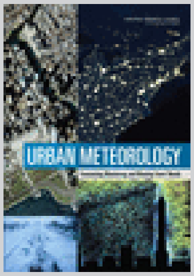


Urban Meteorology: Forecasting, Monitoring, and Meeting Users' Needs

ISBN
978-0-309-25217-1

190 pages
7 x 10
PAPERBACK (2012)

Committee on Urban Meteorology: Scoping the Problem, Defining the Needs; Board on Atmospheric Sciences and Climate; Division on Earth and Life Sciences; National Research Council

URBAN METEOROLOGY

Forecasting, Monitoring, and Meeting Users' Needs

Committee on Urban Meteorology:
Scoping the Problem, Defining the Needs

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS • 500 Fifth Street, NW • Washington, DC 20001

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

Support for this study was provided by the National Aeronautics and Space Administration under contract number NNX08AB07G, the National Oceanic and Atmospheric Administration under contract number NA11OAR4600211, and the National Science Foundation under contract number ATM-0809051. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-25217-1
International Standard Book Number-10: 0-309-25217-2

Additional copies of this report are available for sale from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON URBAN METEOROLOGY: SCOPING THE PROBLEM, DEFINING THE NEEDS

JOHN T. SNOW (*Co-Chair*), University of Oklahoma, Norman, Oklahoma
XUBIN ZENG (*Co-Chair*), University of Arizona, Tucson, Arizona
PETRA KLEIN, University of Oklahoma, Norman, Oklahoma
STEFANIE EBELT SARNAT, Emory University, Atlanta, Georgia
J. MARSHALL SHEPHERD, University of Georgia, Athens, Georgia
ELLIS M. STANLEY, Dewberry, Los Angeles, California

NRC Staff

KATIE THOMAS, Associate Program Officer
ELIZABETH FINKELMAN, Senior Program Assistant

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

ANTONIO J. BUSALACCHI, JR. (*Chair*), University of Maryland, College Park
GERALD A. MEEHL (*Vice Chair*), National Center for Atmospheric Research
RICHARD CARBONE, National Center for Atmospheric Research
KIRSTIN DOW, University of South Carolina
GREG S. FORBES, The Weather Channel, Inc.
LISA GODDARD, Columbia University
ISAAC HELD, National Oceanic and Atmospheric Administration
ANTHONY JANETOS, Pacific Northwest National Laboratory; University of Maryland
HAROON S. KHESHGI, ExxonMobil Research and Engineering Company
MICHAEL D. KING, University of Colorado
JOHN E. KUTZBACH, University of Wisconsin-Madison
ARTHUR LEE, Chevron
ROGER B. LUKAS, University of Hawaii
SUMANT NIGAM, Earth System Science Interdisciplinary Center
RAYMOND T. PIERREHUMBERT, The University of Chicago
KIMBERLY PRATHER, University of California, San Diego
RICH RICHELS, Electric Power Research Institute, Inc.
DAVID A. ROBINSON, Rutgers, The State University of New Jersey
KIRK R. SMITH, University of California, Berkeley
JOHN T. SNOW, The University of Oklahoma
CLAUDIA TEBALDI, Climate Central
XUBIN ZENG, University of Arizona

NRC Staff

CHRIS ELFRING, Director
EDWARD DUNLEA, Senior Program Officer
LAURIE GELLER, Senior Program Officer
MAGGIE WALSER, Program Officer
KATIE THOMAS, Associate Program Officer
DANIEL MUTH, Postdoctoral Fellow
ALEX JAHN, Christine Mirzayan Fellow
RITA GASKINS, Administrative Coordinator

LAUREN BROWN, Research Associate
ROB GREENWAY, Program Associate
SHELLY FREELAND, Senior Program Assistant
AMANDA PURCELL, Senior Program Assistant
RICARDO PAYNE, Senior Program Assistant
ELIZABETH FINKELMAN, Senior Program Assistant
GRAIG MANSFIELD, Financial Associate

Preface

Every two or three years, the Board on Atmospheric Sciences and Climate (BASC) works with its core agency sponsors to select a topic for a special "summer study." The purpose of these summer studies is to provide an opportunity for scientists, the private sector, and agencies to explore current issues in an interactive format. Sometimes these studies address practical problems, such as communicating uncertainties in weather forecasts (NRC, 2003a), developing effective response strategies through a better understanding of the impact of simultaneously occurring environmental changes (NRC, 2007a), or identifying pressing high level, weather-focused research challenges and research to operations needs (NRC, 2010a). Other times they address specialized technical issues, such as improving the physical parameterizations in coupled atmosphere-ocean-land models (NRC, 2005). Summer studies are all designed around a small workshop where participants gather to have candid discussions on a topic identified by the Board and its core sponsors as timely, important, and not likely to be requested by any one agency. We use the opportunity to bring communities together for forward-looking conversation.

The 2011 BASC summer study focused on current and emerging forecasting and monitoring technologies for the urban environment, and sought input and feedback from diverse communities of scholars, technology providers, and users of such information. A planning committee, constituted by BASC and the National Research Council (NRC), developed the workshop agenda, selected participants who contributed presentations and took part in plenary and small group discussions, and synthesized the discussions into this report.

The workshop was held July 27-28, 2011 at the J. Erik Jonsson Center of the National Academy of Sciences in Woods Hole, MA. More than 40 experts from academia, federal and local government, national laboratories, private sector, and the stakeholder end user community participated in the two-day workshop. The format was a mix of keynote presentations, panel discussions, and working groups. Appendix C provides the workshop agenda, participant list, and working group discussion questions. Appendix A contains abstracts from the three keynote speakers. The workshop provided much of the information for this report. To build upon the information-gathering workshop, the committee held one in-person meeting, several teleconferences, and conducted literature reviews to elaborate on the workshop questions. This report is peer reviewed and contains conclusions, but not recommendations, and is primarily addressed to the sponsoring agencies[1] and users of urban meteorology information.

The committee extends its thanks to the many individuals whose contributions have made possible this report on the emerging field of urban meteorology. These include the many invited experts listed in Appendix C who took the time to travel to Woods Hole and actively participate during the plenary sessions and working groups at the workshop. The committee particularly thanks the three keynote speakers, Sue Grimmond, Walter Dabberdt, and Brian Stone, for their invited workshop presentations and their extended abstracts in Appendix A. The committee extends its special appreciation to Fred Carr, Jerry Brotzge, and Brenda Philips for providing the material on "The Dallas-Fort Worth Urban Testbed" in Appendix B.

The committee could also not have achieved its objectives without the support of the BASC staff. Our sincere thanks are extended to Ms. Katie Thomas, Associate Program Officer; Ms. Elizabeth Finkelman, Program Assistant; Chris Elfring, BASC Director; and Rita Gaskins, Administrative Coordinator.

Finally, the co-chairs applaud and thank the committee members who volunteered countless hours planning the workshop and subsequently writing this report.

For the committee, this has been a unique journey in learning some of the diverse needs of end users of urban weather information. What we have learned will motivate us to work to further advance the science and technology of this important emerging field.

John Snow, *Co-Chair*
Xubin Zeng, *Co-Chair*
Committee on Urban Meteorology:
Scoping the Problem, Defining the Needs

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

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 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:

Jeffrey Basara, University of Oklahoma
Michael Batty, University College London
Julie DeMuth, National Center for Atmospheric Research
Teddy Holt, Naval Research Laboratory
Pete Manousos, FirstEnergy Corporation
Thomas Matte, New York City of Department of Health and Mental Hygiene
Jamie Voogt, University of Western Ontario

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

Contents

APPENDIXES

Summary

According to the United Nations, three out of five people will be living in cities worldwide by the year 2030. The United States continues to experience urbanization with its vast urban corridors on the east and west coasts. Although urban weather is driven by large synoptic and meso-scale features, weather events unique to the urban environment arise from the characteristics of the typical urban setting, such as large areas covered by buildings of a variety of heights; paved streets and parking areas; means to supply electricity, natural gas, water, and raw materials; and generation of waste heat and materials. These all combine in various ways to create a very distinct local weather environment characterized by meso- and microscale urban heat island effects, urban flooding, changes in precipitation patterns, elevated concentration levels for gaseous pollutants and aerosols, and street canyon winds.

Given the high density of people and their dependence on infrastructure, urban areas are especially vulnerable to weather-related events like severe thunderstorms, heat and cold waves, winter storms with heavy ice and snow, air pollution, and the rapid spread of airborne disease. To better prepare and respond to these events, the field of urban meteorology has grown from simple observations and forecasts of the general weather for cities and surrounding metropolitan areas to scientific and technological advances that allow us to predict a wide set of environmental parameters at relatively fine temporal and spatial scales. As these capabilities have improved, the uses for urban weather information and its value to decision makers have increased.

Continued advances in these capabilities are needed, but most assessments of research and development priorities have come from discussions within the scientific research community. There is a need for more two-way interactions between urban meteorologists and end user communities, such as emergency managers, public utilities, and urban planners, to better

understand user information needs and the products and services available from urban meteorologists.

This report, based largely on the information provided at a Board on Atmospheric Sciences and Climate community workshop, describes the needs for end user communities, focusing in particular on needs that are not being met by current urban-level forecasting and monitoring. This report also describes current and emerging meteorological forecasting and monitoring capabilities that have had and will likely have the most impact on urban areas, some of which are not being utilized by the relevant end user communities (see full Statement of Task in Appendix D).

The Committee concludes that users of urban meteorological information need high-quality information available in a wide variety of formats that foster its use, within time constraints set by users' decision processes. By advancing the science and technology related to urban meteorology with input from key end user communities, urban meteorologists can better meet the needs of diverse end users. To continue the advancement within the field of urban meteorology, there are both short-term needs, which might be addressed with small investments but promise large, quick returns, as well as future challenges that could require significant efforts and investments (Boxes S.1 and S.2).

END USER NEEDS

End users of urban meteorology information have demonstrated important needs for urban meteorological observations and analyses. They use urban meteorological information either directly or indirectly for planning and decision-making. For example, national security officials may utilize urban dispersion models to plan for an accidental or terrorist release of

BOX S.1
Short-Term Needs

1. Maximum access to observational data in different categories from diverse sources
2. Regularly updated metadata of the urban observations using standardized urban protocols
3. Continued and expanded international urban model intercomparisons over urban areas
4. Development and application of best practices to strengthen the dialog between meteorologists and end user communities

BOX S.2
Challenges

1. How can new capabilities for urban observations be developed and implemented, particularly using the network of personal digital assistants (PDAs; including smartphones) and vehicles and new technologies for measurements in the whole planetary boundary layer?
2. How can weather and climate models be urbanized and how can urban areas be included in the model prediction evaluation and validation metrics?
3. How will the capability for integrated urban meteorology-decision support systems be developed?

chemical or radioactive material in an urban area. Another example is how the construction sector uses historical data regarding the occurrence of heavy rain, snow, and icing to prepare for days in which no outdoor work can take place due to such precipitation events. **A clear mechanism to help the urban meteorological community better identify user groups, reach out to them, and begin an ongoing dialogue to assess and better meet their needs has yet to be identified.**

It is important to recognize that there are multiple types of urban meteorological phenomena that have impacts on different types of users with different types of needs. End users are heterogeneous and cover a vast spectrum of job roles, goals, needs, experience, and understanding. Their needs span a wide range of accurate urban meteorological information, from high frequency and low frequency events that may occur over the short and the long term. To complicate long-term planning, both types of events will be affected by climate change. Acknowledging and understanding this heterogeneity is important for the urban meteorological community to better understand, interact with, and meet the needs of end users.

As many participants noted at the workshop, there are numerous end user needs that are not sufficiently being met (Table S.1). In many cases, the urban meteorological community is simply unaware of the precise data and information needs of various user groups. If such information is not provided, there is a risk that disparate groups of end users will start generating (or more fully develop) their own data streams, not necessarily following best practices in data collection, analysis, or interpretation, and produce not only redundant but also inconsistent information. More importantly, if the urban meteorological community does not provide required information, end users' needs will not be met, reducing the effectiveness of their decision-making.

TABLE S.1 Sampling of Specific Unmet End User Data Needs

Sector	Examples of Unmet Data Needs
Flood Control *(municipal and public safety officials)*	• Rainfall and snowmelt runoff and storm water datasets • Urban flooding and/or overloading of combined storm water/ sewage systems due to localized precipitation and ability/ inability of urban pervious surfaces to store water • Atmospheric river (i.e., narrow corridors of concentrated moisture in the atmosphere that when striking land can produce hazardous storms) information
Electric Power *(power producers, grid operators, local utilities)*	• Air temperature for assessing energy demands and related loads on the grid • Wind and solar radiation data for renewable energy assessments
Insurance/Reinsurance *(company officials)*	• Accurate and timely forecasting of extreme events • Surface roughness, overland decay, and wind speed
Business *(company officials, public and private service providers)*	• Solar radiation, precipitation, and air quality data for agriculture (e.g. for agricultural regions near and/or impacted by cities) • Canyon-level wind flow (e.g. for construction sector)
Urban Design *(architects, urban planners, municipal officials)*	• Vegetations stress index for cities/optimization • Urban air quality • Assessment of urban heat island mitigation measures such as green roofs and tree planting campaigns • Development of climate change mitigation and adaptation strategies of cities and regions, • More dense array of first order meteorological stations in and around urban areas • Improved methods for assessing the extent to which rural meteorological stations are subject to the impacts of local land use change
Transportation Management *(officials in departments overseeing highways, railroads, airports, harbors, and rivers)*	• Canyon-level wind flow • Precipitation and its form (i.e., rain, freezing rain, sleet or snow) • Representativeness of surface observations • High spatial resolution forecasts (e.g. roadway scale) • Road surface temperatures

TABLE S.1 Continued

Sector	Examples of Unmet Data Needs
Public Health *(health department officials, environmental protection agency officials, air quality management districts, public safety officials, emergency managers)*	• Solar radiation, wind, humidity and air temperature at matching scales for health (e.g., heat indices) • Consistent urban heat island baseline datasets for vulnerability/risk assessments (standardized methods and data) • Spatially explicit datasets that characterize the urban heat island (i.e., further than just surface air temperature measurements; surface skin temperature, air temperature, humidity, wind and radiation data may provide a more comprehensive assessment of "heat") • Heat and cold wave and physical stress forecasts with temporal and spatial resolution at city scale • Street-level air quality • Extreme precipitation event forecasts • Extreme localized heat/cold advisories, disease vector, and air quality advisories
Security *(public safety and security officials)*	• Higher temporal, vertical, and horizontal spatial resolution data (e.g. urban boundary layer structure and mixing layer heights, vertical profiles of winds, turbulence, temperature of particular importance to dispersion applications) • Dual-use leveraging of data from other applications (e.g., radar-derived precipitation calibrated with rain-gauge data for flood predictions) • Regularly updated urban data (e.g. land-use characteristics, building footprint data)
Emergency Response *(public and industrial safety officials)*	• Street-level detailed flood information • High spatial and temporal resolution wind, temperature, and moisture data in and above the urban canopy

Although there are many unmet needs, there are some success stories where the needs of the end user are largely met (see Chapter 2 for case studies). A common theme present in these examples is that direct communication throughout the process is key to successful coordination. In some cases, the end users worked directly with researchers to develop tools that are tailored to their specific needs**.** The hallmarks of effective communication are a better understanding of capabilities on both sides, the successful translation of user needs to the research community and research products to the end user community through collaboration and a better understanding in the research community of institutional constraints that end users face.

Coordinated Efforts

Many workshop participants noted that it would be useful if there were more coordinated data sharing strategies among various agencies and training of various end user communities on how to utilize existing data. Coordinated data formats, available metadata, quality assurance, and novel dissemination strategies are increasingly essential as urban meteorological data and model output cross the research-to-operations "valley."

Education

Several discussions at the workshop focused on the underrepresentation of urban meteorological, climatological, and field coursework and training at all educational levels. Advanced approaches to training and workforce development will be critical in producing the next generation of urban meteorological models and applications. Strengthened training would likely give the community a better understanding of what is available and unavailable in urban meteorology and how and what urban meteorology information is used in decision-making by end users.

Ultimately, it is essential that the urban meteorological community understands what data are needed by end users that are not currently produced and/or not conveyed in usable ways to end users.

OBSERVING, MODELING, AND FORECASTING IN THE URBAN ENVIRONMENT

Meteorological observations and forecasting are complex in cities because of the high spatial variability, unique physical characteristics of the urban canopy and its impacts on various processes, and challenges with model initialization. Although cities still pose a number of difficult challenges for both the scientific and end user stakeholder communities that are not adequately addressed by current meteorological observation, forecasting, and information dissemination technologies, there has been significant progress in the past 10 to 20 years (Table S.2).

Current Capacity

One such advancement is ground based remote sensing capabilities, such as scanning radars (e.g., Next-Generation Radar, NEXRAD), radar profilers and sodar, lidar (light detection and ranging), and radiometric profilers.

TABLE S.2 Advances in Urban Forecasting and Monitoring Techniques

Mechanism for Forecasting and Monitoring	Advances in Technology
Monitoring and Observations	Urban campaigns Urban observation networks Ground-based remote sensing • Scanning radars • Radar profilers and sodar • Lidar • Radiometric profilers • Lightning detection Airborne/spaceborne remote sensing • Urban land cover • Thermal imaging and UHIs • Aerosols • Hydrometeorological parameters
Modeling Systems	Urbanization of numerical weather prediction models Atmospheric dispersion and urban air quality models Hydrological models Coastal storm surge-inundation models

Urban observation networks with in situ sensors within the urban canopy have been deployed in several cities. However, the design of networks that capture the spatial variability within the urban canopy layer and integrate in situ observations with remote sensing instruments to obtain a three-dimensional (3-d) picture of the urban atmosphere still poses challenges. A need for urban testbeds for testing of observation and modeling strategies and development of end user applications still exists. Urban observation campaigns have provided sustained, accessible data sets for a specific range of environmental conditions and promote initiatives for future urban studies.

Advancements related to aircraft and satellite remote sensing have been useful in assessing the extent and magnitude of the urban heat island identifying urban rain- and snowfall anomalies, and determining air quality. Additionally, airborne and spaceborne data help properly characterize urban land cover and morphology, which is important for coupled meteorological systems.

Urban treatments have been explicitly included in some numerical weather prediction models. As the model grid size decreases to a few kilometers, cities can cover a significant number of grid cells in the modeling domain. There are several methods to "urbanize" Numerical Weather

Prediction (NWP) models: use of empirical models, implementation of urban canopy parameterization schemes of varying complexity into climate and operations models, and coupling of microscale computational fluid dynamics models with NWP models.

Atmospheric dispersion and urban air quality models have also been advanced for improving the decision-making capabilities in these areas. Such models are essential in protecting people, the natural environment, and urban infrastructures from negative impacts of elevated air pollution in cities. Several approaches are now available for neighborhood to street-scale dispersion modeling (1-5m), which is especially important to emergency managers who require fast and reliable information on dispersion of toxic airborne contaminants in the event of an accidental or terrorist release.

Improved hydrologic models, both conceptual models and physically-based models, provide a methodology for assessing surface water hydrology and water balance changes for an array of surfaces. This is important for cities and their impervious surfaces which modify surface runoff, evapotranspiration, infiltration, and groundwater recharge.

Given that a majority of the U.S. population lives within coastal counties, coastal storm surge models are increasingly important. Such models use population, land cover, elevation, climatological, and oceanographic datasets to model and animate sea level rise and surges associated with storms.

Emerging Technologies

There are also several emerging technologies in meteorological forecasting and monitoring (Table S.3). First, coupled modeling systems are beginning to be used for major U.S. cities. For example, coupling building energy models with urban canopy parameterizations provides tools to study feedbacks between building energy use and urban climate.

In general, there has also been significant progress in data assimilation and probabilistic forecasting techniques over the last decade, but applications for urban areas are still largely unknown. Probabilistic information can aid users in their decision making, but end users are not always trained on how to properly interpret model-generated probabilistic information, and modelers have difficulty in communicating probabilistic information to end users.

There are a number of advanced sensing techniques for the atmospheric boundary layer, such as differential absorption lidars, Doppler-lidar systems, and commercial aircraft-based measurement technologies. These emerging technologies have resulted in improvements of weather forecasts, but there is a need for better observations in the atmospheric boundary layer.

TABLE S.3 Emerging Technologies in Meteorological Forecasting and Monitoring

Mechanism for Forecasting and Monitoring	Emerging Technologies
Modeling Systems	Coupling modeling systems • Use of high resolution building data sets in urban weather and climate models • Coupling of atmospheric models from the global down to urban scales • Advanced exposure assessments • Application of weather and climate models for urban planning
	Data assimilation and probabilistic forecasting techniques
Monitoring and Observations	Advanced sensing techniques for the atmospheric boundary layer
	Nontraditional sensor networks (e.g., mobile vehicles for measurements; Twitter, Facebook, YouTube, and text messaging alerts for reporting events and accessing data)

Lastly, there is a great potential in utilizing nontraditional sensor networks (i.e. the transmission of critical real-time meteorological, hazard, or emergency response data through Twitter, Facebook, YouTube, and text messaging alerts) that are primarily enabled by smart technologies such as Global Positioning System (GPS) or mobile Geographic Information System (GIS) capabilities, which are fairly ubiquitous in urban regions.

SHORT-TERM NEEDS

Based on the information from the workshop and its deliberations, the committee identified four short-term needs in urban meteorology, which can be addressed with small investments but will likely result in large, quick returns.

1. Many end users would like improved high spatial and temporal resolution observational data, including forcing data for urban meteorological models, observational data to characterize urban areas and determine urban model parameters and urban sources/sinks, observational data for urban model validation, and long-term observational data. The committee

noted that a variety of data in each of these categories are available from different communities and that another need is to maximize the access to observational data in different categories from diverse sources by

- securing access to existing data sets from previous urban campaigns,
- assuring that long-term monitoring networks will serve needs of both the global and urban climate communities, and
- integrating data sets from various monitoring networks into central data archives that can be easily accessed by the broader science and end user communities.

2. Observational data have maximum value only if they are accompanied by comprehensive metadata—information about the data that helps facilitate its understanding and use. Without detailed metadata, observational data over the heterogeneous urban areas could be easily misused by the urban meteorology community and others. A plethora of surface monitoring sites often exist in urban areas, but metadata are typically lacking for these sites, data access is not easily available, and data quality may be questionable. Given the heterogeneous nature of urban areas, the site selection, quality assurance, and management of instruments are crucial. Furthermore, because the urban environment evolves rapidly as development proceeds, another need is regularly updated metadata of the urban observations using standardized urban protocols.

