *Monthly Weather Review* 112:2479-2498.

Weitkamp, C. 2005. *Lidar: Range Resolved Observation of the Atmosphere*. Berlin: Springer.

Welles, E., S. Sorooshian, G. Carter, and B. Olsen. 2007. Hydrologic verification: A call for action and collaboration. *Bulletin of the American Meteorological Society* 88:503-511. DOI: 10. 1175/BAMS-88-4-503.

Whiteman, D. N., B. B. Demoz, E. Joseph, D. Venable, R. M. Hoff, B. Bojkov, T. McGee, H. Voemel, L. Miloshevich, J. Ftizgibbon, F. J. Schmidlin, C. D. Barnet, and I. M. Restrepo. 2006. Water vapor validation experiment–satellite/sondes–overview and preliminary results. Proceedings of the American Geophysical Union Fall Meeting, San Francisco, CA, December 11-15, 2006.

Wilson, J. W., H. A. Crook, C. K. Mueller, J. Sun, and M. Dixon. 1998. Nowcasting thunderstorms: A status report. *Bulletin of the American Meteological Society* 79:2079-2099.

WMO. 2004. WMO/GAW Experts Workshop on a Global Surface-based Network for Long Term Observations of Column Aerosol Optical Properties, Davos, Switzerland, March 8-10, 2004. WMO TD No. 1287, Technical Report 162. Geneva: WMO.

WMO. 2006. *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites*, Tim R. Oke, ed., World Meteorological Organization, Instruments and Observing Methods Report No. 81 WMO/TD-No. 1250. Geneva: WMO.

Wu, W.-S., R.J. Purser and D.F. Parrish. 2002. Three-dimensional variational analysis with spatially inhomogeneous covariances. *Monthly Weather Review* 130:2905-2916.

Wurman, J. 2001. The DOW mobile multiple-Doppler network. Preprints, 30th International Conference on Radar Meteorology, American Meteorological Society, Munich, Germany.

Zbinden, R. M., J. -P. Cammas, V. Thouret, P. Nédélec, F. Karcher, and P. Simon. 2006. Mid-latitude tropospheric ozone columns from the MOZAIC program: Climatology and interannual variability. *Atmospheric Chemistry and Physics* 6:1053-1073. Available online at *http://www. atmos-chem-phys. net/6/1053/2006/acp-6-1053-2006.pdf*, accessed September 5, 2008.

Zink, M., D. Westbrook, S. Abdallah, B. Horling, V. Lakamraju, E. Lyons, V. Manfredi, J. Kurose, and K. Hondl. 2005. Meteorological command and control: an end-to-end architecture for a hazardous weather detection sensor network. Proceedings of the ACM Workshop on End-to-End, Sense-and-Respond Systems, Applications, and Services (EESR 05), Seattle, WA, June 2005.

Appendixes

Appendix A

A Rationale for Choosing the Spatial Density and Temporal Frequency of Observations for Various Atmospheric Phenomena

The question is perennial: "How many observations do I need, and how dense and how frequent?" The honest answer is "It depends upon the application." This appendix deals with a single but very important application: observational support of the national infrastructure for weather and climate monitoring and numerical weather prediction. Even for this single application area, the answer to the question depends upon the phenomenon: its size and longevity, which governs its predictability, and whether it has any embedded features that cause localized damage. Consideration of the phenomena is roughly in the order of size/longevity. The list is neither definitive nor exhaustive, but it does cover events that cause the greatest disruption, damage, and loss of life.

FLOODING FROM LARGE-SCALE STORMS

Definition: Steady soaking rains, sometimes with embedded showers and thunderstorms, cause flooding of small streams and larger rivers. Rain falling on melting snow exacerbates the flooding.

Size: Typically 300-2000 km across.

Duration: half a day to several days

Geographic preference: West Coast, Southern Plains, Lower Midwest, Appalachians. Rapid melting of a heavy snow cover, especially when accompanied by rainfall, sometimes causes floods in the northern United States, for example, the Red River flood at Grand Forks, North Dakota, in April 1997 or flooding from Ohio to New England during the January thaw of 1996. Floods can create health risks to humans and the local ecology due to the biological and chemical constituents in flood drainage that otherwise would not be present.

Because these storms are large, typically 1000 km in diameter, they are rather well observed over land. Those that cause flooding and landslides along the West Coast, as in January to February 2005, are almost always centered offshore. Occasionally, however, a long plume of moisture in southwesterly flow will cause soaking orographic rains along the California coastline without the presence of a well-defined cyclonic circulation. In either case, more in-situ observations are needed within a few hundred kilometers of the coast, especially of temperature, wind, and moisture below 600 mb, to supplement satellite observations. In-situ observations inside of cloud systems within a day or so of reaching the West Coast would also be very helpful.

Mesoscale features within the storm circulation often mark the difference between merely soaking rains (say, 0.20 inches per hour) and serious flooding (>0.50 inches per hour, prolonged). In many parts of the country, tropospheric wind observations, especially within cloudy areas, are too far apart to resolve these details. Moisture observations, especially below 600 mb, where most atmospheric moisture is concentrated, are sparse. For these mesoscale features, lower tropospheric soundings at $\Delta x=50$ km, $\Delta z=200$ m, and $\Delta t=3$ h resolution are appropriate. Δx refers to horizontal spacing, Δz to vertical spacing, and Δt to temporal frequency.

For longer forecasts than those considered here, the Winter Storm Reconnaissance Program in the North Pacific Ocean provides targeted aircraft observations. These benefit the entire country but especially the West.

NOR'EASTERS

Definition: A Nor'easter is a large cyclonic storm occurring from late fall through spring that moves northeastward along the U.S. Atlantic coast or a few hundred kilometers offshore. Sometimes intensifying rapidly, Nor'easters bring strong onshore winds, often from the northeast (hence the name), storm tides, flooding, and heavy precipitation. For practical purposes, a Nor'easter may be considered an Atlantic coastal storm accompanied by an onshore component of the wind of at least 40 mph for at least 12 hours.

Size: Typically 500-2000 km across.

Duration: 0.5-4 days

Geographical preference: Atlantic Coast, most often between Cape Hatteras, North Carolina, and Eastport, Maine. Several Nor'easters typically occur during each cold season.

These storms are mentioned separately because the principal form of damage is due to coastal flooding and beach erosion resulting from the storm surge. (It is acknowledged that some West Coast storms also cause beach and headland erosion.) Along the Atlantic Coast, the typical beach erosion rate is 1-3 ft per year, but a severe Nor'easter can erode the coast inland 100 ft in just 24 hours (FEMA, 2000, Fig. 1.1 and p. xxvii). That the coastline can accrete partway back within a decade or so is small consolation to homeowners in the path of the storm surge.

Of course, Nor'easters can also produce heavy rains, strong wind, and if the temperature is low enough, blizzards. For a thorough survey of Northeast snowstorms, including Nor'easters, see Kocin and Uccellini (2004). The most difficult to predict aspect of these storms is explosive deepening, which can reach 8-10 hPa per hour. Details in the sea-surface temperature in the vicinity of the Gulf Stream, strong latent heating in deep cloud systems, and the movement of potent upper air disturbances seem to govern the deepening (see, for example, Wang and Rogers, 2001 or Mailhot and Chouinard, 1989). Accurate sea-surface temperature within a day of deepening at $\Delta x \sim 10$-km, and 3-h sounding data at $\Delta x = 100$ km within 500 km of the storm center with $\Delta z = 0.3$ km up to 12 km would probably improve the prediction of these events.

SNOWSTORMS AND ICE STORMS

Definition: These storms include any storm depositing enough snow or ice to disrupt road or air travel, communications, or the electrical power supply. An ice storm occurs when liquid precipitation falls at surface temperatures below freezing.

Size: Snowstorms and ice storms cause problems in swaths typically 10 to 200 km wide and 50 to 1000 km long.

Duration: 2 hours to 2 days

Geographic preference: With the exception of mountainous areas, the greatest frequency of major snowstorms occurs east of the Rocky Mountains and north of about 35°N. Included here are snowstorms that deliver large liquid water equivalents but also "drier" storms associated with high winds and low temperatures. Also included are lake-effect snowstorms, the best known occurring downwind of the Great Lakes in fall and early winter, that bring crippling amounts of snow in narrow swaths. According to Changnon (2003), the greatest risk of damage and financial loss from ice storms exists in the Northeast U.S. followed by the lower Midwest and the Southern Great Plains.

Both snow and ice storms disrupt daily commerce and transportation, but ice storms commonly pose the additional hazard of power outages with all the collateral damage that implies, and damage to the power distribution infrastructure. The cost of major winter storms can be very high. In the March 1993 Superstorm, newspaper estimates of damage ranged from $1 billion to $6 billion and fatalities from 200 to 300. A National Climatic Data Center Report on the January 1996 blizzard and subsequent flood in the mid-Atlantic and northeast states cited insurance losses of nearly $1 billion and 187 fatalities.[1]

The key to good forecasts for most of these storms is accurate location of frontal zones in three dimensions and detailed knowledge of the wind, temperature, and moisture fields within the storm, particularly if these suggest the potential for embedded convection. Knowing the altitude of single or multiple freezing levels is critical. If this information is available, there is a much better chance of predicting precipitation type and amount, and the boundaries between snow, sleet, freezing rain, and rain. Forecast errors of just a few tens of kilometers in the position of these boundaries can have serious consequences, especially in heavily populated areas. See, for example, the report on an over-forecast of snow for the Washington, D.C., and Baltimore, Maryland metropolitan areas on December 30, 2000 (Petersen and McQueen, 2001).

Lake-effect snowstorms are a special case. Knowledge of lake surface temperature, the temperature profile up to 700 mb in the cold air mass advancing across the lake, and the fetch of the wind across the water (wind direction is crucial) is key for a good forecast.

Temperature, wind, and moisture soundings up to 500 mb are desirable within and surrounding the precipitation zone at $\Delta x=30$ km, $\Delta z=100$ m, and $\Delta t=2$ h.

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[1] See *http://www.ncdc.noaa.gov/oa/reports/billionz.html.*

LANDFALLING HURRICANES AND TROPICAL STORMS

Definition: Hurricanes are powerful cyclonic storms that pose multiple threats: high winds (74 mph or greater) causing structural damage, storm surge causing coastal flooding, and excessive rains causing inland flooding after landfall. Tropical storms (winds from 39-73 mph) are less powerful but still cause damage.

Size: Gale force winds (>39 mph) have been observed within diameters as small as 100 km and as large as 2000 km.