3. Model intercomparison projects help in the discovery of major model deficiencies and the identification of the importance of certain major processes. Recent initial urban model intercomparisons indicate that based on all statistical measures, the simpler models perform as well as the more complex models, partly due to the lack of observational data for complex models and a lack of physical understanding of urban processes. Model performance generally improves when additional information about the surface is provided. Model intercomparisons for different urban types (e.g., coastal, mountainous, tropical, etc.) in developed and developing countries could be useful for future studies. Given that model intercomparisons can show how to improve urban models, the committee concludes another short-term need is for continued and expanded international urban model intercomparisons over urban areas.

4. Effective communication between urban meteorologists and end users is a challenge. There are several reasons for this, such as few communication

experiences and the difficulty in understanding each other's needs, practices, and capabilities. One example is the general difficulty in communicating probabilistic information to end users.[1] Although some end users only need to know the most likely outcome among different options (e.g., the maximum temperature will likely be 57 degrees Fahrenheit), most users require probabilistic urban meteorological information to make informed decisions. The committee concludes that there is a need for development and application of best practices to strengthen the dialog between urban meteorologists and end user communities.

CHALLENGES

Although there are some clear short-term and relatively straightforward steps that could be taken to advance the field of urban meteorology and its usefulness to the end user communities, some potentially valuable advances would require significant efforts and investments. Therefore they will likely be challenging to implement and the value of such activities would need to be weighed against costs. Based on the information from the workshop and its deliberations, the committee identified three overarching challenges.

1. Given the challenge in obtaining representative measurements from individual sites over urban areas, it is important to develop new capabilities. First, technologies that integrate the measurements may be available from the network of personal digital assistants, including smartphones, for reporting and evaluating events, and accessing information. Networks of vehicles with GPS capability (e.g., from U.S. Post Office, United Parcel Service (UPS), Federal Express, and some taxis) also have the potential to be valuable urban measurements (e.g., for temperature and pressure measurements).

Secondly, given that urbanization affects the physical and dynamic structure of the planetary boundary layer (PBL)—roughly the lowest one kilometer of the atmosphere—new technologies for critical measurements within this layer are essential. The PBL influences both local weather and the concentration and residence time of pollutants in the atmosphere, which in turn impact air quality. Urban PBL is also the most understudied and undersampled layer in the urban atmosphere, in large part because of the

[1] Probabilistic forecasts convey the uncertainty, or likelihood, that an event will occur. They assign a probability to each of a number of different outcomes (e.g. there is a 10% chance the maximum temperature will be 56 degrees Fahrenheit, there is a 75% chance it will be 57 degrees Fahrenheit).

difficulty of access, especially over some parts of a city. These measurements are also important for dispersion applications.

Challenge: How can new capabilities for urban observations be developed and implemented, particularly using the network of PDAs (including smartphones) and vehicles and new technologies for measurements in the whole planetary boundary layer?

2. With the increase of horizontal resolution in weather and climate models, it is possible for urban areas to occupy a whole model grid cell or a large fraction of grid cell. Some weather and climate models do not incorporate urban areas; the assumption is made that these areas are covered by the dominant vegetation type in the grid cell. Other models consider urban areas as a specific land cover type which can occupy a fraction of grid cell or a whole grid cell, whereas some land models are urbanized by considering more detailed urban processes.

While an urbanized land model has been integrated into some weather and climate models (e.g., in the UK Met Office Unified Model for weather prediction), it is still not considered yet in most forecasting systems (including the global forecasting system at the National Centers for Environmental Prediction, NCEP). In addition, because observing systems are more or less uniformly distributed, particularly where terrain is not an obstacle, evaluation and validation metrics do not consider urban areas explicitly.

Challenge: How can weather and climate models be urbanized and how can urban areas be included in the model prediction evaluation and validation metrics?

3. It can be a challenge for scientists to understand one another, even for scientists in the same discipline. Therefore it is not surprising that there typically is a lack of mutual understanding between meteorologists and the diverse end users found in urban areas. On one hand, it is important for meteorologists to better understand how individuals and organizations interpret forecast information and integrate it with other inputs, such as socioeconomic, political, and cultural factors, in decision-making processes. On the other hand, it is just as important for end users to better understand how observational data and models generate forecasts and associated uncertainties.

A combination of complementary approaches may help meet the challenge of mutual understanding between users and meteorologists. The first approach is the continued development of urban testbeds. The goal of a testbed is to solve operational and practical regional weather-related phenomenon and/or forecast challenges through a quasi-operational framework which includes measurement specialists, forecasters, researchers, private-sector, and government agencies with a strong connection to the end users. Testbeds can result in more useful observing systems, improved use of data in forecasts, enhanced services and products, economic and public safety benefits, and eventually, more effective decision making by users. The translation of research and development (R&D) findings into better operations, services, and decision-making can usually be accelerated by testbeds.

A second approach is the continued development of applied science projects that involve meteorologists and end users. In particular, interdisciplinary projects are increasingly needed to address critical gaps in the interface between natural, biological, and human systems in the urban landscape. It is also mutually beneficial to jointly train graduate students and postdoctoral researchers. For example, a new postdoctoral training program between National Center for Atmospheric Research (NCAR) and the Centers for Disease Control and Prevention (CDC) requires the candidate to stay at NCAR for one year to become familiar with weather and climate prediction, and stay at CDC for another year to integrate urban meteorology with public health.

A third approach is the development of joint urban meteorology and decision support exercises (e.g., emergency response, climate change and urban planning). These exercises could lead to the successful translation of end user needs to the research community and to help provide a better understanding of capabilities on both sides, including giving the research community a better understanding of institutional constraints that end users face. It could also be beneficial for urban meteorologists and end users to attend joint conferences and each other's professional conferences.

Challenge: How will the capability for integrated urban meteorology-decision support systems be developed through the integration of

- support for future, intensive urban research projects, that integrate modeling and observations and focus on improving the fundamental knowledge of physics and dynamics in the urban atmosphere,
- increased dialogue between urban meteorologists and end users, and
- urban meteorology testbeds?

FINAL THOUGHTS

The field of urban meteorology has grown considerably in the past 50 years, and with the increased growth of cities worldwide, including the United States, there is a pressing need for continued scientific advances within the field. As the capabilities within urban meteorology have improved, the uses for urban weather information and its value to decision makers have increased. Users of urban meteorology information need high quality meteorological information available in a wide variety of formats that foster its use, within time constraints set by end users' decision processes. To help meteorologists provide this tailored information, it is important to foster direct interaction with key end user communities, who can help identify their information needs. By advancing the science and technology related to urban meteorology with input from key end user communities, meteorologists can better meet the needs of diverse end users.

1

Introduction

Around the world, the growth of cities seems likely to continue for the foreseeable future. It is expected that today's urban population of 3.2 billion will increase to nearly 5 billion by 2030, resulting in three out of five people living in cities worldwide (UN, 2008). Urbanization of the world population occurred earlier in developed nations such as the United States compared to less developed nations in Asia, Africa, and Central America. (Figure 1.1).

Urban areas are evident along the U.S. East and West coasts, where long, largely urban corridors house tens of millions of people, as well as at major interior cities such as Atlanta; the Texas triangle of San Antonio, Houston, and Dallas-Ft. Worth; Chicago; Phoenix, and Denver (Figure 1.2 and Box 1.1).

The trend toward such urbanization arises naturally from individual and corporate desires to maximize opportunities and improve efficiency by having jobs, education, housing, and transportation in close proximity. Cities are places where commerce, industry, finance, human services, and culture are centralized. Diversity and social mobility are often enhanced in urban settings.

In addition to these benefits, the growth of cities comes with some environmental costs and challenges that affect the functioning of urban infrastructure, the quality of life of the individuals who live in the cities, and the vulnerability of both to disruption. Many of these costs and challenges have a significant meteorological component that arises from the very nature of cities. The infrastructure that is characteristic of urban settings—large areas covered by buildings of a variety of heights; paved streets and parking areas; means to supply electricity, natural gas, water, and raw materials; generation of waste heat and materials; means to remove sewage and waste/storm water—combine in various ways to create a very distinct local weather environment. This environment is characterized by meso- and microscale urban heat island effects, urban flooding, changes in precipitation patterns,

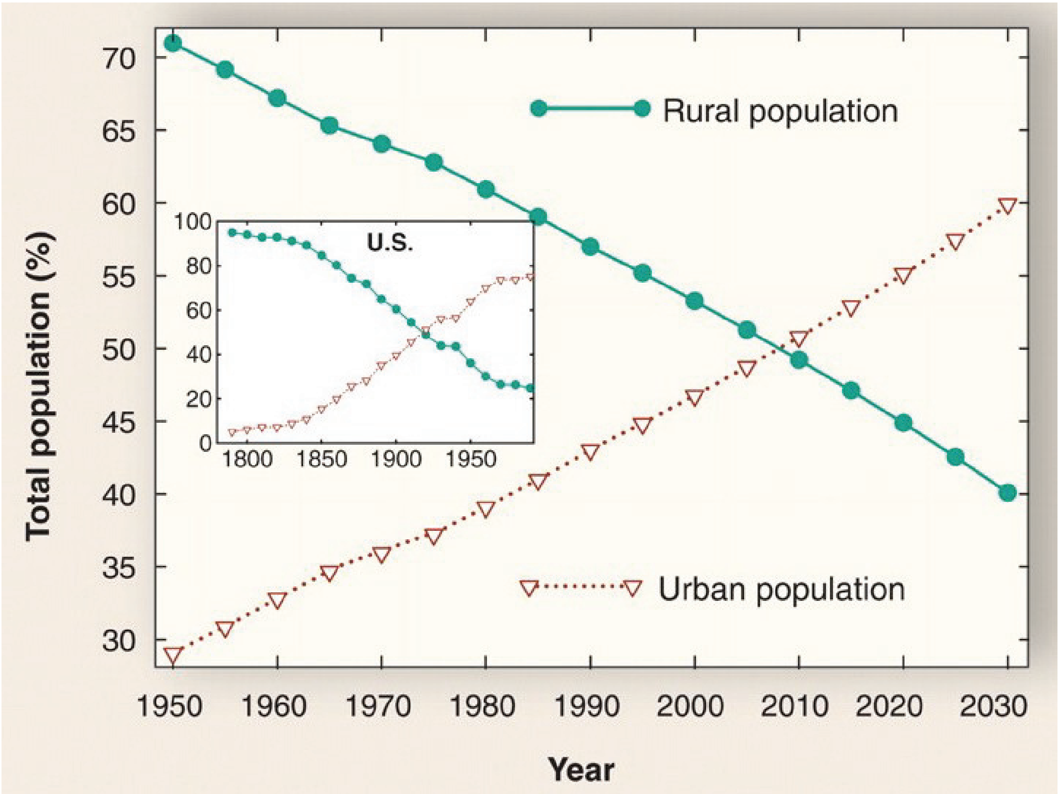


FIGURE 1.1 Change in world urban and rural population from 1950 to 2030 (projected). Inset shows change in world urban and rural population for the United States from 1790 to 1990. SOURCE: Grimm, N. B., S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs. 2008. Global Change and the Ecology of Cities. *Science* 319(756):756-760. Reprinted with permission from AAAS.

elevated concentration levels for gaseous pollutants and aerosols, and street canyon winds.

In addition, the high density of population results in enhanced vulnerability to not only traditional hazardous weather phenomena such as severe thunderstorms and blizzards, but also to heat and cold waves, air pollution, and the rapid spread of airborne disease through a concentrated, susceptible population. Indeed, many of the major weather disasters in the last three decades have been in urban settings. Ranging from tornadoes, major ice and snow events, to floods (often triggered by spring melting of winter snow), to land falling hurricanes, to runaway wild fires, these "Billion

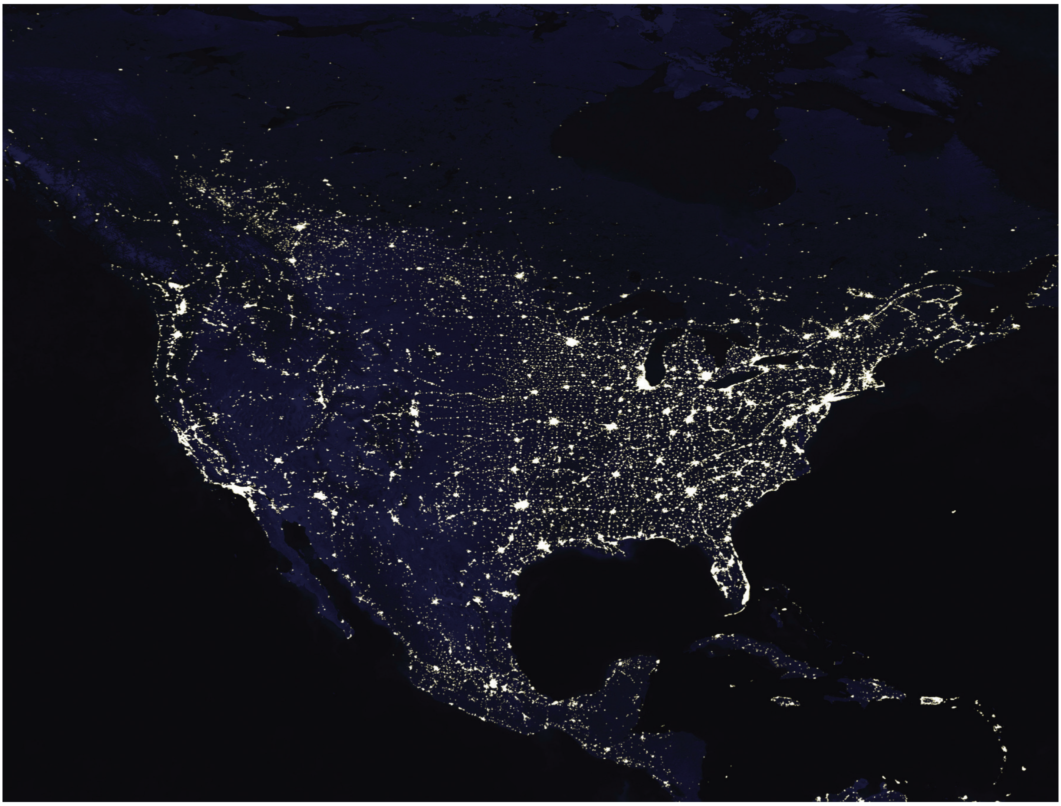


FIGURE 1.2 Human-made lights highlight developed or populated areas of Earth. SOURCE: NASA/Goddard Space Flight Center Scientific Visualization Studio, *http://visibleearth.nasa.gov/view_rec.php?id=11795*.

Dollar" weather events have taken a serious toll on our nation's economy (NCDC, 2011; Figure 1.3).

Responding to these weather needs has led to the development of the field of urban meteorology. For many years, this specialty consisted of simply observing and forecasting the general weather for cities and surrounding metropolitan areas. However, scientific and technological advances of the past 50 years now allow us to predict a wide set of environmental parameters at relatively fine temporal and spatial scales, for times ranging from the next hour to the next several days and for small regions such as street canyons, individual buildings, and small parks.

As these capabilities have improved, the uses for urban weather information and its value to decision makers have increased. The challenge

BOX 1.1
Definitions of Key Terms

Urban area—To define "urban area," the U.S. federal government has formally defined Metropolitan Statistical Areas (MSAs) which are composed of counties or equivalent. MSAs are delineated on the basis of a central urbanized area, which is a contiguous area of relatively high population density with a population greater than 50,000 (NRC, 2010a)

Urban meteorology—The study of the physics, dynamics, and chemistry of the interactions of the Earth's atmosphere and the urban built environment, and the provision of meteorological services to the populations and institutions of metropolitan areas (NRC 2010a)

Urban meteorologist—Denotes a specialist within the broader meteorological community. The urban meteorologist has both the standard background of a meteorologist, but specialized training in boundary layer and microscale meteorology, aerodynamics of airflow around structures, air quality, and human health as impacted by the atmosphere.

User of urban meteorology information—Individuals or organizations who use information directly in their operational decisions or strategic planning; and organizations or institutions (e.g. media, government entities, and weather services) that act as translators between the raw data (observations and models) and the public (adapted from NRC 2006).

to the urban meteorologist has become not only producing high quality meteorological information, but also delivering it to a wide variety of users in formats that foster its use, within time constraints set by users' decision processes. Given the extent of U.S. urbanization, a stronger leadership role of the United States in understanding and responding to urban meteorology would better serve the needs of its citizens, as well as developing nations that are undergoing rapid urbanization.

EXPLORING OPPORTUNITIES TO IMPROVE URBAN WEATHER INFORMATION

The growing demand for urban meteorological products and services has spurred a number of studies and reports that identify opportunities to improve those products and services. Three such reports were produced by Prospectus Development Teams of the U.S. Weather Research Program (USWRP), which convened a few panels of experts to identify critical research needs in different problem areas.

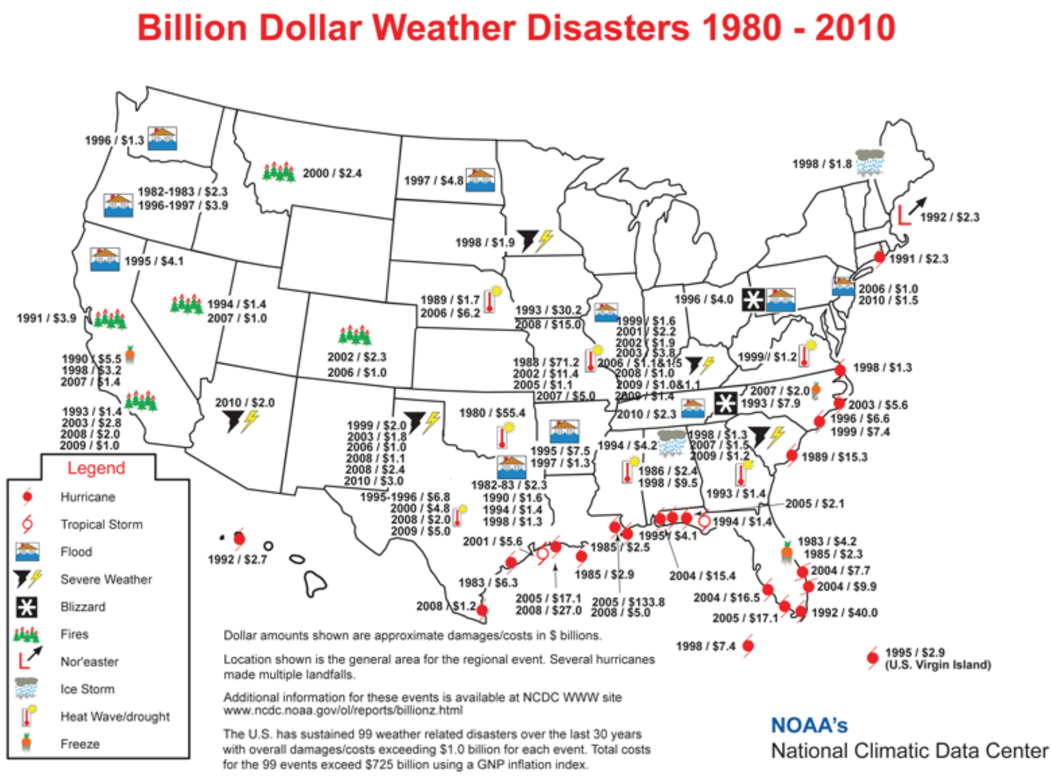


FIGURE 1.3 A synoptic mapping prepared by the National Oceanic and Atmospheric Administration's National Climatic Data Center (NOAA NCDC) showing weather-caused disasters with at least one billion dollars in losses to property and infrastructure in the last three decades. SOURCE: NOAA, *http://www.ncdc.noaa.gov/img/reports/billion/billion2010.pdf*.

Among the most influential of the USWRP reports has been *Forecast Issues in the Urban Zone: Report of the 10th Prospectus Development Team of the U.S. Weather Research Program* (Dabberdt et al., 2000), which identifies research needs and opportunities related to the short-term prediction of weather and air quality in urban forecast zones. It points out that weather has significant impacts on the many people who live in major urban areas and argues that urban users have different weather information needs than rural users. Further, it identifies needs for "improved access to real-time weather information, improved tailoring of weather data to the specific needs of individual user groups, and more user-specific forecasts of weather and air quality."

A subsequent 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., 2004) focuses on the identification and delineation of critical meteorological research issues related to the prediction of air quality. The report has a strong emphasis on urban areas and points out that forecasting air quality is quite different from severe weather forecasting. The latter is often focused on prediction of particular precursor conditions, while the former is typically associated with calm weather associated with large scale weather patterns. Meteorological observing systems, which are essential to effective air quality prediction, are designed to support prediction of severe weather on the mesoscale, not the microscale subtleties of adverse air quality such as daily evolution of the surface boundary layer (from inversion to unstable/convective, and then a shift back to inversion) and the photochemistry that modifies emissions to produce dangerous pollutants.

A third influential study from the U.S. Weather Research Program has been *Multifunctional Mesoscale Observing Networks* (Dabberdt et al., 2005) which explores the need for enhanced three-dimensional mesoscale observing networks. These networks are important to advancing numerical and empirical modeling for various mesoscale applications which could be utilized by many users of urban meteorological information. These applications include severe weather warnings and forecasts, hydrology, air-quality forecasting, chemical emergency response, transportation safety, energy management. It is essential that the public, private, and academic sectors actively participate in mesoscale observing networks' design and implementation. The creation and delivery of products should serve multiple applications to help address end user needs.

Motivated in part by Dabberdt et al. (2000), in 2004, the Office of the Federal Coordinator for Meteorological Services and Supporting Research produced a report, *Urban Meteorology: Meeting Weather Needs in the Urban Community* (OFCM, 2004). This report describes roles to be played by federal government agencies in providing urban meteorological services, while emphasizing the need for partnerships between federal agencies, state and local entities, the academic community, and the residents and businesses of the urban community to provide the full ranges of services that are required.

The report goes on to present a discussion framework that outlines the concept of urban meteorology, the principal application areas, and the roles of the principal partners. It notes that urban meteorology is an evolving field and that a broad dialogue among all interested parties should be fostered to share values and objectives, resulting in the recognition of common problems through which the combined efforts to improve urban meteorology could be coordinated and made more productive.

Partially in response to the above reports, the National Research Council (NRC) has in recent years produced several reports that emphasize the importance of and the need for more attention to aspects of operational meteorology in general and urban meteorology in particular. Particularly relevant studies include the following:

Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts (NRC, 2006). This report concludes that "uncertainty is a fundamental characteristic of weather, seasonal climate, and hydrological prediction, and no forecast is complete without a description of its uncertainty." Effectively communicating uncertainty gives users a better understanding of the likelihood of a particular event which in turn improves their ability to make decisions. Successful incorporation of uncertainty information into predictions can be facilitated through a better understanding of user needs, the creation of relevant and rich informational products, and the utilization of effective communication mechanisms.

Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks (NRC, 2008). This report demonstrated that a plethora of surface monitoring sites often exist in urban areas, but metadata are typically lacking for these sites, data access is not easily available, and data quality may be questionable. It is important that the suitability of these sites is assessed to provide appropriate urban climate data and metadata is collected and documented.

When Weather Matters: Science and Service to Meet Critical Societal Needs (NRC, 2010a). This report concludes that the United States is not mitigating weather impacts to the extent possible and it has fallen behind other nations in operational numerical weather prediction. The report identifies urban meteorology as one important issue that has not been sufficiently recognized or emphasized in previous studies.

From the Ground Up (NRC, 2008) and *When Weather Matters* (NRC, 2010a) both call for the establishment of testbeds to try out new observing concepts and, in concert with users and stakeholders, develop new meteorological products and services for particular user communities, such as urban dwellers. Canadians have provided an example of such an effort with their Environmental Prediction in Canadian Cities (EPiCC) Network. This has an overall objective of providing "…Canadian urban residents with better weather and air quality forecasts through development of an urban-atmosphere modeling system evaluated for Canadian urban climates. This enhanced forecasting capability will contribute to the safety, health, and well being of Canadians through better understanding of the dispersion of smog and particulate precursors in urban environments, accidental and terrorist releases, heat stress and wind chill, and dispersion of air pollutants in urban environments. The research will also contribute knowledge to the better conservation of urban resources (energy and water utilities) …"[1]

In the United States, an example of such an emerging urban testbed is to be found in the Dallas-Ft. Worth, Texas area, where a regional government agency is working with a group of universities to install a high-density network of small radars and other observing systems. This effort is described in Appendix B. Other efforts, such as the modeling and forecasting group at the University of Washington in Seattle, have demonstrated the importance of the testbed concept in reaching out to stakeholders at the earliest stages of designing new, urban-oriented products and services.

CHARGE AND APPROACH

As evidenced by the above reports and the appearance of the first urban testbeds, the field of urban meteorology has grown considerably in the past few decades, and, as discussed above, a number of publications have helped pinpoint pressing needs for scientific advances. To date, however, most assessments of research and development priorities have come from discussions within the scientific research community. There is a need for more direct interaction with key end user communities, who can help identify their information needs.

In the spring of 2011, the NRC's Board on Atmospheric Sciences and Climate (BASC) worked with its core agency sponsors to design a summer study that would open and facilitate a dialog between the research community and the users of urban meteorology information. The BASC Committee on Urban Meteorology: Scoping the Problem, Defining the Needs was tasked to write a report, based largely on the information provided at a workshop, on urban-level weather forecasting and monitoring capabilities and the information needs of specific end user communities. The committee was asked to describe current and emerging meteorological forecasting/monitoring that have had and will likely have the most impact on urban areas. They were also tasked to describe the needs for the end user communities that are not being met by current urban-level forecasting/monitoring and any forecasting/monitoring capabilities that are not being utilized by the relevant end user communities, either due to lack of awareness that such capabilities exist, or

[1] *http://www.epicc.uwo.ca/.*

failure to provide such information in a usable form (see full Statement of Task in Appendix D).

The committee was also asked to plan and convene this workshop with the goal of bringing together scientific experts with a wide array of representatives from the end user stakeholder community. The committee developed the workshop agenda and selected and invited participants who contributed presentations and took part in plenary and small group discussions. The workshop not only included a wide spectrum of representation from the meteorology research community, but close to half of the participants represented a range of end user stakeholder groups. Participants from federal and local government, national laboratories, academia, and the private sector brought expertise in areas such as urban vulnerability, transportation, public health, urban planning, emergency management, security, utilities, urban modeling, and observations (Box 1.2). There was also some international participation (see Appendix C for a participant list).

BOX 1.2
Perspectives from the End User Stakeholder Community at the Workshop

"…when you're on the operational side and you hear [the terms] urban meteorology, turbulent intensity, morphology, dispersion, forcing fluxes, anthropogenic, spatial…that is not our language. Our language is about evacuation, survivors, first responders, preparedness, recovery, mitigation."
Sandra Knight, Federal Emergency Management Agency (FEMA)

"… if we want a very fine spatial resolution [in a model] to look for variations in temperature, pretty much all we have …is land surface temperature, and that is not the temperature in which people experience. Unless we're laying on the ground, we're not experiencing that temperature."
George Luber, Centers for Disease Control (CDC)

"Nothing is worse during an event than getting a piece of measurement data that you think is very important, but you don't understand what instrument it came from, what's the threshold, what's the sensitivity, what did it actually measure…? What was actually the quantity that was there, and what QA [quality assessment] was performed on it?"
Gayle Sugiyama, National Atmospheric Release Advisory Center (NARAC)

"… essentially we are looking for just better, more transparent documentation of those basic products that the Weather Service and others put out."
James Rufo Hill, Seattle Public Utilities

The workshop consisted of keynote talks (see Appendix A for speaker abstracts), panel sessions on user needs and emerging technologies in urban meteorology, and working group sessions (see workshop agenda in Appendix C). The Committee charged workshop speakers, panelists, and participants to address questions drawn from the Statement of Task (see Appendix D) in working groups and to summarize their discussions in plenary session at the end of the workshop.

What follows in this report draws largely from insights and information from the workshop, in addition to previously published works. This report captures the main points of the presentations and discussions at the workshop and identifies the specific, in some cases unique, needs of the urban setting for weather support, as well as opportunities for academic research and operational practice to work with users to address those needs. Given the reliance on a workshop for most of its input and relatively short tenure for deliberations and analysis, the report does not make recommendations. It is also not intended to be a definitive study of the research and development needs for advancing weather monitoring and forecasting in an urban environment. However, the information gathered here is intended to be useful to government agencies, the academic research community, and urban governments in planning for weather services in the future and developing new initiatives to provide those services

ORGANIZATION OF THE REPORT

This report covers two broad areas related to urban meteorology: end user needs and current and emerging technologies. Chapter 2 identifies a range of users of urban meteorology information and their information needs. It goes on to discuss why these needs are not being met by current urban-level forecasting and monitoring capabilities and offers some suggestions to better address user needs.

Chapter 3 provides a brief review of current urban meteorological knowledge to provide context for issues laid out in the report, examines the current state of urban meteorological monitoring and forecasting, and discusses emerging technologies. Chapter 3 also identifies several key needs, challenges, and opportunities.

Finally, Chapter 4 builds on the discussions in Chapters 2 and 3 and suggests possible future directions for the field of urban meteorology. This includes short-term priorities where relatively small investments will be required, as well as future challenges which require significant efforts and investments.

2

End User Needs

This chapter identifies various applications of urban meteorological products and services of value to a range of end users, as informed by the end users who attended the workshop. There is little peer reviewed literature on this topic and much of the available information is anecdotal in nature. Given this, the Committee does not offer conclusions, but rather reflects on the workshop discussions and highlights key themes that emerged.

END USERS OF URBAN METEOROLOGICAL INFORMATION AND THEIR NEEDS

End users of urban meteorology information, such as urban planners, emergency planners, and local utilities in both the public and private sectors of society, have demonstrated important needs for urban meteorological observations and analyses. Policy makers, managers, and regulators at the local, state, and federal levels, as well as those in sectors such as public health, emergency response, security, electric power, flood control, transportation management, urban design, business, and the general public, use urban meteorological information—both real time weather and long-term climate information—either directly or indirectly (e.g., through use of outputs of environmental health and science work that applies urban meteorological data) for planning and decision-making (Box 2.1; also see Dabberdt abstract in Appendix A). There are likely several additional end user groups that have not been identified in this report. The workshop was an attempt to reach out to some of these groups and a few papers and reports have also described end users and their needs (e.g., Dabberdt et al., 2000; OFCM, 2004; Grimmond et al., 2010b; Mills et al., 2010). However, an important question remains unanswered: How can the urban meteorological community better identify these groups, reach out to them, and begin an ongoing dialogue to assess and better meet their needs?

BOX 2.1
Examples of How Some End Users Apply Urban Meteorological Information

Urban meteorological observation and modeling results are used in various applications by a variety of users. The types of data, as well as the temporal and spatial resolution required by these end users, vary substantially by application (Dabberdt abstract, Appendix A).

Insurance/Reinsurance
Decision makers in the insurance sector may use monthly climate summaries to validate industry catastrophe models, which simulate the geographical risk associated with natural and man-made catastrophes.

Business
Retailers, such as local grocery stores, use short-term weather information, particularly about winter weather events. Managers of large-event venues (indoor and outdoor), such as sporting events, fairs/carnivals, concerts, etc., also use short-term weather information to make decisions about canceling events. Larger retailers, such as clothing stores, use longer-range weather and seasonal climate information.

Urban Design
Urban planners use meteorological information to assist in the development of climate change mitigation and adaption strategies of cities and regions. Urban planners could also use weather and climate information to help select urban locations that can ameliorate weather-related human suffering and mortality. Indeed, this would be a good subject for future multidisciplinary studies.

Environmental Regulation
Environmental protection agencies at federal, state, and local levels use meteorological information to monitor, regulate, and set standards for the protection of human health and the environment.

Local Government
County officials, educators, and school superintendants use meteorological information to make decisions about closing schools during winter weather and convective weather events.

Personal Decision Support
The general public makes personal decisions (e.g., weekend activities, outdoor recreation, wedding planning) in daily life.

Research
Basic and applied researchers use meteorological information to conduct research in the various fields discussed in this report.

End users of urban meteorological information are heterogeneous and cover a vast spectrum of job roles, goals, needs, and understanding. Moreover, different end users may be more or less "advanced" in their use of meteorological data for a host of reasons. For example, some users have been working with the meteorological community and using weather data for a longer period of time. Some users have more resources (people, time, money, etc.). Some users have different knowledge (educational or experiential) bases. These differences can vary within and among groups and geographic areas. A given end user's needs may also vary depending on the type of weather observation or phenomenon being considered. Acknowledging and understanding this heterogeneity is important for the urban meteorological community to better understand, interact with, and meet the needs of end users.

Furthermore, end users may be viewed as a "cascade" or "web" of individuals and groups with varying information needs and at varying levels of distance from raw urban meteorological data (Box 2.2). Given this interconnected relationship, it is important to recognize that there are multiple types of urban meteorological phenomena that have impacts on different types of users with different types of needs (see discussion in Dabberdt Abstract, Appendix A). Accurate information on low-risk, high-frequency events (e.g., regular weather patterns) may be of importance to a broad range of end users; whereas knowledge of high risk, low frequency events (e.g., a chemical release emergency) are of utmost importance to emergency planners responsible for public safety in such circumstances. To complicate long-term planning, both types of events will be affected by climate change. As such, end user needs span a wide range of urban meteorological information, from high frequency and low frequency events that may occur over the short and the long term.

As many participants noted at the workshop, end user needs with regard to urban meteorological information currently are not sufficiently being met (Table 2.1). In many cases, urban meteorologists are simply unaware of the precise data and information needs of the various information groups. However, there is a risk that if urban meteorologists do not provide the required information, disparate groups of end users will start generating (or will more fully develop) their own data streams, not necessarily following best practices in data collection, analysis, or interpretation, and producing not only redundant but also inconsistent information. More importantly, if the urban meteorological community does not provide required information, end users' needs will not be met, reducing the effectiveness of their decision-making.

BOX 2.2
Cascade of Users

There are many different end users that require some form of urban meteorological information to help them make informed decisions in their respective fields. End users have a vast array of data needs and require this information at different spatial and time scales. Some end users work with raw data directly, some share the data they have acquired with other users (e.g., a water resource public utility may share their rainfall projections with the emergency response community so they may alert the public), and many work with the research community and weather services to garner the data and information they need. Some end users also share their own urban meteorology data with the research and weather services communities. The general public, itself an end user, often makes decisions based on information from the weather services community or through information provided by other end users. This "cascade of users" diagram is complex and meant to be illustrative (see figure on next page). It does not depict every user of urban meteorological information nor does it depict every pathway that this information is shared among users. Directions of arrows denote the flow of urban meteorological information. Raw data includes both in situ and remote sensing observations. The end goal of the information sharing throughout this cascade is better informed decisions by decision makers.

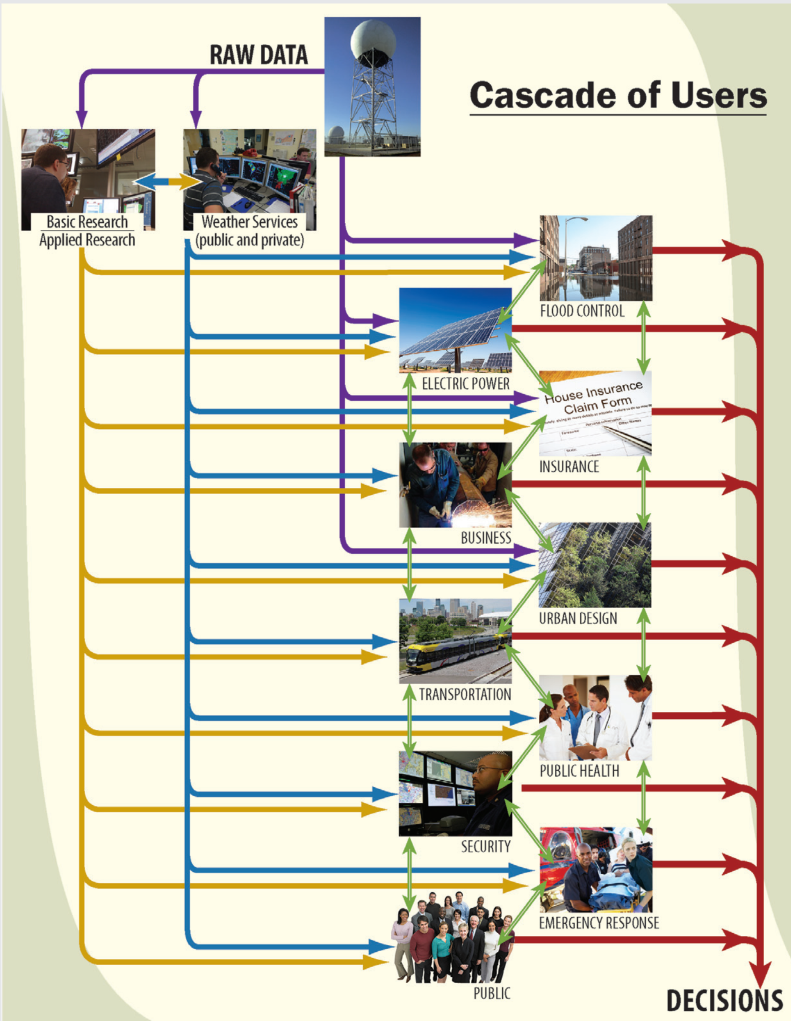
It is also important to note that the end user needs and data needs highlighted in this report are not necessarily equivalent. Data typically needs to be translated into useful information and/or decision support products for end users to utilize. The following sections consider some of the major unmet needs identified by participants at the workshop who use meteorological information in their regular decision making, followed by a discussion of communication needs across disciplines.

END USER NEEDS NOT BEING MET BY CURRENT URBAN LEVEL FORECASTING AND MONITORING

Over the last few decades, clear advances in urban monitoring and forecasting have been made (described in detail in Chapter 3). The needs discussed below were identified at the workshop by end users as being both "significant" and "unmet."

Targeting Observations and Models for User Needs and Preferences

One key role of science in society is to provide information that can be applied to real problems (i.e., tailored, information-rich products and



"Cascade of Users" diagram. End users may be viewed as a 'cascade' of interconnected individuals and groups with varying information needs to make informed decisions.

services that decision makers can use effectively). Figure 2.1 is an example of a heat vulnerability framework advanced by Wilhelmi and Hayden (2010) that illustrates such connectivity.

Over the last decade, the emergence of urban forecasting decision support systems for end users—taking into account user needs and preferences

TABLE 2.1 Sampling of specific unmet end user data needs

Sector	Examples of Unmet Data Needs
Flood Control *(municipal and public safety officials)*	• Rainfall and snowmelt runoff and storm water datasets • Urban flooding and/or overloading of combined storm water/sewage systems due to localized precipitation and ability/inability of urban pervious surfaces to store water • Atmospheric river (i.e., narrow corridors of concentrated moisture in the atmosphere that when striking land can produce hazardous storms) information
Electric Power *(power producers, grid operators, local utilities)*	• Air temperature for assessing energy demands and related loads on the grid • Wind and solar radiation data for renewable energy assessments
Insurance/Reinsurance *(company officials)*	• Accurate and timely forecasting of extreme events • Surface roughness, overland decay, and wind speed
Business *(company officials, public and private service providers)*	• Solar radiation, precipitation, and air quality data for agriculture (e.g. for agricultural regions near and/or impacted by cities) • Canyon-level wind flow (e.g. for construction sector)
Urban Design *(architects, urban planners, municipal officials)*	• Vegetations stress index for cities/optimization • Urban air quality • Assessment of urban heat island mitigation measures such as green roofs and tree planting campaigns • Development of climate change mitigation and adaptation strategies of cities and regions, • More dense array of first order meteorological stations in and around urban areas • Improved methods for assessing the extent to which rural meteorological stations are subject to the impacts of local land use change
Transportation Management *(officials in departments overseeing highways, railroads, airports, harbors, and rivers)*	• Canyon-level wind flow • Precipitation and its form (i.e., rain, freezing rain, sleet or snow) • Representativeness of surface observations • High spatial resolution forecasts (e.g. roadway scale) • Road surface temperatures

TABLE 2.1 Continued

Sector	Examples of Unmet Data Needs
Public Health *(health department officials, environmental protection agency officials, air quality management districts, public safety officials, emergency managers)*	• Solar radiation, wind, humidity and air temperature at matching scales for health (e.g., heat indices) • Consistent urban heat island baseline datasets for vulnerability/risk assessments (standardized methods and data) • Spatially explicit datasets that characterize the urban heat island (i.e., further than just surface air temperature measurements; surface skin temperature, air temperature, humidity, wind and radiation data may provide a more comprehensive assessment of "heat") • Heat and cold wave and physical stress forecasts with temporal and spatial resolution at city scale • Street-level air quality • Extreme precipitation event forecasts • Extreme localized heat/cold advisories, disease vector, and air quality advisories
Security *(public safety and security officials)*	• Higher temporal, vertical, and horizontal spatial resolution data (e.g. urban boundary layer structure and mixing layer heights, vertical profiles of winds, turbulence, temperature of particular importance to dispersion applications) • Dual-use leveraging of data from other applications (e.g. radar-derived precipitation calibrated with rain-gauge data for flood predictions) • Regularly updated urban data (e.g. land-use characteristics, building footprint data)
Emergency Response *(public and industrial safety officials)*	• Street-level detailed flood information • High spatial and temporal resolution wind, temperature, and moisture data in and above the urban canopy

from the very start—is a significant advance. Increased data interoperability and coupling of physical and social science data and models on various scales (global to sub-city scale) provide new opportunities to assess vulnerability, refine decision making, and respond to threats or hazards. Common synthesis of data on exposure will facilitate research on urban vulnerability, impacts thresholds, and adaptive capacity. The outcomes of such integrated research then can be applied via a decision support system. One example of this has been the development of the Maintenance and Decision Support System (MDSS) in 2001 (Box 2.3). Prior to its development, most State Departments of Transportation (DOT) had very little objective information on road conditions. The MDSS provides 72-hour forecasts of atmospheric and weather conditions for many snow-fighting states.

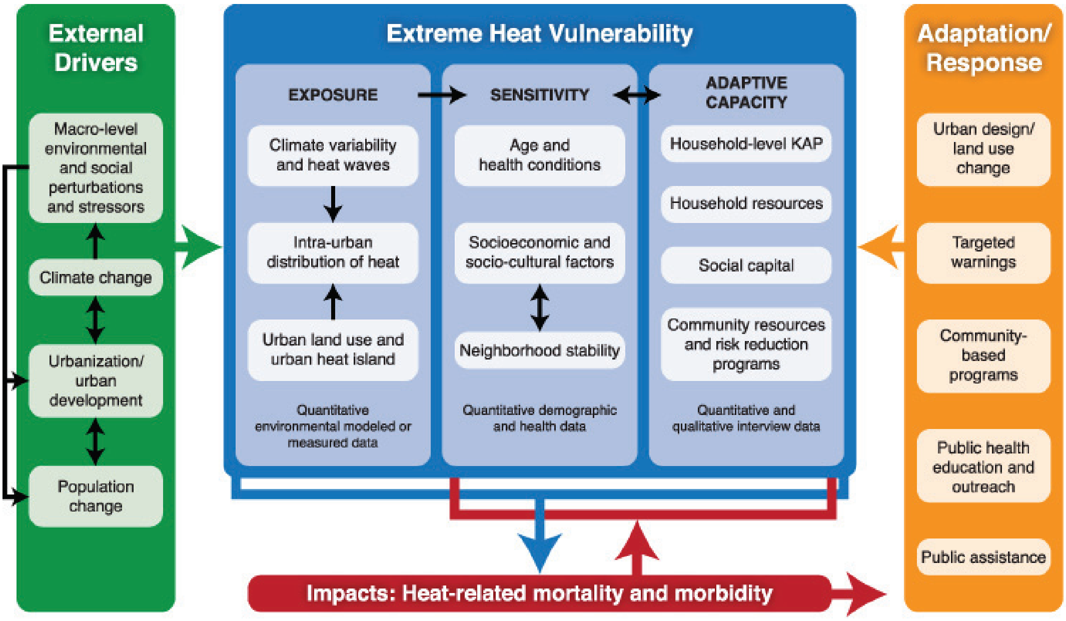


FIGURE 2.1 Heat vulnerability framework (following Wilhelmi and Hayden 2010). SOURCE: Wilhelmi and Hayden, 2010.