Duration: 1 day to more than a week

Geographic preference: On one of its webpages,[2] the Hurricane Research Division of NOAA's Atlantic Oceanographic and Meteorological Laboratory maps the probability that the center of a hurricane will approach to within 110 km of a given location within a single hurricane season. The probability appears to be a little less than 10 percent along most of the Gulf Coast and the Atlantic Coast north to Cape Hatteras, with the exception of southern Florida, where the maximum probability is about 16 percent. The probability is lower north of Cape Hatteras. Tropical storms are virtually unknown along the West Coast, though remnants sometimes move northward into the southwest United States from the Baja region.

Hurricane circulations are large, often 1000 km across, but the diameter of damaging winds is often less than 100 km. Hurricanes last from days to weeks over warm ocean water, but high winds invariably diminish rapidly after landfall. This report deals only with hurricanes and tropical storms close to landfall and with storms making the extratropical transition after landfall, because the hazards are greatest during this time.

Hurricane track forecasts have become ever more skillful, but rapid changes in intensity are still very difficult to anticipate. It is likely that changes in the underlying surface (sea-surface temperature and the depth of the 27°C isotherm, subtle changes in the hurricane's environment, reorganization of the internal structure, or a combination of these govern changes in intensity. Better observations can clarify which mechanisms are the most important. It is noteworthy that dropsondes that enter the hurricane core are not yet assimilated into operational forecast models.

Numerical prediction models often become less skillful during the extra-

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[2] See *http://www.aoml.noaa.gov/hrd/tcfaq/h_prob.gif*.

tropical transition, as the tropical cyclone encounters any combination of the following: frontal zones and increased vertical shear, upper-level trough, moisture gradients, gradients in sea-surface temperature, increased surface drag after landfall, increased Coriolis force as the center of circulation moves poleward, and complex topography. See the review paper by Jones et al. (2003) for more details.

Aberson (2003) documented substantial improvements in track forecasts out to several days when targeted dropsonde observations were made in regions where sensitivity of the forecast to initial conditions was high. The National Centers for Environmental Prediction determine the targeted area by means of the "breeding" method, which employs an ensemble of forecasts. The targeted area must be well sampled by the dropsondes. The use of additional observations taken *outside* the targeted area in the initial conditions did *not* lead to further improvements in the forecast.

The foregoing considerations suggest that further improvements in forecasts of track and of the extratropical transition will require targeted sounding data throughout the depth of the troposphere at roughly 100-150 km spacing and 6-h frequency. To uncover the mechanisms of tropical cyclone intensification and weakening, it may be necessary to sound the full depth of the hurricane core (nominal radius of 100 km from the eye) at resolutions of Δx=10 km, Δz=200 m, and Δt=3 h. The challenge will be to obtain measurements starting from above the cloud shield, which in intense hurricanes can reach to 100 hPa and above.

AIR POLLUTION

Definition: air pollution is the presence of gases or particles in the air, resulting mostly from human activity but sometimes occurring naturally (e.g., pollen), that cause health problems, directly (e.g., difficulty in breathing) or indirectly. As an example of an indirect effect, chemical compounds called chlorofluorocarbons were widely used as refrigerants, propellants in aerosol cans, and cleaning solvents. In gaseous form, these substances slowly diffused upward into the stratosphere, where, under conditions of very low temperature and sunlight, they participated in chemical reactions that depleted ozone, especially at high latitudes. Because ozone absorbs ultraviolet radiation from the sun, a reduction in stratospheric ozone allows more ultraviolet radiation to reach the Earth's surface, thus increasing the incidence of skin cancer—an indirect effect on human health caused by a manufactured gas.

Size: Pollution can be a problem within a single, heavily industrialized valley on scales of tens of kilometers, and it can be a regional problem on scales exceeding 1000 km, when the sources are widely distributed or the wind mixes the pollutants over a wide area.

Duration: hours to several days

Geographic preference: Large cities and heavily industrialized areas. Regional pollution is also a problem, especially in the Northeast Urban Corridor and in the southeast United States (mostly summer).

Atmospheric pollutants concentrate in stagnant air masses. Persistent inversions trap the pollutants close to the ground, where high concentrations pose a health problem. During the day, the pollutants reside in the mixed layer. The depth of this layer is critical: the shallower the mixed layer the greater the potential for high concentrations. At night, pollutants in the residual mixed layer are available for longer-range transport, and winds within this layer contribute strongly to regional pollution in the Northeast. Pollutants emitted at night are confined to the ground-based stable layer, but they interact with the aged pollutants when the boundary layer grows again the next day.

Taking inventory of pollution sources and measuring the concentration of each major pollutant are fundamental requirements. Measurements that relate to the dispersion of pollutants are equally important: high-resolution measurements ($\Delta x=5$ km, $\Delta z=50$ m, and $\Delta t=15$ min within cities) of wind and temperature are essential for gauging the depth of the mixed layer and tracking the drift of the pollution plume. Outside metropolitan areas, Δx could probably be relaxed to 20-30 km and Δt to 30 min, but this may not be sufficient near lakeshores or the seacoast, where the meteorology is complicated by land and sea breezes. These requirements pertain to the surface-based stable layer and the deeper mixed layer, where the pollutants reside.

The toll in human health from fine-particle air pollution (referred to as $PM_{2.5}$—particulate matter with a diameter 2.5 micrometers or less) is slowly being realized, and it is potentially staggering. "Hundreds of studies have suggested that breathing fine particles spewed by vehicles, factories, and power plants can trigger heart attacks and worsen respiratory disease in vulnerable people, leading to perhaps 60,000 premature deaths a year in the United States" (Kaiser, 2005, p. 1858). One of these studies (Cifuentes et al., 2001) argued that a reduction in greenhouse gas emissions would result in a corresponding reduction in particulate matter. If greenhouse gas mitigation technologies reduced particulate matter and low-level ozone concentrations by just 10 percent in four large cities (Mexico City, Sao

Paulo, Santiago, and New York City—combined population 45 million), the authors estimated that 64,000 premature deaths and 65,000 chronic bronchitis cases could be avoided from 2001 through 2020.

Improving the air quality by reducing emissions is one way to avoid the health costs of air pollution. Reducing exposure to existing pollutants is another, and that is possible through enhanced observations and improved forecasts of air quality.

FOG AND LOW CLOUDS

Definition: By the time cloud base descends to 500 ft or fog lowers surface visibility to 1 mile, restrictions on air traffic into and out of most airports have already been imposed. Conditions this bad or worse are the focus of discussion here.

Size: Highly variable, typically from tens to hundreds of kilometers.

Duration: most common from early to mid-morning, typically lasting from an hour to more than a day

Geographic preference: No part of the United States is immune from fog, but the most persistent fog occurs during the wintertime in basins (e.g., central valley of California, Salt Lake Valley). Fog and marine stratus are also common in coastal regions, where large population centers exist.

Limited surface visibility can be a significant hazard to all forms of transportation including automobile traffic, the trucking industry, rail traffic, and marine interests, and to aircraft landings and takeoffs. In the 1980s alone, there were more than 6000 highway deaths attributed to fog (source: U.S. Department of Transportation). In addition, low ceilings impede traffic flow into and out of major airports by curtailing side-by-side landings when parallel runways are within 2500 ft of each other. This is the case in San Francisco, where marine stratus can cut landings by 50 percent when ceilings are below 3000 ft. It is just as important to predict the onset of dense fog (visibility less than ¼ mile for surface-based operations and less than 1 mile for marine interests) as to predict the dissipation.

It is critical to know the height of the inversion layer and the strength of the inversion in order to predict dense fog or the height of a low cloud base. To predict dissipation, it is also important to know the thickness of the fog bank or lower cloud layer, and whether higher cloud layers are present.

Temperature and moisture measurements are required up to 2000 m above ground at $\Delta x=25$ km, $\Delta z=30$ m, and $\Delta t=15$ min to resolve mesoscale variations in inversion depth and strength especially in complex terrain. It is important to know cloud cover above 2000 m.

THUNDERSTORMS

The multiple hazards posed by thunderstorms are discussed separately below. Unlike phenomena discussed so far, thunderstorms have short lifetimes (almost always less than 6 h for a given cell and sometimes less than 30 min), they can merge into clusters, and their outflows can interact with each other or with terrain to spawn new thunderstorms. With high-resolution measurements, some classes of thunderstorms, those with strong dynamical forcing, can be accurately predicted. Thunderstorms resulting from gust-front interactions in the boundary layer, along stationary low-level convergence zones, or within horizontal convective rolls are much less predictable, even with good measurements. See, for example, Weckwerth (2000) or Wilson et al. (1998).

Lightning

Definition: Lightning is a transfer of electrical charge through often branching channels in the atmosphere that causes a bright flash of light. The primary concern is with cloud-to-ground lightning, which causes the most damage.

Size: The lightning stroke itself is a few centimeters in diameter and often kilometers long, but emphasis here is on the aggregate of strokes produced by a thunderstorm cell. Thus, the horizontal dimensions of interest are roughly from 1-20 km.

Duration: the duration of a single stroke is less than 0.1 millisecond, but the main threat from multiple strokes within a single thunderstorm typically lasts from a few minutes to nearly an hour

Geographic preference: Anywhere thunderstorms occur, but see map (Orville and Huffines, 2001) giving the number of cloud-to-ground strikes per square kilometer across the country 1989-1998. The greatest strike density is in the southeast quadrant of the United States.

Cloud-to-ground lightning is a clear threat to life and property, not to mention that it starts many forest fires. In fact, huge economic losses occur when “dry” lightning starts forest fires in the West and Alaska. In one 5-year period, 66,000 lightning-caused fires burned over 20 million acres.[3] Property damage from lightning is also significant. State Farm Insurance alone processes more than 300,000 lightning-related claims annually, amounting to loss reimbursements of over $300 million.[4]

A number of commercial lightning detection systems are available, but they give warning only after the first stroke has occurred. Avoiding the lightning hazard entirely depends upon an accurate prediction of thunderstorm development, and that, in turn, depends upon mesoscale observations of wind, temperature, and moisture, especially in the boundary layer.

For short-term prediction of thunderstorm initiation, observations of wind, temperature, and moisture are needed at $\Delta x \sim 2$ km, $\Delta z \sim 100$ m from the surface to the top of the boundary layer, and $\Delta t \sim 15$ min. The top of the boundary layer (also called the well-mixed layer) is itself defined by high-resolution temperature or refractivity measurements.

Flash Floods

Definition: A flash flood is a sudden rise in water, often in places where deep or rushing water is unexpected, caused by excessive rainfall. The flooding occurs within 6 hours of the causative rainfall.

Size: The area of excessive rainfall is often only a few kilometers wide, but the flood can propagate downstream for tens of kilometers.