BOX 2.3
Indiana's Implementation of MDSS

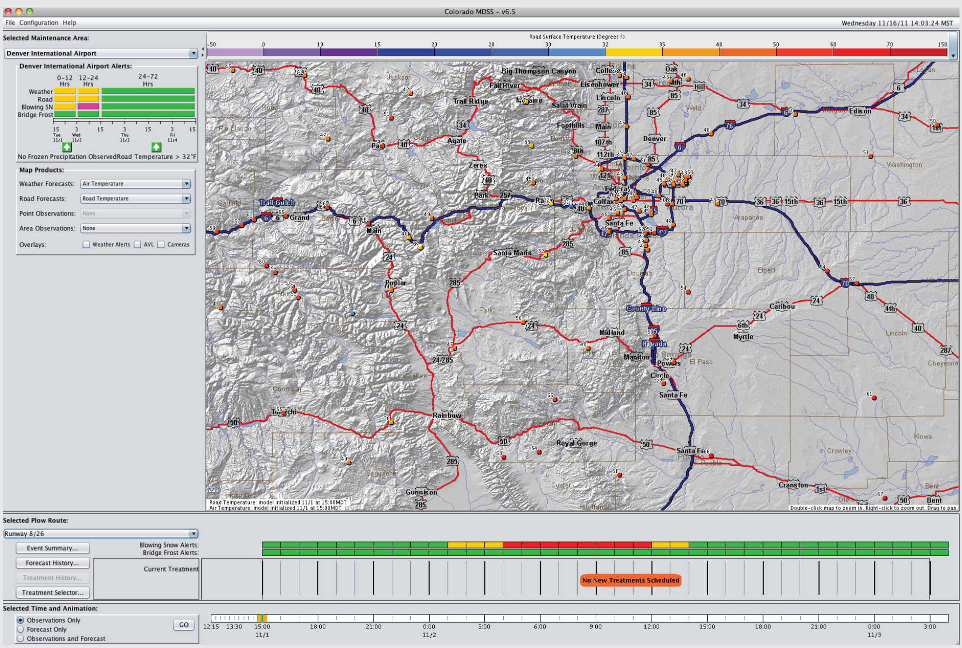
A Maintenance Decision Support System (MDSS) is a tool that utilizes forecasts, predictions, and reports on observed weather and road conditions to assist managers in making informed decisions on how to best utilize resources when planning for and treating snow and ice (see figure below). It also serves as a training tool that can be utilized year round.

In the late 1990s, the Indiana Department of Transportation (INDOT) decided to begin utilizing new technologies to more effectively prepare for and mitigate the impacts from snow and ice. Representatives from INDOT attended one of the Federal Highway Administration's (FHWA) MDSS stakeholder meetings and saw potential in the developing MDSS project, which was created with input from national labs and private contractors.

INDOT was facing declining revenues and eventually progressed from limited use of an MDSS to statewide implementation during the winter season of 2008-2009, largely because of the savings reported by the maintenance units utilizing a MDSS. Compared to the previous winter season, MDSS helped INDOT achieve savings of over $12 million in salt usage and $1.3 million in overtime compensation by the end of the 2008-2009 snow and ice season (McClellan et al., 2010).

Before statewide implementation, effective training had to be provided because a majority of INDOT staff had no experience with MDSS. An introduction to MDSS was presented at the 2008 INDOT Snow and Ice Conference, and eventually six training packets were supplied to relevant end users to ensure that they had the working knowledge required to make the MDSS project useful. In addition to extensive training, forecasts were fine tuned and recommendations to match actual observed conditions were made by communicating with the MDSS vendor during the snow and ice season (McClellan et al., 2010).

To continue the effective use of MDSS and to ensure greatest exposure to MDSS and its capabilities, INDOT plans to increase the focus on hands-on training for the diverse users of MDSS. To date, a group of 14 State DOTs (including INDOT) have pooled their resources to develop a customized MDSS for their respective agencies (Ye et al., 2009).



Maintenance and Decision Support System (MDSS) interface—developed from the start with end user input—provides precision forecasts and treatment suggestions to assist managers in making informed decisions on how to best utilize resources. SOURCE: Sheldon Drobot, NCAR.

Overall, however, there is an inadequate emphasis on providing the necessary observations and modeling activities for meeting the needs of a broad cross-section of urban users. For example, in the quest to create unbiased global-scale temperature records, meteorological services around the world routinely adjust the meteorological record to exclude the urban heat signal (Karl et al., 1988; Peterson, 2003), and monitoring stations affected by urban development are being relocated to remote rural areas. Operational weather and air quality models in the U.S. are also not capable of modeling cities correctly (Grimmond et al., 2011; see Chapter 3 for detailed discussion). As such, the type of data required to study and serve the needs of cities is mismatched with what is currently routinely monitored. It is important that the complementary functions of global and urban climate records be recognized and that the need for quality-controlled long-term urban observations be addressed.

It is crucial that information, including metadata, be collected, analyzed, quality-controlled, and made available to an array of stakeholders and users in formats, timeframes, and presentations appropriate for the application. Sometimes end users do not utilize urban meteorological information because there is a mismatch between the information that is provided to them and the temporal and spatial scales and lead-time of forecasts they need to make decisions. An emergency responder may have very different space, time, and data latency requirements for wind information during a bioterror event within a city than a meteorologist assessing thunderstorm rainfall potential.

Ultimately, it is important that all the communities involved in urban meteorology (e.g., modelers and stakeholders) describe the types of observations and model input and outputs they would need to help ensure the result is a tool that is useful in helping them meet their goals. For example, Seattle Public Utilities has worked with both the local university research and weather services communities to develop and utilize weather products to provide drinking water, drainage, and wastewater services to the residents of Seattle (see Box 2.4). This type of collaboration works to capture commonalities across communities and to optimize return on observation investments and modeling efforts. In order to have the greatest impact, it is important that each community better understand how these resources might best be applied. The leadership of working across disciplines is a key requirement for success.

Data Access and Data Sharing Needs

As discussed above, there is a cascade of end users of urban meteorological information, and this cascade can also be extended to observations and model products. Many of the users of data also gather their own data, which would be a useful supplement to data collected by other agencies. Many workshop participants asserted that there are important limitations and considerations related to data access, data availability, and data sharing that need to be addressed by urban meteorologists working in partnership with stakeholders.

Data access and availability was identified as a major crosscutting issue at the workshop. Agencies typically steward environmental data that suit their operational needs. For various reasons (e.g., legal or institutional), these data are often not shared externally. For example, government lidar (light detection and ranging) data and National Lightning Detection Network (NLDN) data are often difficult to access but would be a significant source of information for several user communities. Information about the environment (including observations, models and all downstream products) is ultimately a commodity that flows according to forces, restraints, filters, and feedbacks that are applied along the information flow path. These mechanisms can transform the information to generate positive as well as negative outcomes for end users (e.g., economic gain, governmental control, private control, quality of life for urban dwellers, etc.). Recognizing the interplay between these mechanisms and how they affect the outcomes is key for understanding how and why urban meteorological monitoring and forecasting capabilities are not being effectively utilized.

Certain restraints and filters that affect the flow of data are worth noting. First, considerable resources (funds, manpower, infrastructure) are required to render data into a form that is user friendly. For example, most emergency management agencies do not have the resources to translate large amounts of unprocessed data into summary information that informs decision making; with stronger relationships and more collaboration, this challenge could be overcome. Second, there are many throttles that restrain the flow of information, such as data security, proprietary concerns over collected data, researchers wanting to publish their data before providing it to others, and preventing harmful or "bad" information from being projected.

Therefore, in addition to the basic need for data to be made more available to end user groups, it is critical that several data sharing issues, including quality assurance and metadata (Grimmond abstract, Appendix A), are addressed by the research and weather services communities as well as end users. Quality assurance is important because it results in internally and externally consistent standards of the data, which would be useful for effective translation of data from measurement to use. Metadata are especially important because they are all the pieces of information necessary for data to be independently understood by users, to ensure proper

BOX 2.4
Weather-Related Tools Utilized by the Seattle Public Utilities
(adapted from workshop presentation by James Rufo Hill, Seattle Public Utilities)

Seattle Public Utilities (SPU) is a department within the City of Seattle that provides drinking water, drainage and wastewater services, and solid waste services to 1.3 million customers (SPU, 2011). Seattle has a misleading reputation for persistent precipitation; the frequency and amount of participation can be quite variable.

Because of this variability, SPU has a long history of managing resources according to the water cycle and is a long-time user and shaper of various weather products. In 2006, SPU partnered with the Mesoscale Analysis and Forecasting Group[a] at the University of Washington to design Seattle RainWatch, a forecasting tool that predicts local rainfall patterns for the next hour and provides 1- to 48-hour rain accumulation totals. It uses rainfall estimates derived from NWS radar data that are calibrated with local rain gauges (in particular SPU gauges) to improve accuracy over other radar-only indicated precipitation estimate products. Seattle RainWatch gives SPU a one-hour window to identify which neighborhoods in the city will experience the highest rates of rainfall. Key operators, managers, and crews receive maps generated from Seattle RainWatch to help them quickly identify where resources should be deployed to ensure storm drains are clear and citizens are alerted (see figure below).

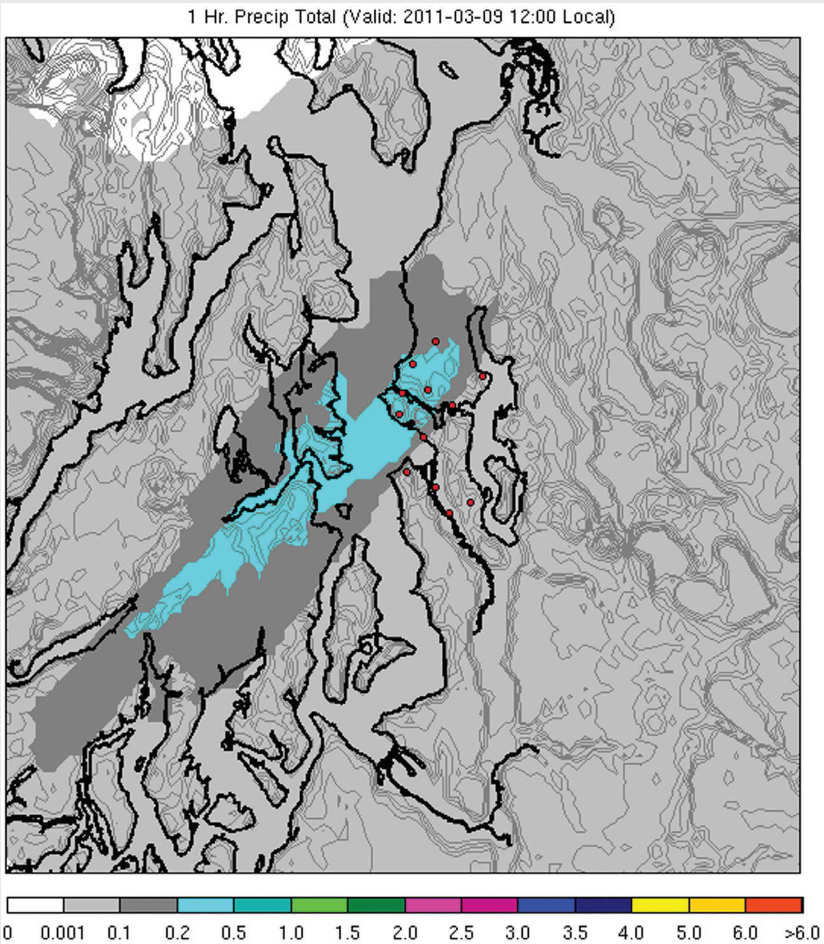
SPU also uses SNOwpack TELemetry (SNOTEL), an automated system that collects snowpack and related climate data in the Western United States, including Alaska. Data on snowpack is critical to SPU because 50-80 percent of the water supply in this region arrives as snow (NWCC, 2009).

Streamflow Forecasting Computer Model System (SEAFM), another tool used by SPU, is a model that is designed to repeatedly simulate the current hydrologic state of the watershed. It can also be used to analyze and assess various future reservoir operating scenarios. It produces probabilistic streamflow forecasts up to 12 months by utilizing the latest climate forecasts from the National Weather Service (NWS) (SPU, 2006).

Seattle RainWatch, SNOTEL, and SEAFM are just some of the tools that allow SPU to make short and longer term preparations in managing reservoir levels, ensuring drainage systems are functioning in the city, and providing drinking water.

---

[a] *http://www.atmos.washington.edu/~cliff/cliff.php.*



Example of a 1-hour RainWatch forecast (total precipitation expected in inches). SOURCE: James Rufo Hill, Seattle Public Utilities, *http://www.atmos.washington.edu/SPU/*.

stewardship of the data, and to allow for future discovery (NRC, 2007b). This information should include, at a minimum: a thorough description of each data set—including its spatial and temporal resolution; the time and location of each measurement, and how the data were originally collected or produced—and a thorough documentation of how the data have been managed and processed (NRC, 2007b).

Short-Term Weather: Longer Forecast Lead Times, Accuracy, and Confidence

To safeguard their services, agencies rely heavily on meteorological forecasts, as do emergency planners for extreme events (e.g., blizzards, heat and cold waves, coastal storms; Figure 2.2). In the transportation sector, for example, each year nearly 700,000 people are injured and over 7,100 perish in weather-related road crashes (FHWA, 2011). Weather is also the leading cause of nonrecurrent traffic congestion, which in turn results in spikes in greenhouse gas emissions (FHWA, 2011). Precise and timely weather information and forecasts enable the traveling public to arrive at their destinations safely and efficiently. A national survey indicates that, outside road closures, information on weather conditions and forecasts are

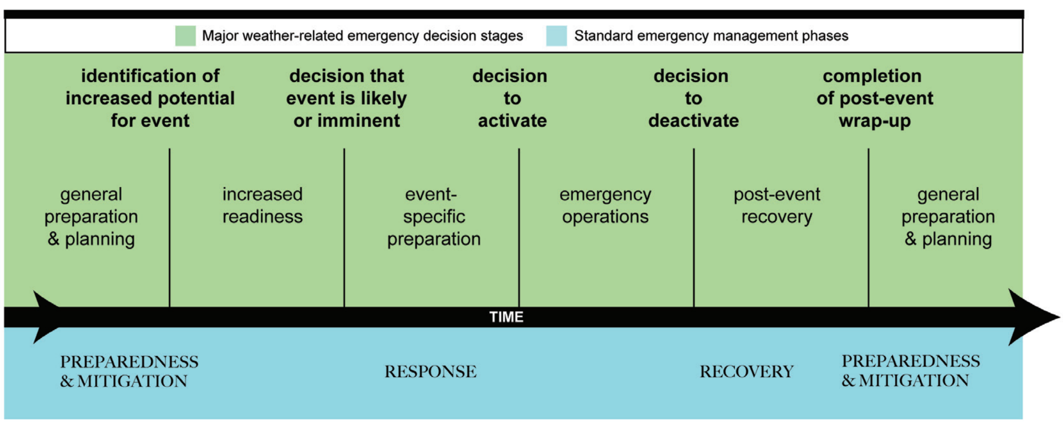


FIGURE 2.2 Emergency planners typically go through several decision making steps as hazardous weather event information becomes available. The vertical lines in the green part of the figure indicate significant decision points that separate major weather-related decision-making stages. As shown in the blue part of the figure (standard phases of emergency management [Godschalk 1991]), the increased readiness, event specific preparation, and emergency operations stages coincide with the response phase. SOURCE: Morss and Ralph, 2007. ©American Meteorological Society. Reprinted with permission.

the most in-demand items for drivers, more so than information on traffic accidents and points of interest (AMS, 2011). Similar to the traveling public, freight haulers by and large operate with very limited weather information. This leads to the loss of several billion dollars annually (Drobot, 2011). In addition, many emergency medical service (EMS) drivers lack accurate and timely weather information, which can lead to increased risk of mortality in patients (Drobot, 2011).

As many agency representatives at the workshop pointed out, being ill-prepared for an adverse event typically has a much higher penalty than preparing for what turns out to be a non-adverse event, and thus agencies would rather err on the side of caution. Improvement in lead times and forecast accuracy are important because they could help reduce false negatives (forecasting a non-adverse event that turns out to be adverse). This could also help reduce false positives (forecasting an adverse event that turns out to be non-adverse) which could help lessen the unnecessary expense of mobilizing the workforce.

Ultimately, providing better evaluations of the plethora of simple to complex urban models and parameterizations under a wider range of conditions (both weather and land surface characteristics) could help the general public be better prepared for adverse events in urban areas.

Long-Term Prediction: Better Forecasting of Extreme Events and Trend Detection

Long-term climate change is expected to affect short-term weather patterns, including a potential increase in extreme weather events (Meehl et al., 2000). Urban areas may be particularly vulnerable. For example, the urban environment will exacerbate climate change-related problems like the potential increases in the frequency and intensity of flash floods (with forced run-off, drainage, and traffic problems likely exacerbating the impact) and increases in the frequency and severity of high levels of heat (exacerbated by neighborhood-scale areas of greatly enhanced excess heating and lack of ventilation; see Box 2.5).

Many workshop participants asserted that it is crucial that the field of long-term forecasting, which traditionally has excluded the urban signal, further develop methodologies to include the urban area. Advances in local climate downscaling techniques[1] will help with achieving this goal in the medium term. It is important to note that improvements in global climate

[1] Downscaling global circulation models to the regional and local level.

BOX 2.5
Central Texas Climate Change Environmental Public Health Indicators Tracking Tool
(adapted from workshop presentation by George Luber, CDC)

Austin, Texas, like several cities in the Unites States, is considering climate mitigation and adaptation policies that aim to reduce the threat to public health and local infrastructure. In particular, public health officials in Austin are concerned of the threat from extreme events that may increase due to climate change.

With a population close to 800,000 people, Austin is the fourth-largest city in Texas and the 15th most populous city in the U.S. In order to help make appropriate public health adaptations, the City of Austin, in partnership with the Centers for Disease Control (CDC), developed the Central Texas Climate Change Environmental Public Health Indicators Tracking Tool (EPHI Tracking Tool).

This vulnerability assessment tool aggregates health, weather, demographic, policy, and environmental data and indicators in a Geographic Information System (GIS) viewer at the census block group scale. The goal for this tool is to create baseline indicators of vulnerability to extreme heat and river flooding (identified as the top two extreme events in Travis County, where Austin is located) at which the City's current and future climate change mitigation and adaptation policy-making priorities can be targeted to reduce burdens on vulnerable populations. The maps generated by the EPHI Tracking Tool increase the City of Austin's ability to create locally appropriate, targeted interventions, such as identifying areas for tree-planting programs and considering future land-use policies.

In the future, the City of Austin would like to improve this tool by gathering input from stakeholders to enhance the user experience. They would also like to add indicators for air quality and extreme weather evacuees (e.g., impact of increased numbers of hurricane evacuee populations being displaced from the Texas Gulf Coast to Travis County). Tracking tools, such as the EPHI that map health data with environmental data, allow city officials to assess community health vulnerability related to climate change, guide policies, and adapt interventions that are specific and operational at the local level.

models (GCMs) to better capture changes in extremes will also be crucial for improving downscaling techniques.

Trend detection is another important need identified by several users at the workshop. When is the change in climate large enough to implement adaptation change, particularly under extreme events? For example, were the spring 2011 floods in the Midwest the old 500-yr flood, or the new 50-yr flood? Accurately answering questions such as these requires that scientists have a better understanding of the current climate regime. Cities are planning staged adaptation strategies, some of which take a long time (e.g., growing trees) and some that might allow for more rapid impacts (e.g., reflective roofs and pavements). It is critical to work closely with end users to develop methodologies and protocols to identify weather and climate trends. This work involves both a monitoring aspect (i.e., an understanding of what has occurred retrospectively) as well as extrapolation into the future.

Understanding the Impact of Specific Environmental Intervention Scenarios

Many cities are deploying large scale greening or albedo modification plans, and models are needed to help justify or understand the expected benefits (or unintended consequences) of these programs (Stone abstract, Appendix A). For example, "vertical gardens," originally an experiment in 1988 by Patrick Blanc, a French botanist, are becoming increasingly popular in some cities (Figure 2.3).

FIGURE 2.3 A "vertical garden" on Jean Nouvel's Musée du quai Branly in Paris, France. SOURCE Patrick Blanc, *http://www.verticalgardenpatrickblanc.com/*.

BOX 2.6
The Phoenix Urban Form Project

With a population close to 1.5 million, Phoenix, Arizona has experienced rapid suburban growth since the late 1940s. Downtown Phoenix, located at the center of the Phoenix metropolitan region, covers an area of 2.6 square miles. Discussion sparked by a new light rail line connecting downtown Mesa, Tempe, and Phoenix and the decision to locate a new campus for Arizona State University in downtown Phoenix has centered on future development of Downtown Phoenix and how to best utilize the many parcels of empty land surrounding the urban core.

The city initiated the Downtown Phoenix Urban Form Project in order to transform the empty land into high density, mixed-use districts. This new development plan is called the “Connected Oasis” (see figure below). It outlines an “open space pedestrian-intensive network of shaded streets, pocket parks and dedicated ‘green connectors’ tying together major downtown destinations and retail zones” (Studio Ma, 2011). The extreme summer heat in Phoenix poses significant challenges to the design of public open space and influences the new development plan. To balance the competing needs of thermal comfort and the urban heat island effect, the proposed zoning code calls for (1) the creation of a building/street profile that optimizes the flow of air through the building mass to flush out accumulated heat and pollutants; (2) shading of ground and building surfaces to improve the thermal comfort of pedestrians; (3) utilization of highly reflective and emissive building materials; and (4) the creation of “cool pockets” along sidewalks and other pedestrian routes to enhance thermal comfort (Studio Ma, 2011).

Another example of greening, but on a larger scale, is the Downtown Phoenix Urban Form Project, which describes a greening plan for downtown Phoenix. This effort proposes a zoning code that “optimizes building massing and street canyon sections to balance the competing needs of thermal comfort and the urban heat island effect” (Box 2.6). As another example, MillionTreesNYC—launched by the Parks Department and New York Restoration Project, in collaboration with community-based and non-profit groups; city, state, and federal agencies; corporations and small businesses; developers, architects, and landscape architects; private-property owners, and the general public—plans to plant and care for one million new trees in New York City over the next decade.[2] Models are needed to characterize how much these efforts will reduce temperatures (and also to explore impact on air quality at street levels, since vegetation may limit ventilation by the wind).

Several workshop participants also identified a need for more scenarios to be modeled, such as impacts of changes in vegetation, albedo, or building

[2]*http://www.milliontreesnyc.org/html/about/about.shtml.*

The Phoenix Urban Form Project outlined a new development plan to create a "connected oasis" that allows for street vibrancy, hospitality, pedestrian comfort, and interesting landscape. SOURCE: Studio Ma, *http://studioma.com/*.

type on meteorological endpoints. For example, results of small pilot programs—such as a pilot white roof heat island mitigation program in New York City—examining the impact of high-albedo white roofs to reduce surface temperatures, shows promise for large scale applications (Gaffin et al., 2012; Figure 2.4). Modeling the impacts of large-scale applications of such scenarios (Akbari et al., 2009; Oleson et al., 2010a) is important (as well as addressing the practical aspects of keeping the "white" surfaces clean so that they function as intended) to better understand how these applications may affect the atmosphere. Additional scenarios that could be modeled include higher-albedo land use changes at grade (e.g., pavements), although the technological challenges associated with land use changes at grade are greater than for roofs.

In addition, it appears end user groups concerned with sustainability are not yet confident in urban meteorologists' ability to accurately model the complex effects that impact quality of life in the urban environment of cities.

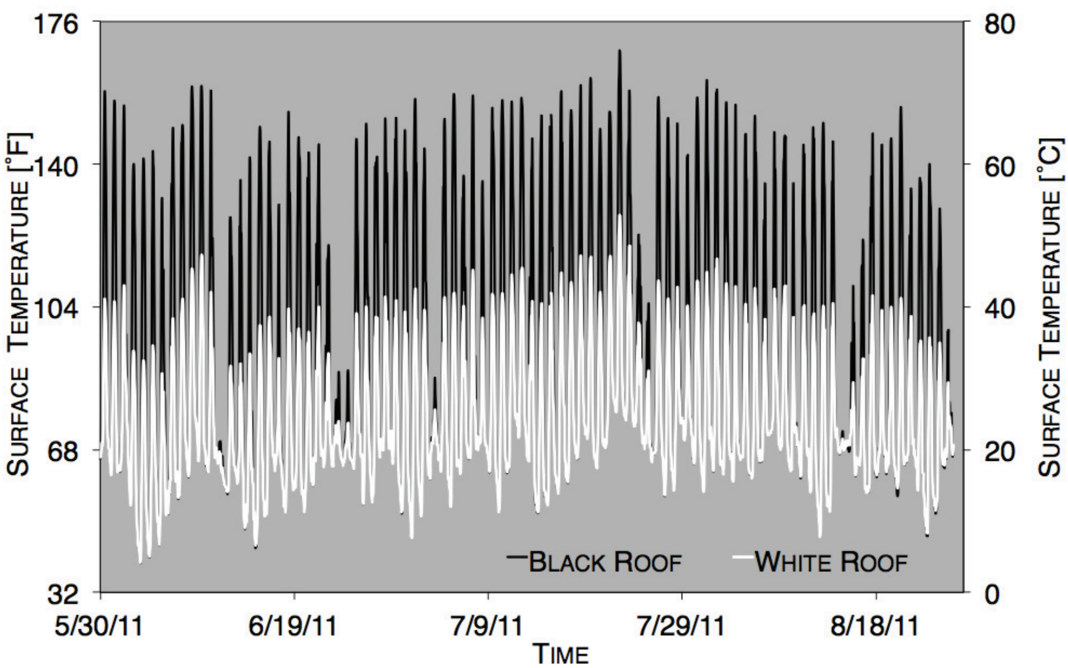


FIGURE 2.4 The pilot white roof heat island mitigation program in New York City. Results of white vs. black roof surface temperatures. While both colors of roof fluctuate with day and nighttime temperatures, the white roofs stay consistently cooler during the daytime. (*www.nyc.gov/coolroofs*) SOURCE: Gaffin et al., 2012.

For example, complex models that consider street, road and building impacts have not consistently been able to improve on simple model forecasts.

Coupling of Urban Meteorological Models with Other "Cascading Events"

Many workshop participants stated that development of coupled models with meteorological and other parameters would be particularly relevant for end users.

Coupled land-ocean-urban effects. Given that a majority of our large cities are in coastal regions, coupled land-ocean-urban effects are becoming increasingly important. The land-urban region does not act independently from the neighboring ocean, and vice versa. There are complex interactions and feedbacks within the coupled environment. Several recent papers highlighting the impact of air-sea interaction processes such as urban heat islands and sea breeze fronts on the urban environment illustrate this point (see Carter et al., 2011; Holt et al., 2009; Thompson et al., 2007). This work is complex in that it may involve the coupling of different modeling frameworks (e.g., NWP, urban canopy models, dispersion-transport, etc.). Coupling of computational fluid dynamics models (CFD) with Numerical Weather Prediction (NWP) models and fast-response emergency management (EM) tools is a good example of this (Boris et al., 2011).

Coupled atmospheric chemistry and meteorological models. A better understanding of gradients in ambient air pollution concentrations and their variation through coupled atmospheric chemistry and meteorological models could be useful to many end user groups. Improved particulate matter predictions could result in increased accuracy and spatiotemporal resolution and better representation of the diversity of (natural, anthropogenic, primary and secondary) sources and risks.

Applied weather forecasts for energy demand. As sustainable development efforts lead to more substantial eco-district[3] (i.e., neighborhood scale) level energy management systems, such as district heating/cooling[4] and electric vehicle connection to grid, there will be an increased need for management products that merge local scale weather forecasts with local scale energy demand and renewable supply availability forecasts. Such products

[3] A concept that aims to reach sustainability goals through action at a neighborhood level.

[4] A method of delivering heating and cooling to surrounding buildings in an eco-district using a highly efficient energy plant.

would allow for optimum use of resources in anticipation of weather events. For example, buildings could be precooled prior to a heat wave, warming shelters preheated before a cold wave, and electric vehicles could be used as energy storage to meet summer daytime peak load needs.

Applied weather and climate forecasts for public health. From a public health perspective, high temperatures influence the risk of cardiovascular and respiratory illness and infectious diseases (Patz et al., 2005). Accurate seasonal forecasts may enable public health systems to rapidly monitor, identify, and respond to new climate change and weather related health risks. Accurate forecasting of inundation areas for evacuation during coastal storms would also enable the public health and emergency response systems to respond more effectively.

UNDERUTILIZED URBAN FORECASTING AND MONITORING CAPABILITIES

Several areas were identified at the workshop where urban meteorological forecasting and monitoring capabilities are currently underutilized. For example, a recent American Meteorological Society report (AMS, 2011) found that drivers can make safer decisions about their travel plans and react appropriately during potentially compromised conditions when high quality weather information, including both current observations and forecasts, has been communicated to them in a timely and effective manner. However, there are several technical, financial, societal, and institutional barriers as discussed below that need to be overcome before the full potential of mobile observations can be realized by the weather and transportation communities.

Although forecasting and monitoring capabilities may exist, there appears to be a lack of accessible products, such as weather applications for smartphones; websites with information relevant to special urban problems such road hazards, flash floods, and drainage problems; and neighborhood-level alerting for areas with particular susceptibility to excessive heat and pollution hot spots. Several workshop participants commented that precision urban weather products are needed to provide personalized, local information that is readily accessible and easy to understand. The creation and provision of these types of products requires close, ongoing collaborations between urban meteorologists and departments of transportation, public health agencies, centers for disease control, urban planners, and others.

Probabilities may also be important to consider with respect to providing longer forecast lead times (see sections above on short-term weather and long-term prediction). Probabilistic forecasting is a major advance in the field of urban meteorology, but to date it has been used primarily for research applications and not for other end users. There is an underutilization of "lead time" and uncertainty/probability information that operational centers can provide. This is because of the need for greater computing power, but also because the end users may not be educated on how to properly interpret model-generated probabilistic information. Similarly, the modelers may not know how to best communicate probabilistic information. As such, provision of probabilistic information will need to be accompanied by better communication of uncertainties to the general public (NRC, 2006).

COMMUNICATIONS ACROSS DISCIPLINES

Improved intra-and extra-community communications on resources, capabilities, and current knowledge is a significant crosscutting issue. The lack of such communications is also one of the reasons for underutilized urban forecasting and monitoring capabilities discussed in the previous section.

Current State of Communication and Exchange Between Communities

In some cities, substantial amounts of data are being generated by urban meteorologists, and a host of tools are available for analysis. However, these resources are not being fully utilized by end users. Workshop participants identified several reasons for the lack of exchange between communities.

Lack of cross-fertilization and cross-discipline training. The models and capabilities may exist at the urban meteorological end, but local management and operations staff are not trained to use the capabilities; they may not even know what they can obtain from the various capabilities. A common theme of "we don't know what we don't know" (regarding existing capabilities) was present at the workshop. Successful cross-fertilization typically involves the urban meteorologist and the end user communicating with each other on a regular basis, leading to a greater understanding of capabilities on both sides.

User needs are not being translated to the urban meteorological community. Exchanges between urban meteorologists and end users need to be encouraged during project planning phases, so that outputs from the urban meteorological community are tailored to user needs (see Section 1). There are important limitations with respect to resources and funding to make such collaborations or discussions successful and worthwhile. For instance, currently, many U.S. cities do not have validated health-based criteria for issuing heat advisories, watches and warnings. The "Heat Health Watch Warning System," based on synoptic weather classification[5] promoted by the NWS, has not been demonstrated to be superior to setting appropriate health-based criteria for simpler weather metrics (e.g., Metzger et al., 2010).

Constraints on end users (i.e., institutional barriers). Due to the nature of operations and funding sources, procurements and services requested by certain groups and sectors are governed by various laws, regulations, agreements, and manuals, thus possibly limiting interactions with relevant representatives of the urban meteorological community. It is important for this community to acknowledge that meteorological information is just one of many inputs into most end users' considerations and decision-making.

These apparent barriers can be overcome by establishing better relationships at the local level. To gain a better understanding of the different constraints by users, end-to-end dialogue as well as end-to-end-to-end dialogue could be developed between end users and urban meteorologists. An end-to-end-to-end dialogue consists of multidirectional communication and sustained interactions among researchers, application developers, and multiple decision makers and is done over several iterations to coproduce information that is useful for various societal applications (Morss et al., 2005). There are numerous opportunities for the urban meteorological community to interact with the end user community both locally and regionally, especially during the mitigation and preparedness phase of planning. The end user community also has a responsibility to reach out and understand the resources and capabilities that exist within the urban meteorological community.

Environmental (and other) data are ultimately a commodity, as discussed in the section on Data Access and Data Sharing Needs.

The Need for Strengthened and Improved Communication

The ultimate goal of the applied science of meteorology is to help society—both in the collective sense and as individuals—better anticipate and take appropriate response to an ever-changing environment or an imminent risk. The effectiveness of improved science is measured as much by society's response to the new information as the quality of the science itself. Weather impact forecasts are needed that communicate hazards and their impacts on people and infrastructure, not simply the meteorological

[5] *http://www.noaawatch.gov/themes/heat.php.*

conditions. To create and communicate weather forecast information that is usable to end users in ways that inform their decision-making requires social science research (conducted in partnership with meteorologists) and ongoing relationships with end users.

Several workshop participants noted that it is crucial that the science of risk perception and risk communication be further applied to evaluate and improve effective dissemination of urban weather and climate risks to diverse urban populations and policy makers. Failure to do so could undermine all the upstream science, observations, and modeling.

A great deal of discussion at the workshop revolved around communicating information specific to urban meteorology and its impacts on the general public, including real-time hazard releases, observations of flooding, and neighborhood-level excessive heat and pollution advisories, as well as short-term forecasts for hazards). While this report cannot discuss the finer points of communication practice in detail,[6] most presenters at the workshop made note of important communication-related needs that can be defined broadly as fitting within risk communication. Typically, risk communication refers to the set of communications conducted prior to the incidence of a threat (often designed to avoid a crisis).

Threat perception differs by the type of threat and by the perspective of those assessing the threat to themselves and their operations. For example, most deaths and illnesses caused by excessive heat cannot be directly observed or attributed on a case by case basis. The risks posed by heat waves, therefore, may be underestimated by both mass media and the general public compared to other natural or manmade disasters (e.g., fires, floods, plane crashes). It is important that the general public identifies the risks as well as how to respond to them. Sharing anecdotes and stories from affected people might be a more effective way of communicating risk than statistical estimates of public health impact. There is also a need for both urban meteorologists and emergency managers to work with communication experts to identify better ways of communicating risks.

Good communication practices necessitate establishing relationships prior to the incidence of a hazard, establishing credibility, and providing for expedient information transfer, as well as utilizing longer lead-times with greater spatial resolution prior to the incidence of hazards (i.e., providing for mitigation). If urban weather products from multiple vendors, whether private or public, were recognized by end users to be in conflict, the

[6]See NRC (2006) for more information on ways to improve the generation, communication, and potential use of uncertainty information for hydrometeorological forecasts.

credibility of the corpus of information presented could be diminished and actionability could be reduced.

The end goal of successful communication of usable forecast information is the protection of life and property, as well as enhancing economic outcomes for private and public sectors. Including these metrics is important for gauging the success of urban meteorology. It is important to highlight socioeconomic benefits, but it should also be stressed that minimizing negative impacts is as important as maximizing direct positive outcomes. This demands that physical, health, and social scientists need to work far more collaboratively than in the past.

It is important to recognize that most of the discussions here are related to communication practices. Communication is also a social scientific field of study with many subfields. Subfields relevant to urban meteorology and end users include risk communication (as noted), science communication, organizational communication, and mass communication. There are myriad theories, concepts, and lessons from past research that can be applied to the urban meteorology context, and future research would further develop these concepts and theories.

APPROACHES TO STRENGTHEN TIES BETWEEN COMMUNITIES

Advanced Approaches to Training and Workforce Development

Numerous workshop participants asserted that advanced approaches to training and workforce development will be critical in producing the next generation of urban meteorological models and applications. In particular, interdisciplinary approaches are increasingly needed to address critical gaps in the interface between natural, biological, and human systems in the urban landscape. In addition to promoting interdisciplinary team approaches, it is becoming increasingly necessary to cross-train scientists in multiple disciplines. Widespread training of meteorologists about the unique weather and climate features of the urban environment is also important (Grimmond abstract, Appendix A).

To strengthen communication, it should be fostered across scientific disciplines and spatial and temporal timescales (Grimmond abstract, Appendix A). It is crucial that urban meteorologists and end users attend joint conferences (such as the workshop for this report) and each other's professional conferences. It is also mutually beneficial to jointly train graduate students and postdoctoral researchers. For instance, a new postdoctoral training program between the National Center for Atmospheric Research

(NCAR) and the Centers for Disease Control and Prevention (CDC) requires the candidate to stay at NCAR for one year to become familiar with weather and climate prediction, followed by another year at CDC to integrate urban meteorology with public health.

It is also mutually beneficial to jointly train graduate students and postdoctoral researchers as well as exchanging personnel. This will give all groups involved a better understanding of what is available and unavailable in urban meteorology and how and what urban meteorology information is used in decision-making by end users. Promoting the use of interns to work with organizations may be a feasible option; such a process may help to cross-pollinate communities. It may also be beneficial to create funds for end users to undergo training with research groups; existing programs tend to only educate young and new students. Grant programs for senior operations managers would be valuable in supporting their interactions with researchers in the field so that they would not need to rely on specialized contractors in order to stay current. There are also approaches in place by several institutions that require and allow for interdisciplinary discussion, such as the Environmental Protection Agency's (EPA) Requests for Applications[7] targeting community-based participatory research and the National Oceanic and Atmospheric Administration's (NOAA) Regional Integrated Sciences and Assessments (RISA) program.[8]

Design Strategies for Communicating Data and Results Between Communities

Geographic Information Systems (GIS) have become a common software tool across disciplines and communities. GIS-based tools allow for relatively easy data visualization and provide a common data management approach that aids in data sharing among disciplines. Repeatedly, stakeholder communities have requested data in formats like GIS and Keyhole Markup Language (KML) rather than discipline-specialized, complex formats (e.g., hdf, netcdf). Emerging technologies such as agent-based modeling, geo-visualization, mobile GIS, and spatial statistics are also powerful resources for expanding the reach and utility of urban meteorological data, decisions, and warnings.

The emergence of real-time social media (e.g., Twitter, Facebook, YouTube) provide new formats for dissemination, warnings, and research within

[7] *http://www.epa.gov/ncer/rfa/.*
[8] *http://www.climate.noaa.gov/cpo_pa/risa/.*

the urban environment (NRC, 2011a). The notion of "social sensors," in which social networking users are considered as "sensors" and the messages that they share are considered "sensory information," has recently been discussed in regard to other natural hazards (Sakaki et al., 2010) and would certainly offer opportunities in urban meteorological forecasting and hazard alerts. Other common dissemination strategies include traditional media (e.g. television, radio, and internet), text message alerts, and telecommunications. However, along with timely communication facilitated by social networks comes a risk of false information spreading rapidly. There is thus a need to use social media actively for dissemination of information and at the same time also to screen/alert to possibly false information posted via unreliable sources on these networks.

Design Strategies for Data Sharing Between Communities

As mentioned earlier, many federal, state, and city government agencies typically collect environmental data that complement their operational needs. For various reasons, whether legal or institutional, that data is often not shared externally. However, such data may be particularly useful for research and operations in urban meteorology, which could potentially enhance the value of the data for the agency from which it originated. For example, if an urban drainage and wastewater utility shared stream flow and built environment information, it may allow operational meteorologists to disseminate better warnings, and it may enhance the modeling capabilities of research meteorologists. Advancements in such data sharing are likely to have significant impacts to public safety and welfare in urban areas. Conversely, urban meteorology researchers could provide end users with metadata such as raw output, model parameterization and/or biases; highlighting areas for model improvement may invite greater sharing from end users and agencies. An example of effective two-way flow of information is the collaboration between Seattle Public Works and the National Weather Service (NWS), where the utility obtains NWS data and returns water flow data to NWS (see Box 2.4).

Although there are considerable logistical and budgetary constraints, a fully resourced data center could facilitate data sharing. A database system could be created to receive data in real time to allow [approved] users to access it in real time. It could facilitate a number of agencies in meeting their objectives (e.g., rainfall data for flood advisories) and allow wider use of current observations and model products. Ideally the system would have capabilities that include the following:

1. Accepting real-time and older data that undergo quality assurance/quality control
2. Receiving multiple formats of data
3. Accepting metadata (siting, instrument characteristics, sampling) that are regularly updated
4. Developing algorithms that can provide additional information in real time to data suppliers (e.g. outliers, data source not online) that provide extra value for those who are supplying the data
5. Creating a database that can be queried in real time and used for re-analysis
6. Providing modeling tools or model outputs that use the observational data and provide modeling data products that can be used by other end users (e.g. meteorological model outputs that could be used by transport modelers, air quality modelers)

The intention would be to build a smart data system that would enhance the use of current measurements. The model output database would allow development of model ensembles.

Interdisciplinary Urban Testbeds Transitioning Research to Operations

There is an increase in numbers of field programs and testbeds developed specifically to explore urban issues. Some modelers are considering using the data from the urban testbeds to examine quality of life issues. These testbeds provide long-term observations and models for city-specific input into planning (Figure 2.5). They have not necessarily been stakeholder driven from the start, but they have presented opportunities for stakeholders to participate and contribute to project design and outcomes (see Chapter 4 for detailed discussion).

KEY THEMES FROM THE WORKSHOP

A significant focus of the workshop was to discuss the needs of users of urban meteorology information and brainstorm possible solutions and strategies to better meet user needs. Several key themes emerged from this discussion.

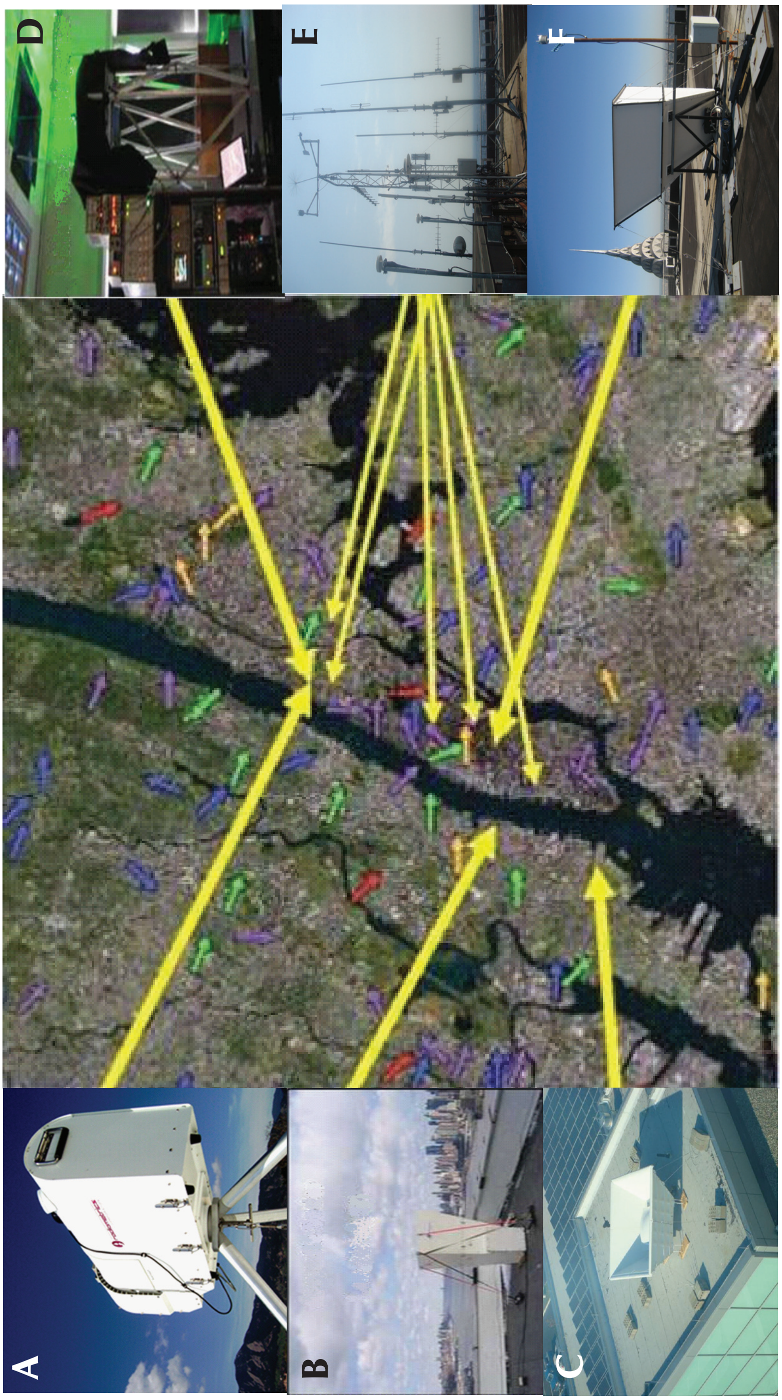


FIGURE 2.5 Locations and pictures of various instruments of the NYCMetNet. (A) Temperature, humidity and liquid water vertical profiler (to 2 km). (B) and (F) Sodar wind profiler to 300/450 m. (C) Radar wind profiler vertical profiler (to 2 km). (D) CCNY Aerosol Raman lidar (to 10 km) and Vaisala ceilometer. (E) Skyscraper-mounted weather stations. Colored arrows are located at the position where weather stations are located and the information is continuously ingested and archived via the NOAA MADIS system. The arrows represent measurement of wind speed and direction. Not shown is a portable eye safe Doppler Lidar, a network of radiation flux observing instruments, a Nephalometer and other particulate matter measurement stations to sample ground level aerosols for comparison to the vertical profiling instruments. SOURCE Mark Arend, CCNY Optical Remote Sensing Lab and NOAA CREST.