Duration: 30 min to several hours

Geographical preference: Flash floods favor steep terrain, especially where the ground is relatively impermeable or the soil is already saturated. However, rainfall of several inches within an hour can cause flooding almost anywhere.

Some flash floods are caused when a thunderstorm becomes anchored to the terrain. Others occur when cells within a line of storms move parallel to the line itself, and this happens most often within a nearly stationary zone of low-level convergence. Still others occur in connection with "mesoscale convective systems," clusters of thunderstorms that form more often at

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[3] Derived from the Fire and Aviation Management Web Applications Database in Kansas City, Missouri, by Heath Hockenberry in Predictive Services, National Interagency Fire Center.

[4] See *http://www.lightningsafety.com/nlsi_lls/nlsi_annual_usa_losses.htm*.

night than during the day. Flash floods cause more deaths per year in the United States than any other convective storm phenomenon.[5]

One predictor of heavy rainfall is vertically Integrated Precipitable Water (IPW), but flooding rains often deliver more than the amount of IPW even within 1 hour. The flux of vapor into the thunderstorm and the rate of condensation within the updraft control the amount of precipitation, and this, in turn, depends upon atmospheric instability, the strength of the wind importing moisture laterally toward the storm, and the amount of water vapor it carries. Good predictions of excessive convective precipitation thus depend upon

- temperature and moisture profiles within an hour of storm formation and approximately within the same air mass as the storm forms (as a measure of the potential instability). Resolution: Δx=50 km, Δz=200 m at least up to 200 mb, Δt=60 min, and detailed terrain elevation measurements (easy to obtain down to 1-km resolution).

- wind and moisture measurements in the sub-cloud layer. Except in the case of elevated thunderstorms (seldom a cause of flash flooding), most of the air participating in the updraft is drawn from the sub-cloud layer. In flash-flood situations, the cloud base is usually lower than the climatological normal; in fact, it is often lower than 1500 m. A cloud base temperature of 10°C or higher is an indicator of high precipitation efficiency; the considerable depth of cloud below the freezing level aids the "warm rain" process (formation of many large drops by collision and coalescence) (Davis, 2001, p. 491). Nominal resolutions for wind and moisture measurements in the sub-cloud layer are: Δx=20 km, Δz=100 m, Δt=15 min. This requirement holds only in the inflow region of the storm, probably not beyond 100 km out.

A common element in many excessive rainfall events is the "low-level" jet, a ribbon of high-speed air 100-200 km wide and 1-2 km deep bringing moisture-laden air, most often from the Gulf of Mexico but sometimes from the Pacific or Atlantic Oceans, either into the storm genesis region or the storms themselves, once formed. A sub-class of the low-level jet is the "nocturnal jet," which forms at night over the gently sloping terrain of the southern and central Great Plains. The horizontal and vertical dimensions of the low-level jet demand measurements at Δx=30 km in the direction perpendicular to the jet but only 100 km along the jet. A Δz of 200 m up to 3 km and a Δt of 2 h is probably sufficient.

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[5] NOAA Natural Hazard Statistics, *http://www.nws.noaa.gov/om/hazstats.shtml.*

Hailstorms

Definition: Hail is a ball of ice that develops and is suspended within a thunderstorm updraft that contains both liquid and frozen particles at temperatures below freezing. A hailstorm is a fall of hail that causes damage or injury on the ground.

Size: Hailstorms typically range from 0.5 to 10.0 km in size.

Duration: hailstorms typically last from a couple of minutes to tens of minutes

Geographical preference: The greatest incidence of hail lies near the western edge of the Great Plains from Wyoming to New Mexico. Winter hail, invariably small, is also frequent along the Pacific Northwest Coast, but hail volume and hail size is a much better indicator of hail losses than hail frequency. Changnon (2001, p.70) maps the "loss cost" due to hail across the United States, which is the dollar amount of crop losses over a specified period divided by the dollar amount of insured liability, multiplied by $100. The maximum ($6-$9) stretches from southeast Montana southward through eastern Wyoming, eastern Colorado, and eastern New Mexico. A secondary maximum is in South Carolina, where tobacco is grown. Tobacco is very easily damaged, even by relatively small hail. Large hail causes property damage (in individual storms up to hundreds of millions of dollars) though very seldom loss of life. The greatest incidence of 2-inch hail is in the central Great Plains from South Dakota to Texas. The greatest risk of property damage from hail is in roughly the same area (Changnon, 1999).

Hail forms in thunderstorms whenever liquid and ice are present within a cloud volume at sub-freezing temperatures. Whenever an ice particle captures a cloud or rain droplet, the liquid freezes to the ice particle, making it larger. The updraft suspends the hail within the cloud while the hailstone grows. Since large hail falls faster than small hail, stronger updrafts are necessary for the generation of larger hail.

Radars are good at detecting hail within a storm, but there is little skill in predicting whether a given thunderstorm will produce large hail, even when conditions seem favorable. What combination of cloud physics and dynamics controls hail growth is still mostly a mystery (Knight and Knight, 2001), but it is clear that convective available potential energy, a measure of atmospheric instability that is correlated with maximum updraft speed, and vertical wind shear, which governs whether or not the precipitation shaft chokes the updraft, are important. Given this situation, the requirements given in the two bullets of the section on flash flooding seem appropriate. One exception to this is hail two inches or larger, almost always associated with supercell thunderstorms. For very large hail, the resolution criteria suggested for tornadoes (later in this appendix) are appropriate. The height of the minus 20°C isotherm and the level at which the wet bulb temperature is 0°C may be diagnosed from the sounding data. These parameters are related to the probability that hail will reach the ground before melting.

Straight-Line Damaging Winds

Definition: In this section, we restrict attention to two specific types of damaging straight-line winds that accompany thunderstorms: (1) those associated with a bow echo, an echo on a display of radar reflectivity that bulges out ahead of other echoes within a line of echoes and (2) a derecho, a thunderstorm producing a long path of damage caused by strong straight-line winds.

Size: The damage swath is usually just a few kilometers wide but ranges from a few to more than 100 km long.

Duration: a few minutes to more than an hour

Geographical preference: A 4-year climatology of cold-season bow echoes over the continental United States shows them confined to east of the Rocky Mountains and south of 45°N (Burke and Schultz, 2004). A longer climatology of derechos covering all seasons from 1986 to 2001 (Coniglio and Stensrud, 2004) shows a corridor of high frequency from the upper Mississippi River valley to Ohio in the warm season.

The bow echoes responsible for damaging winds most often form in an environment of strong low-level shear in association with a convective line. Not infrequently, counter-rotating vortices appear at either end of the bow, both helping to accelerate the air forward in the bow itself. Low-level instability tends to be moderate in cases strongly forced by atmospheric dynamics but high in weakly forced cases. An elevated rear-inflow jet of dry air is often present in lines that produce bow echoes. The hodograph associated with bow echoes (and squall lines more generally) is usually straighter (the shear is closer to unidirectional) than the hodograph associated with supercells.

These generalizations suggest what features to look for in the pre-thunderstorm environment, but trying to predict even an hour in advance which cells will develop bow echoes is largely fruitless. To understand the internal circulations that lead to bow echoes would require observations on the scale of $\Delta x=1$ km, $\Delta z=100$ m, and $\Delta t=5$ min.

Tornadoes

Definition: A tornado is a violently rotating column of air that makes a connection between a convective cloud and the ground. A funnel-shaped cloud usually (but not always) accompanies the tornado. Tornado strength is rated on a scale originally proposed by Tetsuya Fujita and named after him. An Enhanced Fujita (EF) scale was formulated by a team of meteorologists and wind engineers and introduced by the U.S. National Weather Service on February 1, 2007. The scale ranges from EF0 (causing minor damage) to EF5 (causing almost total destruction).

Size: Typically from tens of meters to more than a kilometer in diameter.

Duration: from less than a minute to more than an hour

Geographical preference: Concannon et al. (2000) present a U.S. map showing the mean number of days *per century* with at least one tornado, F2 intensity or greater, touching down in a grid box 80 km on a side. The maximum of 40 days exists just southeast of Oklahoma City, but the 25-day contour includes most of Oklahoma, the eastern two-thirds of Kansas, southeast Nebraska, southwest Iowa, northwest Missouri and west central Arkansas.[6] Few F2 or greater tornadoes occur west of the Rocky Mountains or east of the Appalachians.

Two classes of tornadoes are distinguished here: supercell and non-supercell.

Supercell thunderstorms have strongly rotating updrafts. The probability that a supercell thunderstorm will spawn a tornado is probably no more than 20 percent, and yet it is true that most strong or violent tornadoes (F2 or greater) originate in this way.

Weisman and Klemp (1984) defined a Bulk Richardson Number (a measure of atmospheric instability divided by a measure of vertical shear from the surface to 6 km) that distinguished rather well between thunderstorm types in a storm-scale model. This number is easily calculated from sounding data. Values between 15 and 45 favor supercell thunderstorms. Other good predictors of supercells are the wind shear in the lowest 6 km and the

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[6] The map is on the Web at *http://www.nssl.noaa.gov/users/brooks/public_html/concannon/*.

low-level helicity (higher values favor strong rotating updrafts). Tornadoes spawned by supercell thunderstorms descend earthward from the rotating updraft.

It is important to sample the pre-storm environment in which supercells form. Since the shear can change rapidly, within 2 or 3 hours, the sampling rate must be rather high. Suggested resolution: Δx=50 km, Δz=200 m up to 6 km, Δt=1 h. Though multiple storms may form in this environment, it is very difficult to say in advance which ones will acquire supercell characteristics. If a supercell forms and the shear in the lowest kilometer is high, tornadogenesis is more likely than when the shear is distributed over a deeper layer. Radar detection of mesocyclones (a signature for large rotating updrafts) within supercells is reliable within a range of 100 km or so.

Non-supercell tornadoes (Wakimoto and Wilson, 1989) are most common in environments that are not strongly sheared. The initial rotation is near the surface, concentrated by persistent low-level convergence. If a thunderstorm forms over the convergence zone, the low-level vorticity (a measure of spin or rotation in the wind flow) is drawn into the updraft and vertically stretched. The rotation intensifies. If a tornado forms, it develops from the ground up. Tornadoes formed in this way are called *landspouts* or *gustnadoes*. They are almost always weaker than their supercell counterparts, but, because they are not so strongly forced by atmospheric dynamics, they are much more difficult to predict.

Though Doppler radars can easily detect mesocyclones within supercell thunderstorms, they cannot often see the tornado vortex, unless it is at least several hundred meters wide and at close range. Non-supercell tornadoes, being generally smaller, are even more difficult to detect. To anticipate a non-supercell tornado, one would have to monitor the sub-cloud wind, temperature, and moisture field at Δx=500 m, Δz=100m, and Δt=5 min. One would also have to know whether a growing cell were positioned above the center of rotation.