- A clear mechanism to help the urban meteorological community better identify user groups, reach out to them, and begin an ongoing dialogue to assess and better meet their needs has yet to be identified.
- It was apparent at the workshop that end users of urban meteorological information are heterogeneous and cover a vast spectrum of job roles, goals, needs, experience, and understanding. Acknowledging and understanding this heterogeneity is important for the urban meteorological community to better understand, interact with, and meet the needs of end users.
- Strong communication early in the process and throughout is key to successful coordination. This is a common theme present in several case studies, and examples discussed in this chapter highlighted success stories where the needs of the end user were met to a large degree (see Boxes 2.3, 2.6). In some cases, the end users worked directly with researchers to develop the tool they required (see Boxes 2.3, 2.4), which helped ensure they received a tool that could be tailored to their specific needs. The hallmarks of effective communication are a better understanding of capabilities on both sides; the successful translation (through collaboration) of user needs to the research community and research products to the end user community; and a better understanding in the research community of institutional constraints that end users face.
- Many workshop participants noted that more coordinated data sharing strategies among various agencies and training of various end user communities could help them utilize existing data. Several other data sharing issues are lacking, including quality assurance and metadata needs that could be addressed by the research and weather services communities as well as the end users. Coordinated data formats, available metadata, and novel dissemination strategies are increasingly essential as urban meteorological data and model output cross the research-to-operations "valley."
- The workshop revealed an underrepresentation of urban meteorological, climatological, and field coursework and training at all educational levels. Advanced approaches to training and workforce development will be critical in producing the next generation of urban meteorological models and applications. It is important that students and professional stakeholders continue to be properly educated as the complexities of the urban meteorological/climatological environment evolve and as the academic community approaches cities as coupled human and natural systems that need to be sustainable. To strengthen training, it is crucial that urban meteorologists and end users attend joint conferences (such as the workshop for this report) and each other's professional conferences. It is also mutually beneficial to jointly

train graduate students and postdoctoral researchers as well as exchanging personnel. This will give all groups involved a better understanding of what is available and unavailable in urban meteorology and how and what urban meteorology information is used in decision-making by end users.

Above all, it is essential that the urban meteorological community understands what data are needed by end users that are not currently produced or not conveyed in usable ways to end users. Creating and communicating weather forecast information that is usable to end users in ways that inform their decision-making requires social science research (conducted in partnership with meteorologists) and ongoing relationships with end users.

3

Science and Technology

Various reports have discussed the critical role of urban meteorological observations and forecasting for various aspects of society, such as public health, public safety and security, transportation, water resource management, storm water runoff, and economic development. Although some progress is evident since these reports, cities still pose a number of difficult challenges for both the scientific and end user stakeholder communities that are not adequately addressed by current meteorological observation, forecasting, and information dissemination technologies. This chapter assesses current capacity, emerging technologies, and future needs related to observing, modeling, and forecasting in the urban environment. A brief review of current urban meteorological knowledge is appropriate to provide context for the issues at hand.

As with broader weather systems (i.e., floods, thunderstorms, blizzards, and hurricanes), urban meteorological processes are directly relevant to societal activities and can significantly affect economic, hazard management, and public-health decision-making. For example, in 2010 and again in 2011, the capital of the United States, Washington, D.C., was crippled by record-breaking snowstorms. Scores of federal workers and even the President experienced transportation and work delays as a result.

During the summer of 2010, the country experienced record-breaking urban flooding in places like Atlanta, Georgia, Nashville, Tennessee, and Oklahoma City (Shepherd et al., 2011). In 2011, the south central U.S. experienced extended periods of very extreme heat (>100 degrees Fahrenheit) for days on end. During this regional-scale heat wave event, urban heat islands in cities like Dallas and Oklahoma City likely caused prolonged heat exposure at night (Figure 3.1). Lessons from the 2003 European Heat Wave and the 1995 Chicago Heat wave (Changnon et al., 1996; Menne, 2003; Beniston, 2004) have indicated that heat mortality is exacerbated by excess heat stored in urban landscapes—the well-known Urban Heat Island (UHI) effect.

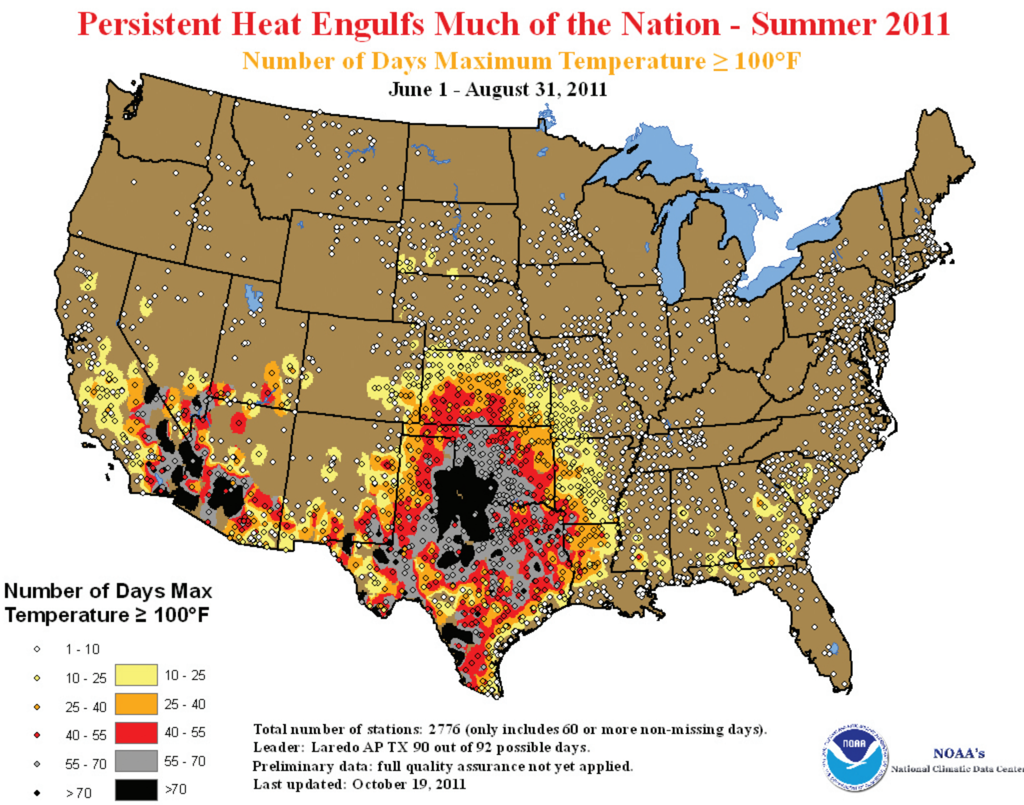


FIGURE 3.1 Number of days that maximum temperature exceeded 100 degrees (F) from June 1 to August 31, 2011. Urban heat islands in cities like Dallas and Oklahoma City likely caused prolonged heat exposure at night. SOURCE: NOAA.

There have been many reports that highlight the effects of anthropogenic greenhouse gases on future weather and climate and a very clear sign of human alteration to atmospheric processes is evident (NRC, 2010b; NRC, 2011b; IPCC, 2007; USGCRP, 2009). There is also emerging interest in understanding the role of urbanization on the climate system, which includes weather (IPCC, 2007).

Cities change properties of the land surface and subsurface, and are also known to influence atmospheric circulation patterns at various spatial scales (Hidalgo et al., 2008; Grimmond et al., 2010b). The high building densities and sparseness of vegetation in cities makes urban surfaces typically much rougher and drier than rural surfaces. In addition, the three-dimensional nature of urban environments affects a number of parameters such as evaporation rates, absorption and reflection of solar radiation, and storage of heat, as well as wind and turbulence fields (Figure 3.2). Gaseous and particulate matter emissions (Figure 3.3) also may contribute to land-atmosphere interactions. Classifications for urban land cover zones have been developed (Stewart and Oke, 2009 a, b) that are useful for documenting metadata of urban monitoring sites and for characterizing surface features in urban modeling tools.

FIGURE 3.2 Variability of land cover zones in New York City characterized by: differences in surface morphology, percentage of surface cover, and sources of heat, water, other gases, and particulates. SOURCE: Sue Grimmond and Bing Maps.

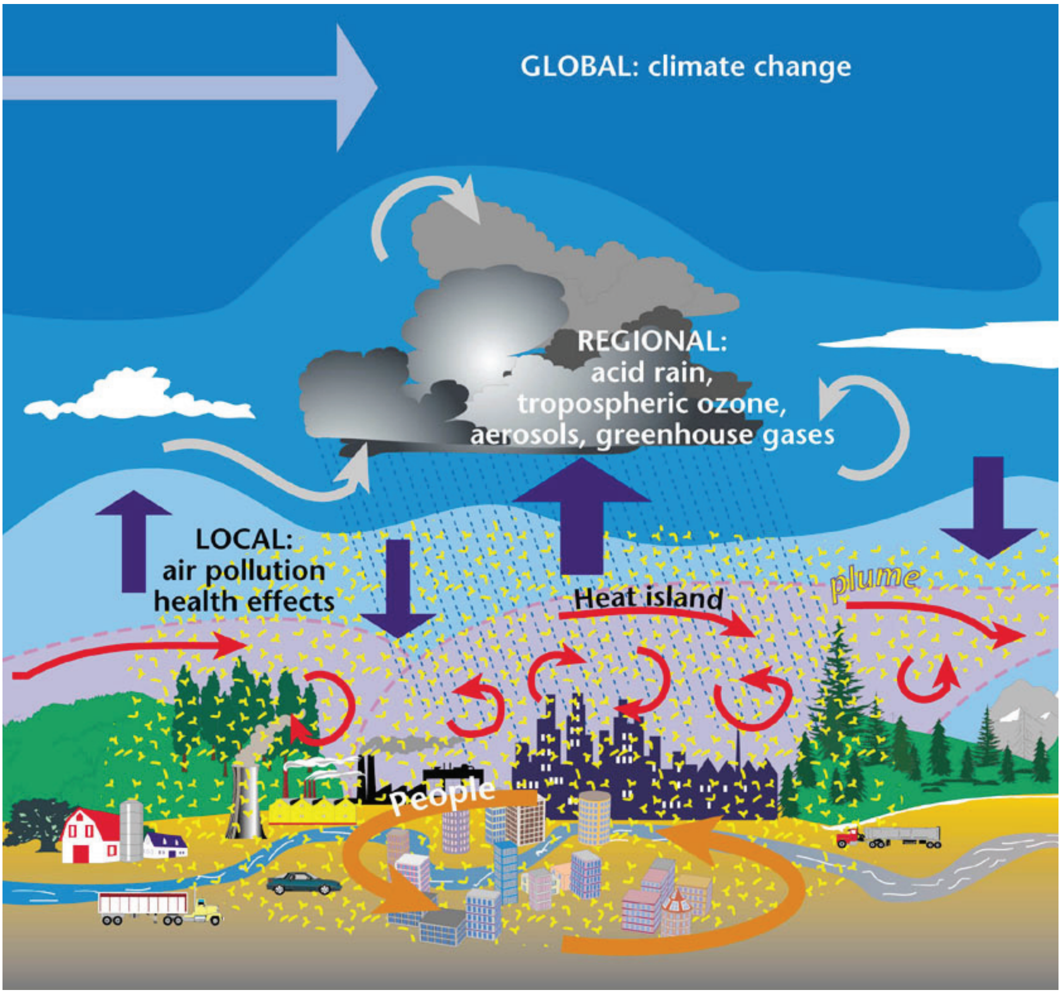


FIGURE 3.3 Urban-atmosphere interactions. SOURCE: adapted from Hidalgo et al., 2008. ©John Wiley & Sons Ltd. Reprinted with permission.

Overall, urbanization results in a suite of complex land surface atmosphere interactions that modify thermodynamic, radiative, dynamic, and hydrometeorological processes within the urban area and its surrounding regional footprint, particularly downwind of the city. Extreme weather and climate events in cities typically occur during unfavorable regional-scale conditions exacerbated by global warming trends and local, urban effects (Hunt et al., 2007). As an example, regional-scale heat waves, which are expected to become more frequent because of climate change, in combination with urban heat island development, exacerbate heat stress for urban populations (Zhou and Shepherd, 2009; Stone et al., 2010). Seto and Shepherd (2009) noted that "the built environment characterized by urbanization is a significant forcing function on the weather climate system because it is a heat source, a poor storage system for water, an impediment to atmospheric motion, and a source of aerosols (e.g., pollutants)." Table 3.1 illustrates several pathways by which urban processes can influence meteorology or climate.

URBAN METEOROLOGY: A SYNOPSIS OF THE SCIENCE

The urban heat island's role on regional and global climate has been the subject of much research (Oke, 1982; Arnfield, 2003; Roth, 2007; Yow, 2007; Hidalgo et al., 2008; Grimmond et al., 2010b) and is one of the most well-studied and familiar manifestations of urban weather modification (Figure 3.4). Research shows that it is spatially correlated with regional land-use and land-use change. During the early phases of urban development, multiple land covers—bare land, vegetated areas, agricultural plots, and built-up areas—emerge in close proximity with each other.

As urbanization increases, resulting in reduced vegetated surfaces, the spatial pattern of the urban heat island becomes less scattered and more intense (Imhoff et al., 2010). Stone et al. (2010) recently argued that temperature increases in sprawling urban environments were as likely (or more likely) to be attributed to urban landscape changes as greenhouse gas warming (see Stone abstract in Appendix A). It should, however, be noted that the types of data used to define UHI characteristics play an important role, and the discussion of UHI often lacks important information about data sources and site characteristics (Stewart, 2011). In situ observations of air temperatures from measurement sites within the urban canopy layer provide information about the urban-canopy-UHI. Remotely sensed observations provide information about boundary-layer heat islands (above the urban canopy layer in the atmosphere) and surface heat islands.

In general, weather patterns in and near cities depend both on the degree of urbanization—characterized by the above mentioned changes in land surface characteristics, subsurface properties, and chemical composition of the atmosphere—and on larger scale meteorological conditions (Mestayer and Anquetin, 1995). For situations with moderate-to-high wind speeds, an urban plume with warmer, polluted air is advected downwind of the city (Figure 3.3). Under such conditions, the lowest portion of the urban boundary layer (UBL), the surface layer, can be divided into two main

TABLE 3.1 Various Pathways for Urbanization to Affect the Weather Climate System

The column headings represent three ways that urban environments can affect weather and climate. The row headings represent different weather processes affected by each of the three. For example, urban land cover affects/causes an urban heat island because urban land cover modifies the surface energy budget gradients—develops and dominates the RSL wind and turbulence patterns. This shear layer also controls the turbulent exchange and ventilation between the UCL and the flow above average roof level, which is typically highly instantaneous and controlled by coherent structures (Christen et al., 2007). Overall, the RSL plays a critical role, and its properties need to be properly resolved in numerical models for accurate urban weather and air-quality forecasts.

	Urban Land Cover	Urban Aerosols	Anthropogenic Greenhouse Gas (GHG) Emissions
Urban Heat Island and Mean Surface Temperature Record	Surface Energy Budget	Insolation, Direct Aerosol Effect	Radiative Warming and Feedbacks
Wind Flow, Dispersion, Transport, and Turbulence	Surface Energy Budget, Urban Morphological Parameters, Mechanical Turbulence, Bifurcated Flow	Direct and Indirect Aerosol Effects and related dynamic/thermodynamic response, Dispersion and Transport	Radiative Warming and Feedbacks
Clouds and Precipitation	Surface Energy Budget, UHI Destabilization, UHI Meso-circulations, UHI-induced convergence zones	Aerosol indirect effects on cloud-precipitation microphysics, insolation effects	Radiative Warming and Feedbacks
Land Surface Hydrology	Surface runoff, reduced infiltration, less evapotranspiration	Aerosol indirect effects on cloud microphysical and precipitation processes	Radiative warming and feedbacks
Carbon Cycle	Replacement of high net primary productivity (NPP) land with impervious Surface	Black carbon aerosols	Radiative warming and feedbacks, fluxes of carbon dioxide
Nitrogen Cycle	Combustion, fertilization, sewage release, and runoff	Acid rain, nitrates	Radiative warming and feedback, NOx emissions

[a] SOURCE: Adapted from Seto and Shepherd, 2009.

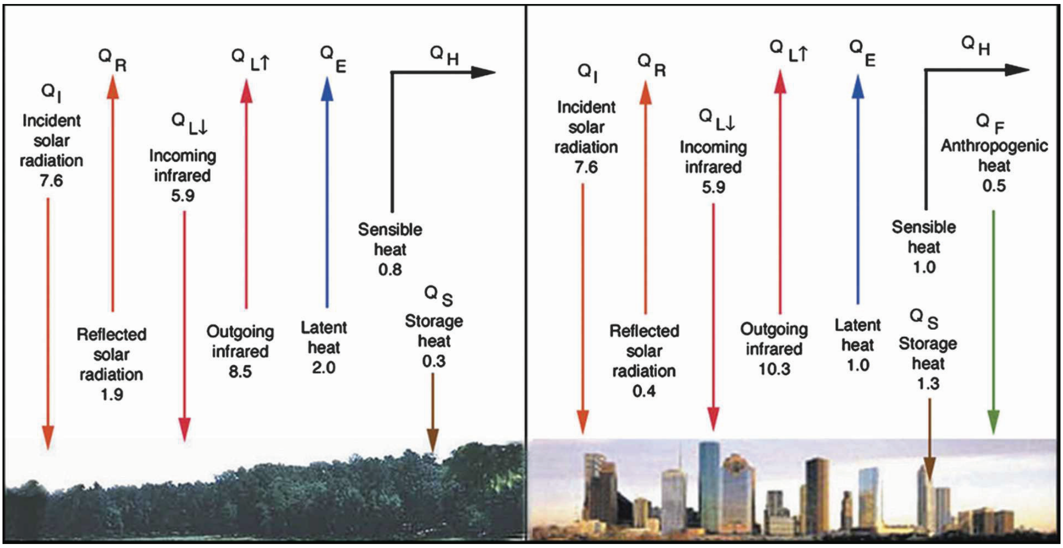


FIGURE 3.4 A qualitative description of typical rural and urban surface energy balance processes. The values are in units of kW h m^2 day^{-1}. Figure courtesy of R. Sass, Rice University. SOURCE: Shepherd, 2005. © Earth Interactions. Reprinted with permission.

sublayers (Figure 3.5): the roughness sublayer (RSL) and the inertial sublayer (ISL). The RSL typically extends from the surface to a height equivalent to 2-5 times the average building height (Raupach et al., 1991; Rotach, 1999; Kastner-Klein and Rotach, 2004). The layer below average roof level, the lowest portion of the RSL, is often referred to as urban canopy layer (UCL). Within the UCL, atmospheric patterns are spatially inhomogeneous, strongly influenced by local effects, and very hard to predict (Klein et al., 2007; Vardoulakis et al., 2003). At the same time, the UCL is the region where most of the urban anthropogenic emissions of atmospheric pollutants occur and where people spend most of their time, and is thus of great relevance. In the upper part of the RSL, above average roof level, a strong shear layer—a layer with high wind velocity gradients—develops and dominates the RSL wind and turbulence patterns. This shear layer also controls the turbulent exchange and ventilation between the UCL and the flow above average roof level, which is typically highly instantaneous and controlled by coherent structures (Christen et al., 2007). Overall, the RSL plays a critical role, and its properties need to be properly resolved in numerical models for accurate urban weather and air-quality forecasts.