WINDSTORMS WITHOUT PRECIPITATION

Downslope Windstorms

Definition: Downslope windstorms are usually localized in the lee of mountain barriers. Wind blowing across a mountain barrier causes waves to form in the flow, similar to water waves in a stream when it flows across a rock in the streambed. When the cross-mountain flow is strong and the mountains are high, strong surface winds can occur at the base of the wave, which goes by the name *mountain wave*. Occasionally a single windstorm will cause property damage in the millions of dollars, or it will cause even greater collateral damage by fanning the flames of a wildfire.

Size: Downslope windstorms are fairly localized, affecting areas from the edge of the foothills to 20 km downwind.

Duration: downslope windstorms typically last from one to several hours. Two or more episodes may occur within a single day

Geographical preference: Downslope windstorms frequent the east slopes of the Colorado Front Range from Fort Collins to Colorado Springs and the west slopes of the Wasatch Range near Salt Lake City, Utah. They also occur near Albuquerque, New Mexico. They are called *Santa Ana winds* in southern California, *Sundowner winds* near Santa Barbara, California, and *Taku winds* in southeast Alaska, especially Juneau.

Most downslope windstorms are caused by mountain wave activity and breaking gravity waves (similar to water waves breaking in the ocean) in the upper troposphere and lower stratosphere (Durran, 2003a,b). They are characterized by strong leeside winds at low levels near the base of the mountain wave and severe clear air turbulence over and near the mountains. Forecasters look for strong cross-mountain winds, a stable layer near mountain-top level, often near 600 hPa along the Front Range of the Rocky Mountains in Colorado, and a lack of strong shear in the mid- and upper troposphere. The strong surface winds typically last for a few hours at a time and can be extremely gusty.

Ground-based lidar measurements during downslope windstorms have demonstrated extreme local variability (Neiman et al., 1988). When and where the strong winds surface seems to be sensitive to terrain features on a scale of less than 1 km and small changes in atmospheric wind and temperature profiles. To diagnose conditions favorable for a downslope windstorm, tropospheric soundings at Δx=100 km, Δz=200m, and Δt=3 h are appropriate from the location of the mountains to 500 km upstream. To understand local variability within a windstorm, suitable resolutions are Δx=1 km, Δz=100 m, and Δt=15 min. Terrain data at Δx=0.5 km are probably necessary.

Pressure-Gradient Windstorms

Definition: Pressure-gradient windstorms arise around the periphery of low-pressure systems, when strong differences in pressure over short distances induce strong winds, without precipitation. Blowing dust has caused many fatal traffic accidents. Strong winds in connection with precipitation (e.g., blizzards, Nor'easters, hurricanes, or convective storms) are covered in other sections.

Size: Pressure-gradient windstorms affect larger areas than downslope windstorms, often hundreds of kilometers across.

Duration: pressure-gradient winds typically last from 2-12 hours

Pressure-gradient windstorms without precipitation are most frequent in winter and spring north of 40°N latitude, merely because low-pressure systems tend to be more energetic there than in the southern United States. The strong winds sometimes occur in the warm sector of an intense low-pressure system but also frequently on the west side of the low after cold-front passage. Prediction of the strong winds 24 h in advance is probably adequate. For this purpose, full-tropospheric temperature and wind soundings within the broad region including the low are necessary at resolutions of $\Delta x=100$ km, $\Delta z=0.5$ km, and $\Delta t=6$ h.

FIRE WEATHER

Definition: Fire weather refers to conditions that favor the rapid spread of brush or forest fires, whether a fire is in progress or not.

Size: The area of interest usually ranges from 10 to 100 km across.

Duration: typically a few hours to a few days

Geographical preference: Most common from the Rocky Mountains to the West Coast in forested areas during the dry season. Many fires are started by cloud-to-ground lightning in "dry" thunderstorms. Half the wildfires in the U.S. West are lightning-caused. In total there are about 10,000 such fires, costing the Bureau of Land Management approximately $100 million annually.[7] Many other wildfires are caused by human carelessness.

Lightning-caused wildfires have already been mentioned in the section on lightning. These fires play a role in the natural evolution of the forest. Whenever forest fires or brush fires threaten life or property, however, they must be brought under control.

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[7] See *http://www.lightningsafety.com/nlsi_lls/nlsi_annual_usa_losses.htm*.

Weather information is important for determining not only when the fire danger will be high but also how quickly a fire will spread and how dangerous conditions will be for the firefighting crews. Antecedent surface conditions (precipitation, temperature, wind, and humidity) signal how dry the fuel on the forest floor has become, but surface conditions alone are inadequate for determining how fast a fire will spread. For example, the lower-tropospheric lapse rate controls how easily stronger winds aloft can mix down to the surface. As another example, the presence or absence of clouds modulates the development of the daytime mixed layer.

The observing requirements when wildfires are in progress are similar to those for downslope windstorms (previous section), except that the atmospheric soundings probably do not need to go higher than 500 hPa. Looking at least 500 km upstream gives adequate forewarning of changes in wind direction or speed in the boundary layer. At the fire site, wind measurements are the most important, followed by relative humidity and temperature.

HAZARDS TO AIRCRAFT

Aside from thunderstorms, several meteorological phenomena pose specific hazardous to those who fly: icing, downbursts, and turbulence. Clear-air turbulence is potentially more dangerous than other kinds of turbulence, because there is no visual cue of its presence and sometimes no forewarning (e.g., from planes recently flying through the same airspace).

In-Cloud Icing

Definition: Ice accumulates on the airframe as the pilot flies through a cloud containing liquid water at temperatures below freezing.

Size: Supercooled clouds blanket areas from tens to hundreds of kilometers across.

Duration: typically from half an hour to half a day

Geographic preference: None. Any supercooled cloud can produce aircraft icing.

A supercooled cloud contains liquid water at temperatures below 0°C. An aircraft flying through such a cloud will accrete ice on the wings and other surfaces, sometimes faster than it can be shed, resulting in decreased lift. The larger the droplets in a supercooled cloud, the faster the ice accumulates. Larger drops can in fact roll off the de-icing boots and freeze on the wings, severely degrading performance and lift within just a few minutes of entering the supercooled cloud. Airframe icing has caused 583 accidents and more than 800 fatalities in the United States from 1982 through 2000 (Petty and Floyd, 2004). Less than one-quarter of these accidents resulted from airframe icing on the ground before takeoff.

Successful prediction of icing depends upon successful prediction of cloud location and in-cloud temperatures. Cloud top temperatures between –10° and 0°C usually provide the greatest potential for aircraft icing due to the lack of natural ice. (At lower temperatures, ice particles are more probable. These grow at the expense of supercooled droplets when both are present, and they collect the droplets through collisions, causing them to freeze. Thus ice particles act to deplete the supercooled water.)

Supercooled clouds whose tops are no colder than –10°C are common in post-frontal stratocumulus clouds. Models have moderate skill in predicting cloud cover and cloud altitude, marginal skill in predicting cloud properties, and little skill in predicting the location of individual clouds. In one way, the prediction of clouds is more difficult than the prediction of precipitation, because the spatial, temporal, and physical variability of clouds is greater. The specification of cloud fields as observed from the ground and remotely from satellites is an aid to progress, but more detailed measurements of wind and water vapor concentration would more directly address the need for accurate vapor fluxes, which in turn would lead to better predictions of vertical motion and clouds.

Prediction of the freezing level is much less a problem than the prediction of liquid water at sub-freezing temperatures.

The detection of icing requires observation of clouds positioned between the 0°C and minus 20°C isotherms at $\Delta x=5$ km, $\Delta z=100$ m, and $\Delta t=1$ h. Measurements of temperature and hydrometeor type are necessary in this layer. Infrared measurements from space and ceilometer measurements from the ground will not detect supercooled clouds unless the cloud base or cloud top lies within the critical temperature layer.

Downbursts

Definition: A downburst is a strong downrush of air from a convective cloud that strikes the ground. Also called a *microburst*.

Size: Typically from 100 to 2000 m across.

Duration: typically from 1 to 10 minutes

Geographic preference: Downbursts can accompany any convective storm. The most dangerous to aircraft are those with low reflectivity, little or no precipitation at the ground, and no lightning, because they offer few visual cues. Such "dry" downbursts occur most often in summer from early afternoon until early evening in the dry climates of the western Great Plains and the Intermountain West (Caracena et al., 1989).

Downbursts pose a serious risk to an aircraft on takeoff roll or one about to land. An aircraft first experiences the downburst as a sudden headwind. Once past its nearest approach to the center of the downburst, it experiences a sudden tailwind. The loss of lift can cause departing aircraft to roll off the end of the runway and landing aircraft to crash short of the runway.[8] Wet downbursts are associated with a descending core of heavy precipitation, perhaps mixed with unsaturated air from mid-levels. These downbursts look menacing, at least in the daytime, and are reliably detected by radar. They are not difficult to avoid.

Dry downbursts are more sinister. They are caused by the evaporation of droplets falling into a deep layer of fairly dry air below a high cloud base in the presence of a steep lapse rate (rapid decrease of temperature with height, about 1°C for each 100 m of altitude). If the droplets are numerous and small, but do not completely evaporate until reaching the ground, the downrushing air can accelerate enough to produce radial outflows exceeding 30 m s^{-1}. Sometimes the only visual cue is a circular ring of blowing dust at the ground.

Early afternoon soundings would aid in the prediction of downbursts. Moist air in mid-troposphere to support high-based thunderstorms and a steep lapse rate below cloud base are the hallmarks of downburst conditions (Wakimoto, 1985). Mid-tropospheric winds of 20 m s^{-1} or so will strengthen the downburst if momentum at this level is incorporated in the descending precipitation. A single sounding such as a rawinsonde would suffice in the vicinity of the airport.

Once convective showers form, monitoring from the surface to 400 hPa (within the convective cloud) becomes critical. Given that most downbursts last for only a few minutes and affect small areas (on the order of 10 km^2), the appropriate sampling resolution is Δx=1 km, Δz=200 m, and Δt=1 min.

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[8] See, for example, *http://www-das.uwyo.edu/~geerts/cwx/notes/chap08/microburst.html*.

Aircraft Turbulence

Definition: Frequent fliers invariably experience turbulence, differential air motions that shake the aircraft and its passengers.

Size: Turbulence that affects aircraft occurs on scales of tens to hundreds of meters.

Duration: Though individual bumps last about a second, the eddies in the air flow that cause the bumps probably last tens of seconds; some flights experience turbulence for many minutes at a time.

Geographic preference: None. Clear-air turbulence is most common in the vicinity of upper air fronts, which are associated with strong three-dimensional wind shears. Clear-air turbulence is also common, and may be severe, in mountain wave situations. Turbulence in convective clouds is taken for granted because of the up-and-down air motions, but pilots try to avoid thunderstorms.

Turbulence is the leading cause of non-fatal injury to flight attendants and passengers. Under the Federal Aviation Administration's (FAA's) Safer Skies Program, the Commercial Aviation Safety Team commissioned the Turbulence Joint Safety Analysis Team to study the increasing rate of air carrier turbulence incidents and accidents from 1987 to 2000. The average annual cost of the rare fatality and all non-fatal injuries combined for all airlines is approximately $26 million.

Because of the ephemeral nature of turbulence, its existence is almost always inferred and predicted from the larger-scale wind field. Aircraft experiencing turbulence routinely inform following aircraft about what to expect.

Measurements in clear and cloudy air on the scale of tens to hundreds of meters every few seconds are needed to detect aircraft turbulence. If this is ever to become a practical reality, it may have to be done from the aircraft itself. The prediction of aircraft turbulence will be based on parameterizations (approximations in computer models that account for physical processes too small to be captured on the grid of points where model computations occur) for many years to come. It has yet to be shown that observations of turbulence can lead to better predictions of turbulence in models.

Appendix B

Tables of Surface-Based Observing Systems

This Appendix includes two tables of surface-based observing systems. One attempts to summarize all networks in the United States that are potentially useful for mesoscale weather applications. The second table focuses on air-quality measurements. The first table catalogues surface-based meteorological observations in the United States. It comes from a presentation that was given to the Committee by Scot Loehrer and is based on a database that he developed at the University Corporation for Atmospheric Research/National Center for Atmospheric Research (UCAR/NCAR) over the last decade, with Global Energy and Water Cycle Experiment (GEWEX)/GEWEX Americas Prediction Project (GAPP) funding.[1] Some of the entries were updated from the National Science Foundation-sponsored database,[2] which is currently being developed to serve the dual purpose of providing users with information about available resources and identifying future observational needs in atmospheric research. The table is not completely up-to-date; the number of networks (500+ documented) is large, and they appear, disappear, and evolve continuously. Some of the entries have been updated based on reviewer comments or other websites. Other useful sources of information appear in the main text. The second table, which focuses on air quality instrumentation, comes from Scheffe (2007).

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[1] See *http://www.eol.ucar.edu/projects/hydrometnet*.

[2] See *http://www.eol.ucar.edu/fadb/*.

TABLE B.1 Inventory of U.S. surface-based observing networks

Network Type	Number of Sites	Operating Agencies	Collective or Archive Location	Remarks
Cooperative observing climate network	8000	NOAA	NCDC	Includes ~75 modernized sites in the northeast U.S.
Climate reference network	80	Federal agencies	NCDC	Placed to be representative of climate change
Aviation	~900 ASOS ~1000 AWOS ~15 AWSS	Mostly federal, some state.	Many at NCDC, some MADIS and MesoWest	ASOS, AWOS, and follow-on AWSS
Road transportation networks	2400 stations in 34 networks	Mostly state departments of transportation, some cities	MADIS MesoWest FHWA Clarus upcoming	RWIS. More states have observations, but they are not on the database. Meteorological data plus pavement temperature, etc. (Only meteorological data typically available.)
Railway networks	450 sites	Union Pacific Railroad	MADIS MesoWest	Primarily air temperature; winds and water level also of interest
Agriculture/evapotranspiration and mesonets	61 networks, ~1700 stations	State, local, universities, private sector (many TV stations), Bureau of Reclamation	Some MADIS, MesoWest	General monitoring of weather and agricultural conditions. Meteorological plus ET, radiation data at some sites. Includes Oklahoma Mesonet, which has 120 stations, plus 35 stations in two rural micronets and 40 stations in the new OKC mesonet (revised August 08)

continued

TABLE B.1 Continued

Network Type	Number of Sites	Operating Agencies	Collective or Archive Location	Remarks
Other weather networks	10,000 sites	Public, private, hybrids		Non-automatic METAR ~250 CWOP ~3000 sites WCforYou.com ~150 AnythingWx.com ~100 AWS ~6000
Military plus radiation monitoring	20 networks, 350 stations	Military agencies and national labs	Most MADIS, MesoWest	Weather, sometimes radiation
Coastal (meteorology plus water level, water quality tsunami, port transportation)	Great Lakes/Atlantic Coast: 20 networks, ~300 sites Gulf of Mexico: 13 networks, ~200 sites Pacific Coast (incl. Alaska, Hawaii): 14 networks, ~200 sites	NOAA, states, private	NOAA/NDBC makes QC's met data available real time	Divided into 11 regions. Most observations on or close to coast
Precipitation	12,000	NOAA COOP plus CoCoRaHS	NCDC COOP	
	5,000	NCEP	NCAR	
Precipitation, severe weather warnings	150	NWS, FAA, USAF	NCDC	Source: NOAA
Precipitation, severe weather warnings	150 estimated	TV stations		Estimated
Flood warning	350 meteorological stations 1250 stream gauges 3500 precipitation gauges	Local		Precipitation, streamflow, reservoir level, weather

TABLE B.1 Continued

Network Type	Number of Sites	Operating Agencies	Collective or Archive Location	Remarks
Snow	750 SNOTEL 175 avalanche/ski networks	USDA/NRCS, avalanche forecast centers, ski areas, etc.	MesoWest MADIS	Monitor snowpack for water supply, stability, skiing. Air temperature, snow water equivalent. Some also have meteorology, soil conditions
Real time (non real time) water resources	Stream gage 8500 (25000) Groundwater 1100 (5100) Water quality 1400 (5700)	USGS, USACE, USBR, other fed, state, local agencies.	USGS	Stream, reservoir, groundwater conditions
Fire weather	1700 RAWS sites (now 2200)	USFS, state forestry agencies	WRCC, MADIS, MesoWest	Meteorology plus fuel temperature and moisture
Air quality	>2000 from 50 networks	EPA, NPS, state and local, some NPS, Tribal agencies, private sector		Pollutants (CO_2, NO_2, SO_2, C_3. PM-2.5, PM-10, lead) and/or metals, organics, inorganics. Near sources or in populous regions. Highly variable. Few include all standard meteorological variables
Radiation	~100 total sites	Federal, universities		Solar energy resource, surface radiation budgets, UVB. Meteorology, direct and diffuse solar; some more detail.
Energy/CO_2 flux	ARM: 24 AmeriFlux: 80 OK Mesonet: 10	Federal, universities		Surface meteorology, latent and sensible heat flux, CO_2/water vapor flux, surface energy balance NOAA Tall Tower Network upcoming

continued

TABLE B.1 Continued

Network Type	Number of Sites	Operating Agencies	Collective or Archive Location	Remarks
Soil temperature/ moisture	ARM: 22 ISWS: 20 OK Mesonet: 115 SCAN: 122 AmeriFlux: 80	Federal, universities		Soil temperature, moisture ~ meteorology
Ecological networks	LTERS: 22	Federal agencies, universities	LTER	NEON upcoming
Radiosondes	NOAA: 80 Other: 11	NOAA, state and local	NOAA	Vertical profiles of temperature, water vapor, wind speed and direction
Profilers	CAP: 76(50 RASS) NPN 35 (11 RASS)	Public, Private, Hybrid	NOAA	Vertical profiles of wind speed and direction, some with virtual temperature (RASS) and spectrum width.
Aerosol column values/aero-sol profiles	AERONET: 48 MPLNet: 5 REALM(7) ARM (3), Shadowband Network	Variety of agencies	AERONET	Backscatter, aerosol optical depth
GPS-based networks	NOAA/GSD ground-based GPS-Met	~150 (estimated from map)	NOAA, USCG/ USACE, DOT, SuomiNet (UCAR/ COSMIC, universities, NSF funding)	Integrated Precipitable Water; from NOAA GPS-Met web site.

NOTE: Some entries were updated March 2008; additional entries noted under "remarks."
SOURCE: Scott Loehrer, April 4, 2007 presentation to the Committee. Work sponsored by GEWEX/GAPP and the National Science Foundation.

TABLE B.2 Major routine operational air quality monitoring networks (Some networks listed separately may also serve as subcomponents of other larger listed networks. As a result, some double counting of the number of individual monitors is likely.)

Network	Lead Federal Agency	Number of Sites	Initiated	Measurement Parameters	Location of Information and/or Data
NCore[1]	EPA	75	2008	O_3, NO/NO_2/NO_y, SO_2, CO, PM-2.5/PM-10-2.5[2], PM-2.5 speciation, NH_3, HNO_3, surface meteorology[3]	*http://www.epa.gov/ttn/amtic/monstratdoc.html*
SLAMS[1]	EPA	~3000	1978	O_3, NO_x/NO_2, SO_2, PM-2.5/PM-10, CO, Pb	*http://www.epa.gov/ttn/airs/airsaqs/aqsweb/aqswebhome.htm*
STN PM-2.5	EPA	300	1999	PM-2.5, PM-2.5 speciation, major ions, metals	*http://www.epa.gov/ttn/airs/airsaqs/aqsweb/aqswebhome.htm*
PAMS	EPA	75	1994	O_3, NO_x/NO_y, CO, Speciated VOCs, carbonyls, surface meteorology & upper air	*http://www.epa.gov/ttn/airs/airsaqs/aqsweb/aqswebhome.htm*
IMPROVE	NPS	110 plus 67 protocol sites	1988	PM-2.5/PM-10, major ions, metals, light extinction, scattering coefficient	*http://vista.cira.colostate.edu/improve/*
CASTNet	EPA	80plus	1987	O_3, SO_2, major ions, calculated dry deposition,wet deposition, total deposition for sulfur/nitrogen, surface meteorology	*http://www.epa.gov/castnet/*

continued

TABLE B.2 Continued

Network	Lead Federal Agency	Number of Sites	Initiated	Measurement Parameters	Location of Information and/or Data
GPMP	NPS	33	1987	O_3, NO_x/NO/ NO_2, SO_2, CO, surface meteorology, (plus enhanced monitoring of CO, NO, NO_x, NO_y, and SO_2 plus canister samples for VOC at three sites)	*http://www2.nature.nps.gov/air/Monitoring/network.cfm#data*
POMS	NPS	14	2002	O_3, surface meteorology, with CASTNet protocol filter pack (optional) sulfate, nitrate, ammonium, nitric acid, sulfur dioxide	*http://www2.nature.nps.gov/air/studies/portO3.cfm*
Passive Ozone Sampler Monitoring Program	NPS	43	1995	O_3 dose (weekly)	*http://www2.nature.nps.gov/air/Studies/Passives.cfm*
NADP/NTN	USGS	200plus	1978	Major ions from precipitation chemistry	*http://nadp.sws.uiuc.edu/*
NADP/MDN	None	90plus	1996	Mercury from precipitation chemistry	*http://nadp.sws.uiuc.edu/mdn/*
AIRMoN	NOAA	8	1984	Major ions from precipitation chemistry	*http://nadp.sws.uiuc.edu/AIRMoN/*