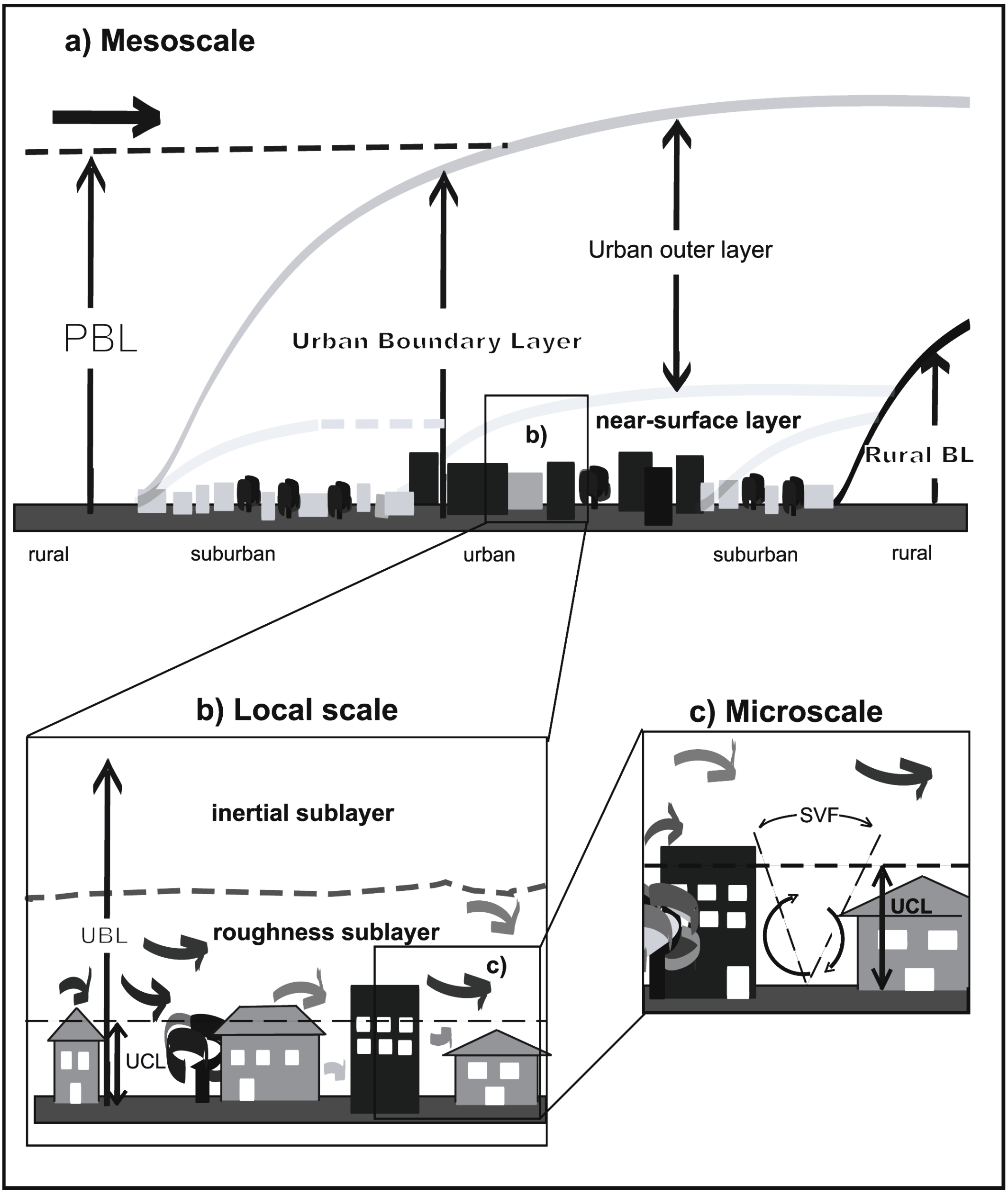


FIGURE 3.5 Sketch of the urban boundary layer structure indicating the various (sub)layers and their names. SVF in box c) stands for sky view factor. SOURCE: Rotach et al., 2005, modified after Oke, 1987. ©Springer-Verlag Wien. Reprinted with permission.

For large-scale weather patterns with weak dynamic forcings (i.e., weak winds), urban flow patterns are primarily thermally driven, and a dome-like circulation pattern develops in cities that are located in flat terrain and away from large water bodies. Canopy-layer UHI signatures are typically strongest under such conditions, with the highest values recorded at night. Historical and current literature has also persistently shown that UHI destabilization, urban surface roughness, and pollution can independently or synergistically initiate, modify, or enhance precipitation cloud systems. The so-called "urban rainfall effect" is clearly established in the literature; the majority of studies note an enhancement of rainfall in warm season convection (Changnon et al., 1981; Bornstein and Lin, 2000; Shepherd et al., 2010). However, there is discourse about the sign of precipitation change (i.e., the increase or decrease of precipitation) associated with urbanization and what physical mechanisms are of primary significance (Ashley et al., 2011; Shepherd et al., 2010). Studies continue to verify that urbanization may also modify lightning (Rose et al., 2008), freezing rain (Changnon, 2004), and snowfall climatologies (Shepherd et al., 2010) as well. Further, urban land use accelerates hydrologic response through surface runoff variability and stresses on conveyance systems (Shepherd et al., 2011; Villarini et al., 2010a; Reynolds et al., 2008) and thus amplifies urban flooding risks.

Human activities in urban areas (e.g., transportation, energy, and industrial processes) result in the production of "urban" aerosols or pollution which is associated with increased greenhouse gas emissions. Although urban areas have significantly higher carbon dioxide concentrations than in rural areas, greenhouse gas emissions per capita may be lower for urban dwellers than those for rural dwellers (Dodman, 2009). Jacobsen (2010) has recently discussed the implications of urban carbon domes on public health and the climate system. Urban modification of winds, temperature, and turbulence (including mixing height) affect the concentration, dispersion, and transport of atmospheric pollutants which, in addition to higher emission rates, contributes to poor air quality in cities (Grimmond et al., 2010b). Numerous studies have focused on predicting and reducing urban air pollution, yet deficiencies in both observational and modeling capacity are still evident (NRC, 2004). Ozone and particulate matter (up to 2.5 and 10 micrometers; PM2.5 and PM10) concentrations still exceed the National Ambient Air Quality Standards (NAAQS) in many metropolitan areas, and millions of people in the U.S. live in so-called non-attainment areas (EPA, 2012). Beyond conventional air quality concerns, accidental and intentional releases of chemical, biological, or radiological pollutants in cities remain as potential threats and pose particular challenges. Emergency-response forecasting necessitates models that capture essential features of urban flow and dispersion processes and provide fast exposure predictions. The NRC (2003b) concluded that no model system exists that fulfills all critical requirements for emergency response.

Aerosols affect climate, directly and indirectly, through radiative forcing (Kaufman et al., 2005). The "direct" radiative effect of aerosols is to scatter, reflect, or absorb solar radiation. Most aerosols, including sulfates found in urban environments, promote a cooling effect in the radiative budget; however, carbon-based aerosols absorb solar radiation and may warm the atmosphere and surface. Such warming can affect the atmospheric stability profile and thereby alter cloud and precipitation development. Climate-aerosol interactions are quite complex and beyond the scope of this discussion, but it is clear from emerging literature that the negative and positive effects associated with the urban production of aerosols must be placed in the context of scale: local (or urban), regional, and global. For example, aerosols augment UHI-effects (mainly in the surface or boundary layer) on temperature through direct interactions with solar radiation (Jin et al., 2011). Anthropogenic aerosols also act as condensation nuclei or "seeds" for cloud microphysical processes (Rosenfeld et al., 2008). This so-called "indirect effect" of aerosols further perturbs the radiation budget, cloud distribution, and precipitation variability.

Souch and Grimmond (2006) and Grimmond et al. (2010b) provide very comprehensive assessments of current knowledge, gaps, and needs within the urban weather climate community. Expanding on these assessments, the current state of urban observational and modeling techniques in research and operations, emerging technologies, and remaining needs and challenges for urban meteorology were discussed at the workshop. The following section summarizes these discussions and relevant literature.

ADVANCES IN URBAN FORECASTING AND MONITORING TECHNIQUES

Meteorological observations and modeling are tightly coupled and require continual emergence of new understanding, measurements, and technology (Dabberdt abstract in Appendix A). The measurements needed for particular meteorological processes are typically a function of the spatio-temporal scale of the process, the latency requirements of the application, and technological capacity. Shorter-range forecasts (< 60 minutes) may rely on heuristic methods involving extrapolation, but beyond this time period (and even inclusive of it), numerical weather prediction is the primary mechanism for forecasting. These models require detailed four-dimensional representation of the atmosphere provided by surface in situ measurements, surface-based remote sensing systems, upper air soundings, and satellite data (often through data assimilation techniques).

In cities, meteorological observations and forecasting become even more complex because of the high spatial variability, unique physical characteristics of the urban canopy and its impacts on various processes, and challenges with model initialization. Although such challenges exist, over time there have been several key advances in urban forecasting and monitoring. Some of the key advances that have emerged in the past 10-20 years in the observational and modeling communities are highlighted here.

Monitoring and Observations

Urban Campaigns

The need for urban data sets has been recognized by the scientific community. A number of major field campaigns have been successfully completed in the United States (e.g., Salt Lake City, Allwine et al., 2002; and Oklahoma City, Allwine et al., 2004) and Europe (e.g., London, UK, Arnold, et al., 2004; Basel, Switzerland, Rotach, 2005; and Marseille, France, Mestayer et al., 2005). Grimmond (2006) provides an overview of progress in urban observations which includes references to additional studies. Most of the urban observation studies were short-term measurement campaigns that provided data sets for a limited range of environmental conditions. Improving models to predict dispersion of hazardous material within the urban atmosphere was the major objective for many of these studies (Hanna et al., 2007; Hanna and Baja, 2009), but the data sets have also served for evaluation studies (Liu et al., 2006; Lemonsu et al., 2009) of urban surface-energy balance parameterizations and urbanized mesoscale models. In addition, these studies have provided new insights about the structure of the UBL, the impact of atmospheric stability on mean and turbulent processes within the UBL, and fundamental properties of turbulence within the RSL (Christen et al., 2007; Klein and Clark, 2007; Nelson et al., 2007b, 2011). These efforts further document the significance of urban observations in the urban surface layer and the whole boundary layer for advancing research and operations in urban meteorology. It is critical that efforts be undertaken to sustain and ease access to these datasets and to promote initiatives for future urban studies.

Urban Observation Networks

Two National Research Council (NRC) reports (2008, 2010a) emphasize the need for better observations of boundary-layer profiles and for urban testbeds that integrate in situ and remote sensing observations with modeling efforts and promote opportunities for various stakeholders to provide input and to participate. The committee endorses the recommendation that "urban testbeds are needed in cities with widely different annual climates" (NRC, 2010a) and agrees that testbeds provide an opportunity for interdisciplinary cooperation, learning how to interact and identifying appropriate communication practices between end user and forecasting/monitoring communities. For a detailed discussion of urban testbeds, see Chapter 4 and Appendix B. A need for appropriately-sited urban monitoring stations and methodologies for the design of three-dimensional urban networks was also recognized. The World Meteorological Organization (WMO) guidelines for urban surface monitoring sites (WMO, 2008) are a first, important step towards urban network design, and widespread implementation of these guidelines could lead to more appropriately-sited urban monitoring stations.

Since many of the remote sensing instruments that are needed to obtain profiles of atmospheric variables over the whole depth of the UBL have emerged or significantly advanced during the last decade, more detailed information about these types of sensors are provided below.

Ground-Based Remote Sensing

Several ground based remote sensing capabilities have emerged. Many of these systems have advanced our knowledge in urban meteorology and revealed potential opportunities and pathways forward. Dabberdt (Appendix A) highlights many of these systems, and a recent book by Emeis (2011) provides technical details about surface-based remote sensing instruments for profiling of the atmospheric-boundary layer as well as examples of successful operation of these instruments. The reader is referred to these resources for detailed descriptions of the instruments briefly described in the following.

Scanning Radars The emergence of the national Weather Surveillance Radar 88 Doppler (WSR-88D or, Next-Generation Radar, NEXRAD) weather radar network has significantly improved capacity for monitoring and quantifying precipitation and storm-scale monitoring in the urban environment. The WSR-88D system is limited for urban meteorological use due to gaps in boundary layer coverage, scan rate, coarse range resolution, and precipitation type determination (NRC, 2002). The National Weather Service (NWS) is currently rolling out its dual-polarization Doppler radar systems. Full deployment began in September 2011.[1] Dual-polarization systems will provide improved precipitation estimation and discrimination of precipitation type. Additionally, testbeds involving the multi-university Collaborative Adaptive Sensing of the Atmosphere (CASA) project are showing promise (Appendix B).

Radar Profilers and Sodar Radar wind profilers are systems that transmit pulses of electromagnetic energy into the atmosphere vertically. They are capable of measuring mixing layer height, the planetary boundary layer and the vertical component of velocity. These attributes are ideal for urban meteorological monitoring**.** Sodars are similar to radar wind profilers but emit sound or pulses of acoustic energy. They can provide measurements of the vertical profile of the wind, mixing layer height, and vertical velocity. They provide very useful measurements of the lower boundary layer, but applications in urban areas are limited due to the noise emitted by the sodar, as well as low signal-to-noise ratios caused by urban background noise from vehicular traffic and other sources.

Lidar Atmospheric lidar (light detection and ranging), as noted by Dabberdt (Appendix A), "refers to a family of profiling devices that emit short pulses of visible, ultraviolet or infrared beams of electromagnetic energy to obtain height-resolved profiles of winds, gaseous molecules, or fine particles, depending on the design of the system." Aerosol (or elastic backscatter) lidars detect cloud and aerosol properties. Ceilometers measure cloud base heights and urban aerosol profiles. Profiles of water vapor and certain trace gases (e.g., sulfur dioxide, ozone) are measured by two classes of advanced lidar systems: Raman scattering and differential absorption (DIAL). Airborne lidars are also widely used nowadays to scan the earth's surface, and data from such scans provide important information about urban surface characteristics for urban weather and air quality models (Ching et al. 2009a,b).

Radiometric Profilers Ground-based microwave radiometric profilers are passive, multi-channel, all-weather systems that can measure profiles of atmospheric water vapor, temperature, and cloud liquid waters. Similar systems may also be flown on aircraft or satellite systems.

---

[1] *http://www.roc.noaa.gov.*

Lightning detection Emerging knowledge about the role of urban environments and lightning drives the need for lightning detection capability. The National Lightning Detection Network (Orville, 2008) measures cloud-to-ground (CG) lightning but does not detect intra-cloud (IC) lightning, which is often a useful predictor of subsequent CG strokes and heavy precipitation. Some commercial total (CG+IC) lightning detection systems (Hembury and Holle, 2011) have emerged and are operational (Dabberdt abstract in Appendix A).

Airborne/Spaceborne Remote Sensing

Airborne and spaceborne data have proven to be very advantageous in many aspects of the urban meteorological observations and prediction. These systems have been useful in assessing the extent and magnitude of the urban heat island, identifying urban rain- and snowfall anomalies, and diagnosing air quality (Seto and Shepherd, 2009). Additionally, airborne and spaceborne data help properly characterize urban land cover and morphology which is important for coupled meteorological systems.

Urban Land Cover Several remote sensing methodologies have emerged to delineate urban land cover. Satellite imagery comes from an array of platforms and instruments over the past 40 years. The earliest generation of satellites (1963 to 1972), such as Corona, Argon, and Lanyard, were limited in resolution and capability, but after 1972 several improvements led to an explosion of resources: Landsat (Derived from Land Satellite), SPOT (Satellite Pour l'Observation de la Terre), and IRS (Indian Remote Sensing Satellite). More recently, a third generation of satellites with very high geometric resolution (IKONOS-2, Quickbird-2, etc.) (Maktav et al., 2005; Mitra et al., 2011) has emerged. Imhoff et al. (1997), Sutton (2003), and Sutton et al. (2006, 2010) applied nighttime satellite imagery, typically from the DMSP OLS (Defense Meteorological Satellite Program Operational Linescan System) image to map urban areas and sprawl. Nighttime imagery can be beneficial over daytime imagery because it measures emitted rather than reflected radiation, avoiding classification problems in separating developed vs. nondeveloped land cover (Sutton, 2003). There are also several hybrid techniques involving many of the aforementioned data sources as well as population or economic data.

Thermal imaging and UHIs Voogt and Oke (2003) provide an overview of how thermal remote sensing has been used to study urban climate, with a particular focus on UHI. Such techniques, both airborne and spaceborne, have been useful in characterizing the magnitude and extent of the UHI, land cover, and input for modeling systems connecting the atmosphere and land surface. Voogt and Oke (2003) argued that thermal techniques are needed to advance beyond descriptive studies of patterns and correlations. They also predicted that improvements in spatial and spectral resolution in contemporary and future satellite/airborne-based sensors would provide important breakthroughs. Figure 3.6 is a high-resolution visible and thermal characterization of the urban land cover and heat island signature of Atlanta, Georgia. Imhoff et al. (2010) recently demonstrated the value of impervious surface area from the Landsat TM and land surface temperature (LST) from Moderate Resolution Imaging Spectroradiometer (MODIS) in determining the UHI skin temperature and its relationship to both urban development and ecology. Such information is invaluable for observational analysis, model initialization, and decision making. Other advanced thermal sensors like Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) are also valuable for urban climate applications.

Aerosols Kaufman et al. (2005) discuss how satellite-based datasets have evolved to observe aerosols, air quality, and atmospheric pollution. They provide a historical context, noting earlier methods, and describe the TOMS (Total Ozone Mapping Spectrometer) instruments, which use two channels sensitive to ultraviolet light and have been in operation since 1979. POLDER (Polarization and Directionality of the Earth's Reflectances, Sano et al., 2009) was specifically designed for aerosol measurements and uses several spectral channels (0.44-0.86 m). It can also detect light polarization associated with land-based fine aerosols. Since 2000 MODIS and MISR (Multi-angle Imaging Spectroradiometer) have also provided global aerosol data to the scientific community (see Jin and Shepherd, 2008; Yu et al., 2006). MODIS leverages multi-spectral information, while MISR utilizes reflected light from multiple viewing angles to disentangle aerosol signals from surface reflectance. The ASTER instrument is another spaceborne instrument that also provided aerosol information (Wen et al., 2007).

The NASA-"A-Train" is a notable example of satellite remote sensing capacity for urban meteorological studies (Anderson et al., 2005; Yu et al., 2006). This system carries a full complement of satellite instrumentation for measuring aerosols, clouds, greenhouse gases, and other atmospheric variables. NASA and other agencies have recently explored the ability to quantify particulate matter (e.g. PM2.5) from space (NASA/EPA/NOAA, 2011). Similar spaceborne capabilities are emerging from NASA counterparts in other countries as well.

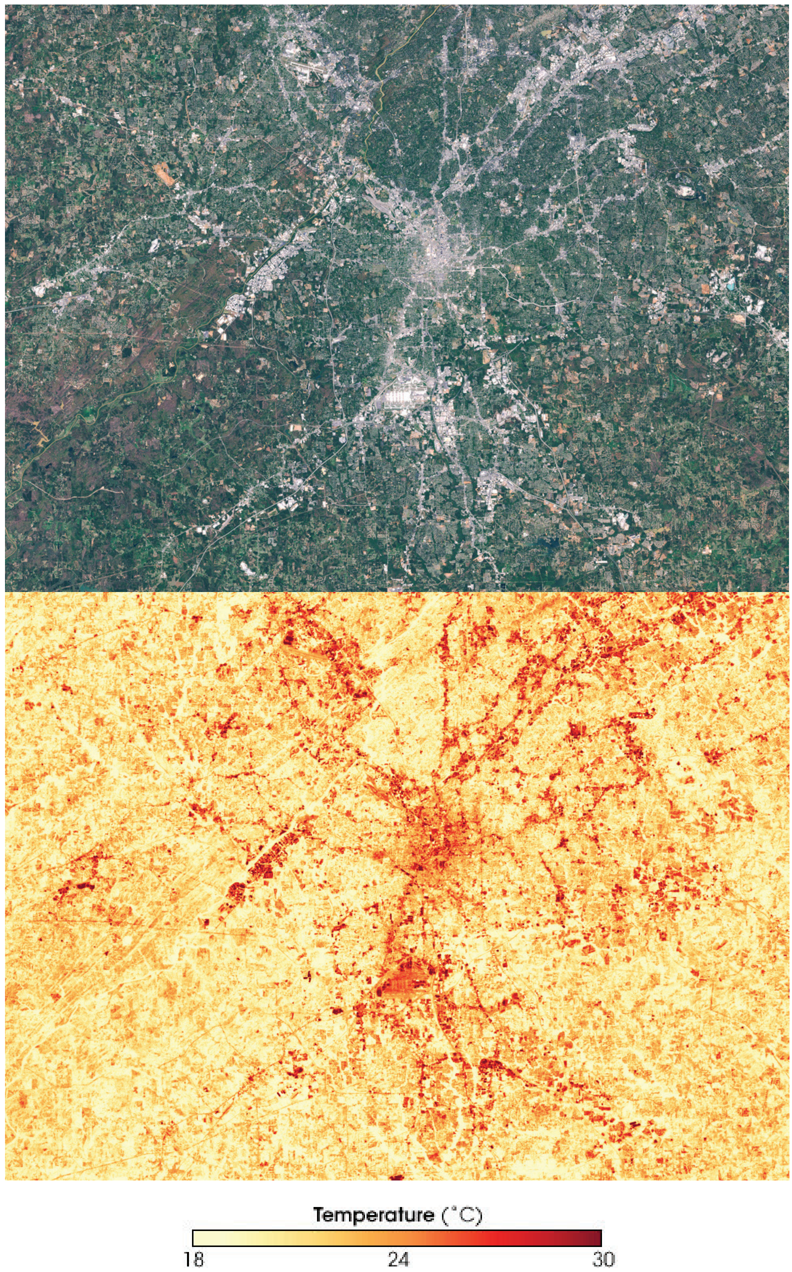


FIGURE 3.6 Landsat optical and thermal images of Atlanta, Georgia, which is considered a "surface" urban heat island. SOURCE: NASA.

Hydrometeorological Parameters Shepherd et al. (2002) and Hand and Shepherd (2009) pioneered the use of space-borne precipitation measurements from the Tropical Rainfall Measurement Mission (TRMM) and associated merged products (i.e. blending TRMM data with other passive microwave and geosynchronous infrared datasets). These studies have revealed that space-based precipitation measurements can provide a credible methodology for simultaneously investigating potential urban rainfall effects for multiple cities. The Global Precipitation Measurement (GPM) mission (circa 2014 launch) will further extend such measurements. The NASA Land Information System (LIS) is a satellite-based modeling and land data assimilation system that resolves key elements of the land-atmosphere interface (Kumar et al., 2006).

While Landsat and MODIS are somewhat common to urban researchers and stakeholders, other systems (e.g., TRMM, GPM) and their potential capabilities remain relatively obscure beyond their discipline-specific communities. Additionally, there are still deficiencies in resolution, data latency, and data interoperability that limit utility beyond research communities.

Modeling Systems

The urbanization of four types of models discussed here has improved the forecasting of weather and climate (e.g., temperature, wind speed, rainfall, and cloud cover), atmospheric dispersion and air quality (e.g., concentration of gaseous pollutants and particulate matter), hydrological events (e.g., urban flooding), and coastal storm surge inundation in urban areas. Additionally, emerging modeling technologies that focus on coupling of models from global down to the microscale, or target specific end user applications such as exposure assessments and urban planning tools, are discussed later in this chapter.