TABLE B.2 Continued

Network	Lead Federal Agency	Number of Sites	Initiated	Measurement Parameters	Location of Information and/or Data
IADN	EPA	20	1990	PAHs, PCBs, and organochlorine compounds are measured in air and precipitation samples	*http://www.epa.gov/glnpo/monit oring/air/*
NAPS	Canada	152plus	1969	SO_2, CO, O_3, NO, NO_2, NO_x, VOCs, SVOCs, PM-10, PM-2.5, TSP, metals	*http://www.etcentre.org/NAPS/*
CAPMoN	Canada	29	2002	O_3, NO, NO_2, NO_y, PAN, NH_3, PM-2.5, PM-10 and coarse fraction mass, PM-2.5 speciation, major ions for particles and trace gases, precipitation chemistry for major ions	*http://www.msc.ec.gc.ca/capmon/index_e.cfm*
Mexican Metropolitan Air Quality Network	Mexico	93		O_3, NO_x, CO, SO_2, PM-10, TSP	See CEC, 1997
NATTS	EPA	23	2005	VOCs, Carbonyls, PM-10 metals[4], Hg	*http://www.epa.gov/ttn/airs/airsaqs/aqsweb/aqswebhome.htm*
State/Local Air Toxics Monitoring	EPA	250plus	1987	VOCs, Carbonyls, PM10 metals, Hg	*http://www.epa.gov/ttn/airs/airsaqs/aqsweb/aqswebhome.htm*
NDAMN	EPA	34	1998 - 2005	CDDs, CDFs, dioxin-like PCBs	*http://cfpub2.epa.gov/ncea/cfm/recordisplay.cfm?deid=22423*

continued

TABLE B.2 Continued

Network	Lead Federal Agency	Number of Sites	Initiated	Measurement Parameters	Location of Information and/or Data
Tribal[5] Monitoring	EPA	120plus	1995	O_3, NO_x/NO_2, SO_2, PM-2.5/PM-10, CO, Pb	*http://www.epa.gov/ttn/airs/airsaqs/aqsweb/aqswebhome.htm*
HRM Network	None	9	1980	O_3, NO_x, PM-2.5/PM-10, CO, SO_2, Pb, VOCs, surface meteorology	*http://hrm.radian.com/houston/how/index.htm*
ARIES / SEARCH	None	8	1992	O_3, $NO/NO_2/NO_y$, SO_2, CO, PM-2.5/PM-10, PM-2.5 speciation, major ions, NH_3, HNO_3, scattering coefficient, surface meteorology	*http://www.atmosphericresearch.com/studies/SEARCH/index.html*
RadNet—formerly ERAMS	EPA	200plus	1973	Radionuclides and radiation	*http://www.epa.gov/enviro/html/erams/*
SASP	DHS	41	1963	89Sr, 90Sr, naturally occurring radionuclides, 7Be, 210Pb	*http://www.eml.doe.gov/databases/sasp/*
NEWNET	DOE	26	1993	Ionizing gamma radiation, surface meteorology	*http://newnet.lanl.gov/stations.asp*
CTBT	DOE	80	1996	Radionuclides and noble gases	*http://www.clw.org/archive/coalition/briefv3n14.htm*
UV Index EPA Sunwise Program	EPA	~50 U.S. cities	2002	Calculated UV radiation index	*http://www.epa.gov/sunwise/uvindex.html*
UV Net Ultraviolet Monitoring Program	EPA	21	2002	UV solar radiation (UVB and UV-Abands)	*http://www.epa.gov/uvnet/access.html*

TABLE B.2 Continued

Network	Lead Federal Agency	Number of Sites	Initiated	Measurement Parameters	Location of Information and/or Data
UVB Monitoring and Research Program	USDA	35	1992	UVB radiation	*http://uvb.nrel.colostate.edu/UVB/jsp/uvb_climate_network.jsp*
SURFRAD	NOAA	7	1993	Solar and infrared radiation, direct and diffuse solar	*http://www.srrb.noaa.gov/surfrad/index.html*
PRIMENet	NPS	14	1997	Ozone, wet and dry deposition, visibility, surface meteorology, and ultraviolet radiation	*http://www.forestry.umt.edu/research/MFCES/programs/primenet*
BioWatch	DHS	>30	2001	Pathogens into the air, providing warning to the government and public health community of a potential bioterror event	*http://www.fas.org/sgp/crs/terror/RL32152.html*

NOTES:

[1] NCore is a network proposed to replace NAMS as a component of SLAMS; NAMS are currently designated as national trends sites.

[2] PM-10-2.5–proposed new NAAQS

[3] Surface meteorology includes wind direction and speed, temperature, precipitation, relative humidity, and solar ration (PAMS only).

[4] PM-10 metals may include arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, and others.

[5] The number of sites indicated for tribal monitoring is actually the number of monitors rather than sites. The number of sites with multiple monitors is probably less than 80.

SOURCE: Scheffe, 2007.

Appendix C

Acronyms and Initialisms

ABL	atmospheric boundary layer
ACARS	Aircraft Communications Addressing and Reporting System
AERI	Atmospheric Emitted Radiance Interferometer
AERONET	Aerosol Robotic Network
AGL	above ground level
AIRMoN	Atmospheric Integrated Research Monitoring Network
AIRS	Atmospheric Infrared Sounder
AMDAR	Aircraft Meteorological Data Relay
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
ARIES	Aerosol Research Inhalation Epidemiology Study
ARM	Atmospheric Radiation Measurement
ASOS	Automated Surface Observing Systems
AVHRR	Advanced Very High Resolution Radiometer
AWIPS	Advanced Weather Information Processing System
AWOS	Automated Weather Observing System
AWSS	Automated Weather Sensing System
BASC	Board on Atmospheric Sciences and Climate
BLP	boundary layer profiler
CAA	Clean Air Act
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation

CAP	Cooperative Agency Profiler
CAPMoN	Canadian Air and Precipitation Monitoring Network
CARL	ARM/CART Raman Lidar
CART	Cloud and Radiation Testbed
CASA	Collaborative Adaptive Sensing of the Atmosphere
CASTNet	Clean Air Status and Trends Network
CEM	Corporation for Environmental Monitoring
CEOS	Committee of Earth Observing Satellites
CGMS	Coordination Group for Meteorological Satellites
CMIS	Conical image: Rain rate Scanning Microwave Imager/Sounder
CoCoRaHS	Community Collaborative Rain, Hail & Snow Network
CONUS	continental United States
COOP	Cooperative Observer Program
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CPB	Corporation for Public Broadcasting
CPR	Cloud Profiling Radar
CTBT	Comprehensive Nuclear Test Ban Treaty
CUAHSI	Consortium of Universities Allied for Hydrological Sciences, Inc.
CWOP	Citizen Weather Observer Program
DCAS	distributed-collaborative-adaptive sensing
DCP	data collection platform
DHS	Department of Homeland Security
DIAL	differential absorption
DoD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EARLINET	European Aerosol Research Lidar Network
EEZ	Exclusive Economic Zone
ENVISAT	Environmental Satellite
EPA	Environmental Protection Agency
ERAMS	Environmental Radiation Ambient Monitoring System
ESIP	Earth Science Information Partnership
ESRL	Earth System Research Laboratory
ESS	environmental sensor stations
EUCOS	EUMETNET Composite Observing System
EUMETNET	Network of European Meteorological Services

FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FRM	federal reference method

GALION	Global Aerosol Lidar Observation Network
GAPP	GEWEX Americas Prediction Project
GAW	Global Atmospheric Watch
GCOS	Global Climate Observing System
GEOSS	Global Earth Observing System of Systems
GEWEX	Global Energy and Water Cycle Experiment
GOES	Geostationary Observation Environmental Satellites
GOOS	Global Ocean Observing System
GOS	Global Observing System
GPMP	Gaseous Pollutant Monitoring Network
GPS	global positioning system
GPS Met	GPS Meteorology
GSD	Global Systems Division
GTOS	Global Terrestrial Observing System
GTS	Global Telecommunications System
GUAN	GCOS Upper Air Network

HIRS	High Resolution Infrared Radiation Sounder
HRM	Houston Regional Monitoring Network
HSRL	high spectral resolution lidar

IADN	Integrated Atmospheric Deposition Network
IASI	Infrared Atmospheric Sounding Interferometer
IEOS	Integrated Earth Observation System
IMPROVE	Interagency Monitoring of Protected Visual Environments
IOOS	Integrated Ocean Observing System
IPCC	Intergovernmental Panel on Climate Change
IPW	Integrated Precipitable Water
ISWS	Illinois State Water Survey
ITU	International Telecommunication Union

LDAS	land data assimilation system
LIDAR	light detection and ranging
LLWAS	Low Level Wind Shear Analysis System
LME	Large Marine Ecosystems
LTER	Long-Term Ecological Research Network
LTM	Long term monitoring

MADIS	Meteorological Assimilation Data Ingest System
MDCARS	Meteorological Data Collection and Reporting System
MDN	Mercury Deposition Network
METAR	Meteorological Aviation Report
MODIS	Moderate-resolution Imaging Spectroradiometer
MOZAIC	Measurements of Ozone, Water Vapor, Carbon Monoxide, and Nitrogen Oxides by In-Service Airbus Aircraft
MPL-NET	Micro-Pulse Lidar Network
MSL	above mean sea level
MWRP	Microwave Radiometer Profilers
NAAQS	National Ambient Air Quality Standards
NADP	National Atmospheric Deposition Program
NAMS	National Ambient Monitoring Stations
NAOS	North American Observing System
NAPS	National Air Pollution Surveillance Network
NASA	National Aeronautics and Space Administration
NATTS	National Air Toxics Trends Stations
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NCore	National Core Monitoring Network
NDAMN	National Dioxin Air Monitoring Network
NDBC	National Data Buoy Center
NEON	National Ecosystem Observing Network
NEWNET	Neighborhood Environmental Watch Network
NLDN	National Lightning Detection Network
NMHS	National Meteorological and Hydrological Services
NOAA	National Oceanic and Atmospheric Administration
NPN	National Profiler Network
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPR	National Public Radio
NPS	National Park Service
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NSF	National Science Foundation
NTN	National Trends Network
NWA	National Weather Association
NWP	Numerical Weather Prediction
NWS	National Weather Service
NWSMC	National Weather Service Modernization Committee

OCS	Oklahoma Climatological Survey
OLETS	Oklahoma Law Enforcement Telecommunication System
OMI	Ozone Monitoring Instrument
OSE	observing system experiment
OSSE	observing system simulation experiment
PAMS	Photochemical Assessment Measurement Station
PAR	photosynthetically active radiation
PARASOL	Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PBL	planetary boundary layer
PHOTONS	Photométrie pour le Traitement Opérationnel de Normalisation Satellitaire
PHS	Public Health and Safety
PM	particulate matter
PMc	coarse size fraction of particulate matter
PMOD	Physikalisch-Meteorologisches Observatorium Davos
PORTS	Physical Oceanographic Real-Time System
PRIMENet	Park Research & Intensive Monitoring of Ecosystems Network
RAOB	Universal Rawinsonde Observation program
RASS	Radio Acoustic Sounding System
RAWS	Remote Automated Weather Stations
RBSN	Regional Basic Synoptic Networks
RCOOS	Regional Coastal Ocean Observing System
REALM	Regional East Atmospheric Lidar Mesonet
RO	radio occultation
RRR	Rolling Requirements Review
RWIS	Roadway Information System
SASP	Surface Air Sampling Program
SCAN	Soil Climate Analysis Network
SEARCH	SouthEastern Aerosol Researchand Characterization Study experiment
SLAMS	State and Local Ambient Monitoring Stations
SMAP	Soil Moisture Active-Passive
SNOTEL	Snow Telemetry
SOA	Service Oriented Architecture
SSM/I	Special Sensor Microwave Imager
SST	sea-surface temperature
STN PM2.5	Speciation Trends Network
SURFRAD	Surface Radiation Budget Network

SV	Seeded Viral Model
TAMDAR	Tropospheric Aircraft Meteorological Data Relay
TDWR	Terminal Doppler Weather Radar
TES	Tropospheric Emission Spectrometer
TRMM	Tropical Rainfall Measuring Mission
UAS	Unmanned Aeronautical Systems
UCAR	University Corporation for Atmospheric Research
UHF	ultra-high frequency
UPS	United Parcel Service
USACE	U.S. Army Corps of Engineers
USAF	U.S. Air Force
USBR	U.S. Bureau of Reclamation
USCRN	U.S. Climate Reference Network
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGEO	U.S. Group on Earth Observations
USGS	U.S. Geological Survey
USWRP	U.S. Weather Research Program
UTC	Coordinated Universal Time
UVB	Ultraviolet B
VAD	Velocity-Azimuth Display
VHF	Very High Frequency
VII	Vehicle Infrastructure Initiative
WFO	Weather Forecast Office
WHYCOS	World Hydrological Cycle Observing System
WMO	World Meteorological Organization
WRCC	Western Regional Climate Center
WWW	World Weather Watch

Appendix D

Statement of Task

This committee is charged to develop an overarching vision for an integrated, flexible, adaptive, and multi-purpose mesoscale meteorological observation network and seek to identify specific steps to help develop a network that meets multiple national needs in a cost-effective manner. Starting from existing information, the ad hoc committee appointed to conduct the study will:

1. Characterize the current state of mesoscale atmospheric observations and purposes;
2. Compare the U.S. mesoscale atmospheric observing system to other observing system benchmarks;
3. Describe desirable attributes of an integrated national mesoscale observing system;
4. Identify steps to enhance and extend mesoscale meteorological observing capabilities so they meet multiple national needs; and
5. Recommend practical steps to transform and modernize current, limited mesoscale meteorological observing capabilities to better meet the needs of a broad range of users and improve cost effectiveness.

The study will focus primarily on mesoscale observational requirements over the United States and adjacent coastal zones, with emphasis on characterizing the planetary boundary layer (defined as extending from approximately 2 meters below the surface to 2-3 kilometers above), forecasting on time scales up to 48 hours, and the needs of urban areas. The study will provide a practical approach, stressing applications and how to design and implement an enhanced atmospheric observation system in a manner that the resulting information significantly improves users' decision-making. The study will address the roles to be played by federal, state, and local government and by commercial entities. In essence, the study will provide a framework and recommendations to engage the full range of weather-sensitive information providers and users in the development of an integrated, multi-purpose national mesoscale observation network.

Appendix E

Biographical Sketches of Committee Members and Staff

Richard E. Carbone (Chair) is a senior scientist and director of the Institute for Integrative and Multidisciplinary Earth Studies (TIIMES) at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. He has authored more than 100 scholarly works. A pioneer in meteorological radar, he has published on physical processes in clouds and storms, topographically-influenced circulations, predictability of warm season rainfall, and societal aspects of weather prediction. Mr. Carbone led the U.S. Weather Research Program and served as chairman of the World Meteorological Organization's World Weather Research Programme. He was elected fellow of the American Meteorological Society (AMS) in 1994. Among other honors, Mr. Carbone received the 2001 AMS Cleveland Abbe Award for distinguished service to atmospheric science by an individual and the 2003 NCAR Publication Prize. He has served on several National Research Council committees including the Committee on Weather Forecasting Accuracy for FAA Air Traffic Control and the Panel on the Global Energy and Water Cycle Experiment (GEWEX).

James Block is chief meteorologist at DTN/Meteorlogix and has over 25 years of experience in commercial meteorology. At DTN/Meteorlogix, he is responsible for all of the weather content used in all of the DTN companies' products and services. This includes weather forecasts and products used by over 150,000 businesses to make critical decisions. Mr. Block holds both a bachelor's degree and a master's degree in meteorology from the University of Wisconsin-Madison. Mr. Block has been a member of the American Meteorological Society (AMS) since 1976, and in 1989 he was named a Certified Consulting Meteorologist (CCM) by the AMS. He was also elected to the National Council of Industrial Meteorologists (an organization of CCMs) in 1990, elected to its board of directors in 2000, and served as its president in 2002. Mr. Block has also served on the board of the Commercial Weather Services Association, a weather industry trade group.

S. Edward Boselly is the founder and president of Weather Solutions Group, Inc., which provides consulting services to public and private entities to assist them in the reduction of the impact of weather on their operations and conducts research in and training for winter maintenance practices in highway agencies. He also served as the road weather program manager for the Washington State Department of Transportation from 2002 to 2005, integrating weather technologies into maintenance operations. Mr. Boselly has led numerous research projects and authored many publications related to road weather. From 1986 to 1993, he worked for the Matrix Management Group in Seattle, Washington, where he served as principal investigator on the National Academy of Sciences' Strategic Highway Research Program investigation into the use of weather information for winter highway maintenance activities. Mr. Boselly authored the American Association of State Highway and Transportation Officials Guide for Snow and Ice Control, and served as principal investigator (PI) on seven snow and ice control projects for state departments of transportation. He also served as PI on three Transportation Research Board projects, including the Strategic Highway Research Program project investigating road weather information systems. Mr. Boselly also served 23 years as a weather officer in the U.S. Air Force, retiring as a Lieutenant Colonel. Mr. Boselly is a member of the American Meteorological Society's Committee on Interactive Information and Processing Systems; the AMS Intelligent Transportation Systems (ITS) and Surface Transportation Committee; the ITS America's Weather Information Applications Special Interest Group; and the American Public Works Association. He has also served on the National Weather Association's corporate activities committee and as special advisor to the Council on Road Weather Initiatives. Mr. Boselly is considered among the founders of road weather management and is a frequent guest speaker on road weather related activities. He received his M.S. in meteorology from the University of Utah and B.S. degrees in both chemistry and atmospheric sciences from the University of Washington.

Gregory R. Carmichael, professor of chemical and biological engineering at the University of Iowa, is a leader in the development of emissions inventories for natural and pollutant substances and of chemical transport models at scales ranging from local to global. He has worked extensively on issues of long-range transport of acidic and photochemical pollutants from Asia, and on the impact of Asian development on the environment. He is an active instructor and advisor, having supervised 29 M.S. and 24 Ph.D. students. Dr. Carmichael received his Ph.D. in chemical engineering from the University of Kentucky in 1979. He has served as department chair and is co-director of the Center for Global and Regional Environmental Research. He is presently chair of the Scientific Advisory Committee of the World Meteorological Organization Urban Environment Research Program and serves on the steering committee of the Commission on Atmospheric Chemistry and Global Pollution. He has been a member and chair of the American Meteorological Society's Committee on Atmospheric Chemistry and on numerous other committees and boards. Dr. Carmichael has over 220 refereed journal publications and serves on a number of editorial boards.

Frederick H. Carr is the Mark and Kandi McCasland Professor of Meteorology and the director of the School of Meteorology at the University of Oklahoma. He received his Ph.D. in meteorology from Florida State University, followed by a postdoctoral appointment at State University of New York-Albany. His research interests include synoptic, tropical, and mesoscale meteorology, numerical weather prediction and data assimilation, and the use of new observing systems in diagnostic and numerical weather prediction studies. Dr. Carr has held visiting scientist positions at the National Centers for Environmental Prediction, the National Center for Atmospheric Research, and National Oceanic and Atmospheric Administration's (NOAA's) Forecast Systems Laboratory. He is the associate director of the Center for the Analysis and Prediction of Storms at the University of Oklahoma and is also an associate director of Collaborative Adaptive Sensing of the Atmosphere, a National Science Foundation (NSF) Engineering Research Center. Carr is a fellow of the American Meteorological Society (AMS) and has served as chair of the AMS Board on Higher Education, a member of the AMS Council, and a member of the AMS Educational Advisory Committee, and he has also served as an editor of *Monthly Weather Review*. Dr. Carr was chair of the first COMET Advisory Panel and was named one of the 10 "Founders of COMET." In addition, he has served on the NSF Committee of Visitors to evaluate ATM, the University Corporation for Atmospheric Research Nominating Committee (as chair), the North American Observing Systems committee, and NOAA External Review Panels of the Forecast Systems Laboratory and the Mesoscale Development Laboratory, and was co-organizer of the U.S. Weather Research Program Workshops on Data Assimilation and Mesoscale Observing Systems.

V. (Chandra) Chandrasekar is currently a professor at Colorado State University (CSU). Dr. Chandrasekar has been involved with research and development of weather radar systems for over 20 years and has approximately 25 years of experience in radar systems. He has played a key role in developing the CSU-CHILL National Radar facility as one of the most advanced meteorological radar systems available for research, and continues to work actively with the CSU-CHILL radar by supporting its research and education mission and by serving as co-principal investigator of the facility. In addition he also serves as the associate director of the newly established National science Foundation Engineering Research Center, Center for Collaborative Adaptive Sensing of the Atmosphere. Dr. Chandrasekar's current research funding includes National Aeronautics and Space Administration (NASA) support for precipitation research. He is an avid experimentalist, conducting special experiments to collect in-situ observations to verify the new techniques and technologies. Dr. Chandrasekar is co-author of two textbooks, *Polarimetric and Doppler Weather Radar* and *Probability and Random Processes*. He has authored more than 85 journal articles and 150 conference publications and has served as academic advisor for more than 40 graduate students. His past National Research Council committee service includes the Committee on Weather Radar Technology beyond NEXRAD and the Committee on the Future of Rainfall Measuring Missions. He is the general chair for the 2006 Institute of Electrical and Electronics Engineers (IEEE) International Geoscience and Remote Sensing Symposium, and he has served on numerous review panels for various government agencies. He has received numerous awards including the NASA technical achievement award, and the ABELL Foundation Outstanding Researcher Award. He was elected a fellow of IEEE (Geo-Science and Remote Sensing) in recognition of his contributions to Quantitative Remote Sensing.

Eve Gruntfest is a professor of geography and environmental studies at the University of Colorado at Colorado Springs. She has been working in the field of natural hazard mitigation for 30 years. She has published widely and is an internationally recognized expert in the specialty areas of warning system development and flash flooding. She recently completed a year sabbatical, during which she worked at National Center for Atmospheric Research (NCAR) workshops for physical and social scientists dedicated to culture change within meteorology to actively incorporate social impacts into weather forecasting. The effort is called WAS*IS (Weather and Society Integrated Studies). As of November 2006 there are 85 WAS*ISers. She has spoken to many professional organizations in the United States, including the Association of State Floodplain Managers, the National Weather Service, the Hydrologic Engineering Center of the U.S. Army Corps of Engineers, COMET at NCAR, and the Forecast Systems Laboratory of the

National Oceanic and Atmospheric Administration. She has participated in numerous workshops, sharing lessons from research on warning systems and flash flooding. Dr. Gruntfest received her B.A. in geography from Clark University and her M.A. and Ph.D. in geography from the University of Colorado, Boulder.

Raymond M. Hoff is a professor of physics at the University of Maryland, Baltimore County. He is also director of the Joint Center for Earth Systems Technology. Dr. Hoff has 31 years of experience in atmospheric research. His research interests are in the optical properties of aerosols and gases in the atmosphere and the pathways and fates of toxic organic and elemental chemicals in the environment. Dr. Hoff has been central in formulating major research programs on differential absorption, airborne and space-borne lidar, volcanic emissions, atmospheric transport of toxic chemicals to the Great Lakes, atmospheric visibility, Arctic haze, and dispersion of pollutants. He has led or participated in more than 20 major field experiments. He is the author of 83 journal articles and book chapters, 94 other refereed works, and numerous public presentations of his work. Dr. Hoff obtained a B.A. in physics at the University of California, Berkeley in 1970 and a Ph.D. in physics from Simon Fraser University in 1975. He has had committee and peer review roles at the National Aeronautics and Space Administration (NASA), the Environmental Protection Agency (EPA), Environment Canada, and the European Economic Community. He has held memberships in six scientific societies and served as chairman of committees for those societies.

Witold F. Krajewski is the Rose and Joseph Summers Chair in Water Resources Engineering and professor of civil and environmental engineering at the University of Iowa. He was a research hydrologist at the Office of Hydrology of the National Weather Service until 1987 when he joined the University of Iowa. Dr. Krajewski's special fields of knowledge include hydrology and hydrometeorology, water resources systems, radar and satellite remote sensing, uncertainty modeling, and systems analysis. His present research interests include remote sensing of hydrologic processes, radar and satellite estimation of rainfall, statistical error structure of rainfall observations, real-time hydrometeorological forecasting, and uncertainty analysis in hydrology. Dr. Krajewski is a member of the Science Team of the Global Precipitation Measurement satellite mission, serves on the board of directors of Hydrologic Research Center, and is the University of Iowa representative to the Consortium of Universities for the Advancement of Hydrologic Science. He is fellow of the American Meteorological Society and the American Geophysical Union. He has served on numerous committees and panels of various professional organizations, and editorial boards of several journals. Currently he is an editor of *Advances in Water Resources*. He received his Ph.D. in water resources systems and his M.S. in environmental engineering from the Warsaw University of Technology.

Margaret A. LeMone (NAE) is a senior scientist at the National Center for Atmospheric Research (NCAR). She has two primary scientific interests: the structure and dynamics of the atmosphere's planetary boundary layer and its interaction with the underlying surface and clouds overhead, and the interaction of mesoscale convective with the boundary layer and surface underneath and with the surrounding atmosphere. Dr. LeMone is a fellow of the American Association for the Advancement of Science and the American Meteorological Society. She is also a member of the National Academy of Engineering (NAE), and the Board on Atmospheric Sciences and Climate (BASC). She has served on the National Research Council's Panel on Improving the Effectiveness of U.S. Climate Modeling, the Committee on Weather Research for Surface Transportation, and the Special Fields and Interdisciplinary Engineering Peer Committee of the NAE. She currently serves on the Committee on Challenges Strategic Guidance for NSF's Support of Research in the Atmospheric Sciences. Dr. LeMone received her Ph.D. in atmospheric sciences from the University of Washington.

James F.W. Purdom is a senior research scientist at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. Before joining CIRA, Dr. Purdom spent four years as Director of NOAA/NESDIS's Office of Research and Applications. His research focuses on remote sensing of the earth and its environment from space, as well as the development and evolution of atmospheric convection, with an emphasis on the study of mesoscale processes using satellite data. He received the Department of Commerce Silver Medal in 1994, the National Weather Association Special Award in 1996, and the American Meteorological Society Special Award in 1997. Purdom currently chairs the World Meteorological Organization's Commission on Basic Systems Open Program Area Group on Global Observing Systems.

Thomas W. Schlatter is an associate scientist with the Cooperative Institute for Research in the Environmental Sciences (CIRES), a cooperative institute between National Oceanic and Atmospheric Administration (NOAA) and the University of Colorado. Retired from government service, he now works part time at NOAA's Earth System Research Laboratory. He has been active for most of his career in the evaluation (including quality control) and use of many kinds of atmospheric observational data: surface- and space-based, in-situ and remotely sensed. His early work was in data assimilation methods for global forecasting, but in recent years he has concentrated on data assimilation and prediction for mesoscale applications. Dr. Schlatter spent most of his career with NOAA, working on mesoscale data assimilation and prediction, mostly in the context of the Rapid Update Cycle, an operational system that generates hourly analyses of surface and tropospheric conditions and short-range predictions. He has been heavily involved in the NOAA Profiler Network and in planning for North American upper air observing systems. He held several posts in the former Forecast Systems Laboratory: branch chief, division chief, and acting director for 6 months in 2004. He has written the "Weather Queries" column for *Weatherwise* magazine since 1980. He received his B.S., M.S., and Ph.D. degrees in meteorology from St. Louis University.

Eugene S. Takle joined the Iowa State University faculty in 1971 and currently serves as professor of atmospheric science in the Department of Geological and Atmospheric Sciences, professor of agricultural meteorology in the Department of Agronomy, and holds an affiliate appointment in the Department of Aerospace Engineering. He has a B.A. in physics and math from Luther College and a Ph.D. from the Iowa State University Department of Physics. He is co-director of the Regional Climate Modeling Laboratory at Iowa State University that currently is centrally involved in developing future scenarios of regional climate change and impacts for the United States. He is primary or co-investigator on contracts with the National Science Foundation, the U.S. Department of Agriculture, the National Aeronautics and Space Administration (NASA), and the U.S. Department of Energy totaling more than $3.7 million. His service on national and international boards and committees includes atmospheric science editor of *Earth Science Reviews*, associate editor of Journal of *Applied Meteorology and Climatology*, and chair of the Transferability Working Group of the Hydrometeorology Panel of the World Climate Research Programme. He has more than 200 publications and research presentations on topics such as climate change, turbulent flow through agricultural shelterbelts, and roadway weather. Although the primary focus of these research reports is numerical modeling and analysis of mesoscale and microscale flow, he also has been engaged in boundary-layer field experiments studying flow characteristics in the vicinity of shelterbelts and the role of atmospheric processes in "pressure pumping" of trace gases in soils. The Iowa Environmental Mesonet was initially established in 2001 under a grant from USDA with Professor Takle as co-principal investigator. His online course titled Global Change was introduced in 1995 as Iowa State's first and longest running internet-based course. Since January of 2006 he also serves as Faculty Director of the University Honors Program.

Jay Titlow is a senior meteorologist with WeatherFlow Inc. He has a B.S. in meteorology from North Carolina State University and an M.S. in geography from the University of Delaware. Mr. Titlow's meteorological and oceanographic professional experience encompasses positions at the College of Marine Studies at the University of Delaware, Louisiana State University, and two National Aeronautics and Space Administration (NASA) facilities (Goddard Space Flight Center and Langley Research Center). For the past 10 years, he helped build WeatherFlow from a small regional sailing weather service to a national business offering commercial marine meteorological products with over 60,000 customers nationwide. The cornerstone of this successful business model is WeatherFlow's national coastal mesonet. This expanding network now numbers over 300 sites on both U.S. coasts, the Gulf of Mexico, Hawaii, plus sites in Mexico and Canada. The increasingly diversified group of users includes an operational feed of WeatherFlow national mesonet to the Defense Threat Reduction Agency (DTRA) for use in hazardous plume modeling. Mr. Titlow's position responsibilities at WeatherFlow include mesonet engineering (siting, installation, data quality control, and maintenance), leading product development, and special projects. One sample project included a leadership role in the DTRA-sponsored The Sea Port of Debarkation (SPOD) Vulnerability and Ship Protection in the Littoral Region Weather Model Experiment that occurred during the summer of 2001. Among the numerous tasks associated with this project included leading the installation of the regional mesonet used for the experiment. More recently, Mr. Titlow has been leading a project with the City of Boston Police Department involving installation of 20 mesoscale monitoring sites within the metro area to aid in improving hazardous plume tracking.

NRC Staff

Curtis H. Marshall is a senior program officer with the Board on Atmospheric Sciences and Climate (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 in the National Oceanic and Atmospheric Administration. Since joining the staff of BASC, he has 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.

Rob Greenway is a senior program assistant at the National Academies Board on Atmospheric Sciences and Climate. He has worked on National Research Council studies that produced the reports *Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission: A Perspective from the Research and Operations Communities*, *Review of NOAA's Plan for the Scientific Stewardship Program*, *Where the Weather Meets the Road: A Research Agenda for Improving Road Weather Services*, and *Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts*, among others. He received his A.B. in English and his M.Ed. in English education from the University of Georgia.