Urbanization of Numerical Weather Prediction Models

One of the most important advances in urban meteorological forecasting in the last decade has been the development of urban surface energy balance and urban canopy models for Numerical Weather Prediction (NWP) models. Given the significant increases in computing resources over the last decades, NWP models can now be run at horizontal resolutions down to a few kilometers; that is, cities can cover a significant number of grid cells in the modeling domain. The better resolution of cities in NWP models also requires modifications to the model physics to account for the urban effects on evaporation rates, absorption and reflection of solar radiation, and storage of heat, as well as wind and turbulence fields. Masson (2006) and Martilli (2007) provide overviews of various approaches to "urbanize" NWP models. One of the simplest urbanization techniques is to use empirical models, such as the local-scale urban meteorological parameterization scheme (LUMPS; Grimmond and Oke, 2002; Loridan et al., 2011). Such schemes are computationally efficient, but a large amount of observational data (from multiple cities) may be necessary to develop robust empirical relationships.

Another common approach in operational urbanized models is to use urban canopy models (UCM) embedded within the NWP model. These schemes either model the urban canopy effects of streets and buildings using a slab (or single layer) or multiple layers. Recent model evaluation and intercomparison studies demonstrated that the implementation of multiple-layer schemes does not necessarily increase the predictive skill of surface energy balance parameters (such as sensible and latent heat fluxes) over simpler slab schemes (Grimmond et al., 2011). One hypothesis for a lack of increase in skill is due to the myriad of parameters necessary to characterize the building, road, and wall effects. Recent work by Salamanca et al. (2011) illustrated that urban parameterizations within NWP models are sensitive to the urban canopy parameters that define the urban morphology.

While most of the urbanization efforts have focused on mesoscale models, a parameterization for urban surfaces has recently been implemented into the Community Land Model as part of the Community Climate System Model (Oleson et al., 2010b). This allows global simulations of future climate with more realistic predictions of urban heat islands and temperatures in cities.

Weather services worldwide (UK MetOffice, Best et al., 2006; Meteo-France, Masson, 2000, 2006; and Environment Canada; Mailhot et al., 2006) have successfully implemented or are currently testing versions of urban surface parameterizations of varying complexity with their operational models. Chen et al. (2011) document the efforts for developing an integrated urban modeling system for the Weather Research and Forecasting (WRF) Model.

As a result of these efforts, three different urban canopy parameterizations (a bulk approach, a single-layer canopy model, and a multi-layer canopy model) were integrated into WRF and evaluated against various urban data sets. While this modeling system provides a great tool for various applications, its transition into operations needs to be further explored. Further model improvements are needed, as well as a concept of operations for the deployment and utilization of an operational version. Evaluations and transition into operations of the urbanized WRF would need to be actively pursued to close the current gap between models used in operations by the U.S. weather service and weather services in Europe and Canada. Within several agencies in the U.S. (e.g. Department of Homeland Security, DHS) building-resolving modeling suites have been developed and evaluated against data sets from urban field campaigns. These models have the potential to provide high-resolution data sets, but little is known about these models, and they are not easily accessible to various end user communities. There should be a "call for sharing" and coordination as it cannot be afforded that these resources remain underutilized.

Atmospheric Dispersion and Urban Air Quality Models

Two areas in which model development has been specifically targeted for improving the decision-making capabilities of end users are urban air quality (AQ) and urban transport and dispersion (T&D). Baklanov et al. (2009) give an overview of recent progress of meteorological and air quality models for cities. Such models play a key role in protecting people, the natural environment, and urban infrastructures from negative impacts of elevated air pollution levels in cities. Urban air quality and dispersion of atmospheric pollutants are strongly influenced by wind, temperature, and turbulence patterns in cities, and depending on the type of problem, spatial scales can vary from street, neighborhood, city, and regional scales (Britter and Hanna, 2003; Figure 3.7). Recent studies have also focused on the interactions of urban pollution and transport of air pollutants on continental and global scales (Holloway et al., 2003; Fenger, 2009).

In the United States, a recent collaborative effort between the National Oceanic and Atmospheric Administration (NOAA) and Environmental Protection Agency (EPA) focused on coupling of NWP models with chemical transport models such as Community Multiscale Air Quality (CMAQ; Byun and Schere, 2006) to develop the real-time National Air Quality Forecast Capability (NAQFC) (Otte et al., 2005; Eder et al., 2009). The system was first operational in 2004 for the northeast part of the country and initially provided next-day forecasts of surface-level ozone (O_3) concentrations (both 1-h and 8-h averages) at a 12-km resolution. Since then, several upgrades have been made to the NAQFC, and the spatial domain was extended to the contiguous U.S. and bordering areas (Eder et al., 2006, 2009; Figure 3.8).

Within the NAQFC system, the chemical transport model (CMAQ) uses output from the meteorological models in an "offline" approach. In other words, transport and dispersion of pollutants are driven by the

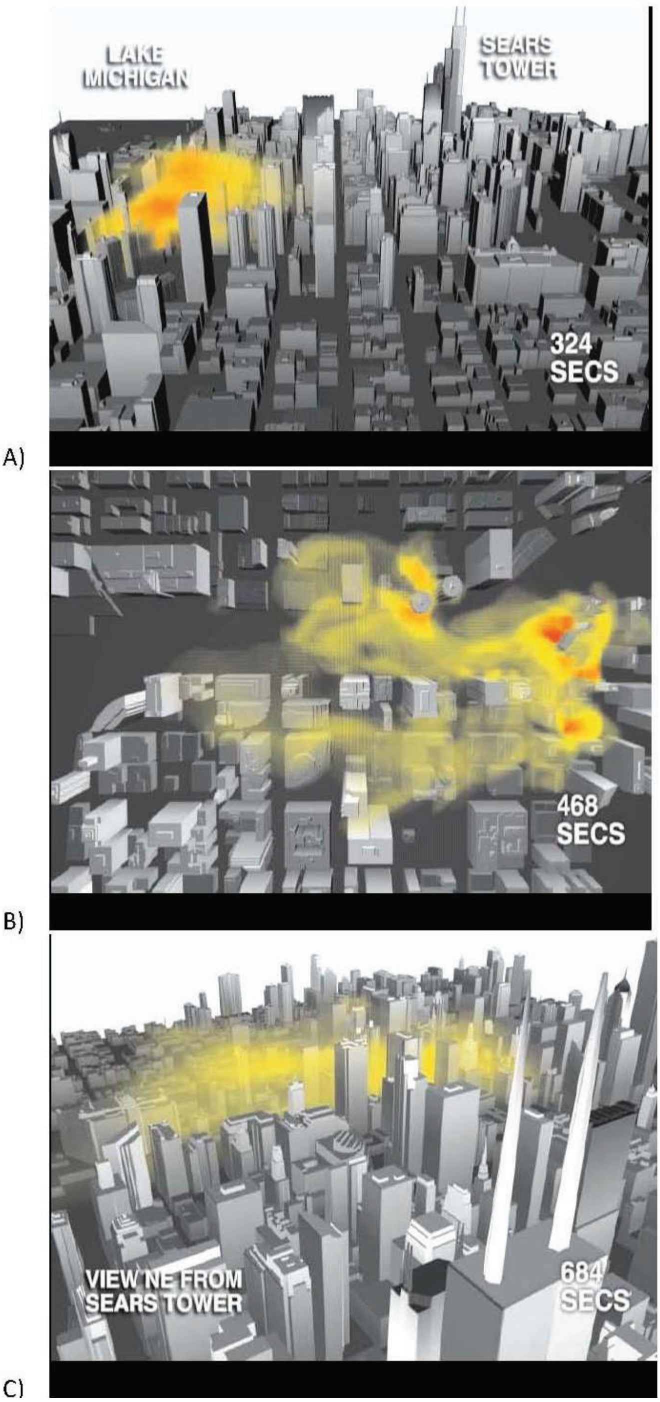


FIGURE 3.7 Different views of a contaminant cloud from a FAST3DCT simulation of downtown Chicago. (A) view of contaminant release looking east toward downtown Chicago and the Sears tower. (B) overhead view of contaminant concentrations over Chicago River. (C) view of contaminant from the Sears tower. These panels show that the contaminant is lofted quickly above the tops of the majority of the buildings. This vertical dispersion of the contaminant results from the geometry of the buildings producing vertical lee-side vortices that draw pollutants from street level to above the tops of the structures. SOURCE: Patnaik et al., 2005.

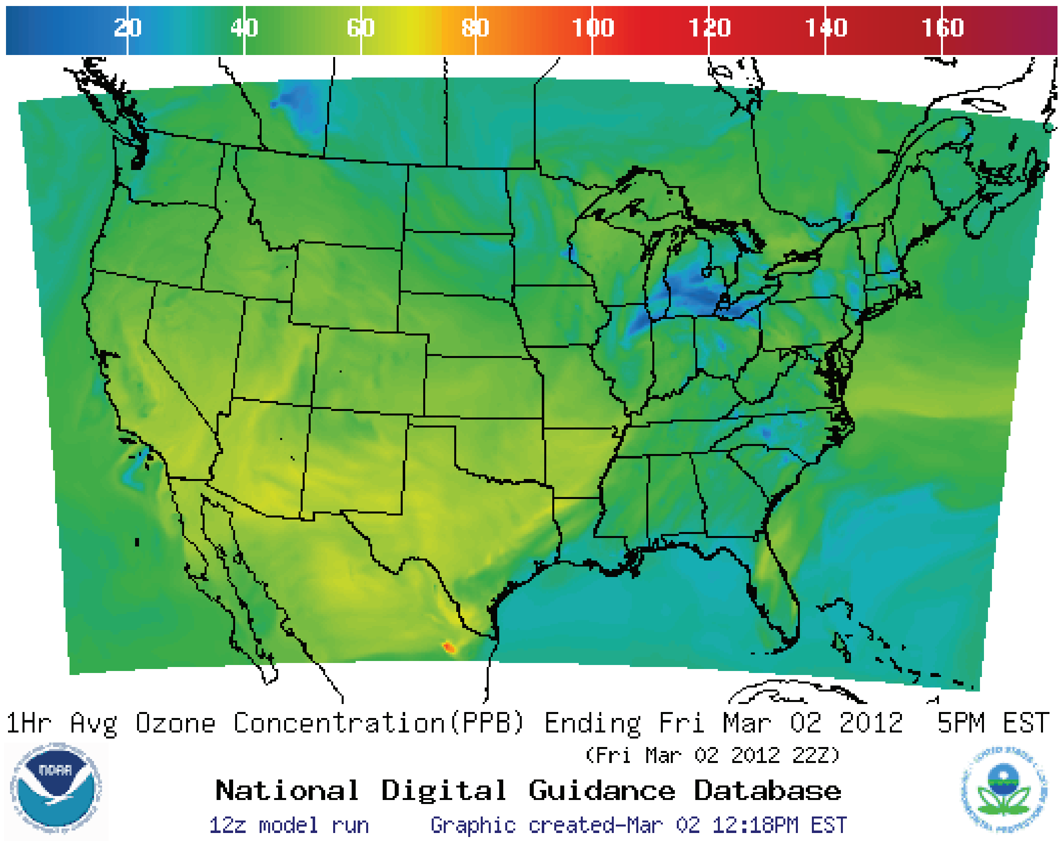


FIGURE 3.8 An example of NOAA's Air Quality Forecast National Digital Guidance Database for the maximum 1-h O_3 concentrations, depicting the WRF-CMAQ modeling domain, available at www.weather.gov/aq/. SOURCE: NOAA.

meteorological model output (typically updated every 30 to 60 min), but there is no feedback from the chemical transport model to the meteorological model. This one-way coupling between chemistry and meteorology ignores important feedback processes (e.g. aerosol feedbacks from CMAQ to the radiation budget, cloud microphysics, and precipitation in the meteorological model) and also has limitations because changes in the meteorological output variables happen over time scales of less than one hour.

Such limitations are critical when simulating air quality in urban areas where grid resolutions of less than 1-km are desirable. To address these limitations, Grell et al. (2005) developed a fully coupled air quality model, the Weather Research and Forecasting/Chemistry (WRF/Chem) model. In this model, chemistry and meteorology components are fully consistent. A two-way coupling of CMAQ and WRF is also under development (Mathur et al., 2010). Herwehe et al. (2011) presented a comparison of ozone observations with predictions with the one-way coupled CMAQ-WRF and the two-way coupled WRF/Chem models. They concluded that small changes in the model configurations can have significant impacts on air quality predictions. Differences in the land-surface models, planetary boundary layer schemes, dry deposition, and convective cloud schemes all impacted the ozone predications (Herwehe, 2011). However, the greatest impacts were associated with differences in the photolysis schemes.

Although these model developments and related evaluation efforts mark a clear progress in producing operational air quality forecasts, their accuracy for producing reliable urban air quality predictions is still unclear. The current horizontal resolutions are too coarse to resolve cities, and urban canopy parameterization schemes are not yet implemented in the operational models. Ching et al. (2009b) used an urbanized version of MM5 community model and the CMAQ model to investigate the influence of urban canopy parameterizations on air quality predictions for Houston. They observed significant differences in the urban ground-level ozone distributions for the non-urban versus urban simulations. Martilli et al. (2003) came to similar conclusions when simulating air quality for Athens, Greece. They observed differences in the ozone concentrations of up to 30ppb between simulations with and without urban canopy parameterizations. The strong sensitivity of the ozone distributions to urban canopy parameterizations would be a motivation to further develop truly urbanized air quality forecast systems. The incorporation of urban canopy parameterizations into WRF (Chen et al., 2011) and the efforts to develop two-way coupling between WRF and chemistry models (Grell et al., 2005; Mathur et al., 2010) provide the necessary basis for further advancements. However, access to datasets that provide detailed information about three-dimensional weather and chemistry in urban areas are key for promoting further model evaluation studies and model improvements.

For neighborhood to street-scale dispersion modeling, there are a number of different approaches available, ranging from semiempirical Gaussian-type models that account for the urban canopy, through various parameterizations and diagnostic wind field models coupled with Lagrangian particle models, to computational fluid dynamics (CFD) models that either use a Reynolds-averaged or Large-Eddy simulation (LES) approach. Grimmond et al. (2010b) includes an extensive overview of these various approaches and related model development and evaluation studies. The models differ not only in terms of model physics but also in terms of simulation times, computational resources needed, and the number of input parameters needed. Models that explicitly resolve buildings (diagnostic wind and CFD models) require horizontal grid resolutions of 1-5 m, and the spatial domain simulated is thus typically limited to a few hundred meters in each direction. In some studies, CFD models have thus been coupled with NWP models that provide the boundary conditions for the CFD runs (Tewari et al., 2010).

Meeting the needs of emergency managers in urban environments (i.e., police, fire, and hazardous materials first responders), who require fast and reliable information on the transport and dispersion of toxic airborne contaminants in the event of an accidental or terrorist incident, remains challenging. The simulation times of CFD models typically limit their use as fast response models, but progress has been made. Hanna et al. (2007) compare measurements from Manhattan, NY to model output with various urban CFD codes. The diagnostic wind field approach reduces run times from several hours down to minutes, but at the cost of simplified model physics (Hanna et al., 2011). New research advances have also addressed early timeliness issues by using precomputed three-dimensional urban aerodynamics computations, based on high-resolution LES, which include solar heating, buoyancy, complete building geometry specification, trees, and impressed wind fluctuations (Boris et al., 2011; Patnaik et al., 2005). Typically, urban aerodynamics simulations would be preprocessed for each urban region for a complete set of wind directions and atmospheric stabilities, then extended to all wind directions, speeds, and probable sources and source locations through an advanced look-up table technology. Real-time weather information would then be used via linkage to an NWP model to provide updates to the look-up tables. The utilization of these accurate tools, precomputed for cities well in advance, would allow first responders and emergency crisis managers to act immediately without having to wait for supporting analyses or more simplistic models. The successful transition of such models into operations at major cities still needs to be seen.

Hydrological Models

Transformation of natural landscapes to urban impervious surfaces modifies surface runoff, evapotranspiration, infiltration, and groundwater recharge. Reynolds et al. (2008) found that impervious surfaces in Houston helped to distribute storm water to conveyance systems over shorter periods of time and with greater volume, which can overwhelm capacity and lead to local flooding. Shepherd et al. (2011) suggested a similar response with historic flooding in Atlanta in 2009.

Urban flooding exposes critical flaws in urban emergency response, urban drainage, and water management systems (Reynolds et al., 2008) and also raises questions about the complex interactions between the coupled human and natural systems. Current assessments of urban flood potential are often based on outdated assumptions and statistical "curve number hydrology"[2] on rainfall intensity and frequency. Flood-frequency estimates are required for effective management and planning to save lives, protect property, and set flood-insurance rates. Such estimates can also be useful for providing guidance in locations where data is limited. While modeling advances are the focus of this discussion, many workshop participants noted that modernization of flood frequency and intensity methods continue to evolve, particularly in light of climate change extreme event associations.

Hydrological modeling systems have evolved significantly in recent decades and provide a methodology for assessing surface water hydrology and water balance changes for an array of surfaces. Essentially, two classes of hydrological models have emerged: conceptual models and physically-based models (Poelmans et al., 2010). Conceptual models characterize the catchment or sub-catchment as a discrete unit and model the rainfall to run-off conversion by simple parameterizations (Moore, 2007). Physically-based models explicitly represent the land and hydroclimate attributes within a catchment but require precise input data and computing capacity (Bhaduri et al., 2001). Hybrid category (physico-conceptual distributed) models are based on actual physical processes but simplify aspects of them at the catchment scale (Poelmans et al., 2010).

Urban landscape may be represented in hydrological models in numerous ways. Impervious surface and urban morphological parameters can be characterized using remote sensing methodologies including a vegetation-impervious surface-soil (V-I-S) model, vegetation changes, high resolution optical imagery, aerial photography, night lights, synthetic aperture radar, and lidar (Jacobson, 2011). Future urban land cover and hydrological response can even be determined by coupling urban growth models (Poelmans et al., 2010).

Coon and Reddy (2008) noted that several sources of uncertainty are prevalent in hydrological models. These may include (1) errors in input precipitation data, (2) model assumptions and parameterization, (3) errors in

[2]Refers to an empirical method for predicting runoff or infiltration from precipitation.

calibration data, (4) land cover classification error or changes in land cover, and (5) catchment scale and transfer errors. Such errors contribute to further errors in the output or stakeholder product.

Coastal Storm Surge Inundation Models

Along with urban growth, there has been an increase in coastal population density. Coastal counties contain nearly 53% of the population of the United States, even though they comprise only 17% of its land area (excluding Alaska) (Crossett et al, 2004). Coastal urban areas are vulnerable to inundation associated with storm-induced surges and sea level rise. A generation of models has emerged that use population, land cover, elevation, climatological, and oceanographic datasets to model and animate sea level rise and surges associated with storms (Usery et al. 2010).

Many of these models leverage advances in geographic information systems (GIS) and hydraulic modeling. For example, some approaches constrain predictions of a typical coastal flood inundation model using observations and historical reconstructions (Smith et al., 2012). These authors have also noted that two-dimensional hydraulic models with simple physics can effectively simulate coastal flood events if high-accuracy, high-resolution terrain data such as lidar are available. This suggests that hydrodynamic characteristics of fluvial and coastal flooding may be similar. This review captures a small segment of this modeling field but acknowledges the importance of this aspect of the urban meteorological problem.

EMERGING TECHNOLOGIES IN METEOROLOGICAL FORECASTING AND MONITORING

Coupling Modeling Systems

Use of High-Resolution Building Data Sets in Urban Weather and Climate Models

As discussed earlier in this chapter, significant advances have been made to better represent cities in numerical weather prediction and air quality models. There are now several operational and research models that include urban canopy models. To run these models effectively, they require detailed information about urban morphology and form. Over the past decade, techniques have been developed that use 3-D building databases, airborne lidar, digital elevation models (DEMs), synthetic aperture radar (SAR), and satellite data (Carter et al., 2011; Jeyachandran et al., 2010). Martilli (2009) discusses the derivation of input parameters for urban canopy models from such data sets. The National Urban Database and Access Portal Tool (NUDAPT; Ching et al., 2009a, b), developed by the Environmental Protection Agency, is an important effort to provide building datasets, including computed input parameters for the urban canopy models (such as roughness length, building area fraction, and mean building height for each grid cell), for major U.S. cities. Such a database is an important resource for the urban modeling community. It is also important that efforts be undertaken to secure access and future development of NUDAPT.

Coupling of Atmospheric Models from Global Down to Urban Scales

Grimmond et al. (2010a) noted that most operational and climate models still fail to resolve urban areas and their associated atmospheric impacts. Jin and Shepherd (2005), Jin et al. (2007), and Oleson et al. (2008a, b) have argued that emerging climate modeling systems must adequately represent urban processes. McCarthy et al. (2010) discussed results from global climate simulations after an urban land surface scheme (Best et al., 2006) was implemented within the Hadley Centre Global Climate Model (HadAM3, Pope et al., 2000). The notion of "convergence" is a critical issue. Global climate model (GCM) spatial resolution is rapidly improving (that is, grid cells are becoming smaller) with increasing computational capacity, while urban footprints are enlarging. This leads to a convergence effect whereby urban-related interactions will become increasingly relevant for proper characterization of atmospheric circulations, fluxes, and weather and climate prediction. Lamptey (2010) established that current and future climate modeling at regional scales will have to properly resolve urban contributions and modifications to the surface energy equation.

"Urbanization" of GCMs and regional climate models will involve parameterization of urban processes in the land surface components of most modeling systems. The models are most effective when they are simple enough to ensure structural compatibility and computational efficiency (Oleson et al., 2008a), yet complex enough to capture key urban-atmosphere interactions. Current urbanized GCMs resolve the spatial attributes of the urban landscape as well as the three-dimensional morphology ("urban canyon structure"). This construct captures many of the radiative, dynamical, and flux processes adequately. Jin and Shepherd (2005) offered a discussion of how emerging satellite data may provide critical information on urban surfaces (e.g. emissivity, temperature, albedo, vegetation fraction) for GCMs.

Oleson et al. (2008b) found that of the atmospheric and surface conditions they considered in their study, heat storage and sensible heat flux were most sensitive to uncertainties in the input parameters. They recommend that "attention be paid not only to characterizing accurately the structure of the urban area (e.g., height-to-width ratio) but also to ensuring that the input data reflect the thermal admittance properties of each of the city surfaces."

Advanced Exposure Assessments

Ambient concentrations from centrally located monitoring stations have been widely used as exposure surrogates (Sarnat et al., 2001; Burke et al., 2001; Ozkaynak et al., 2008). However, errors may occur depending on the study design and scale at which individual exposure to air pollutants from central pollution monitors are analyzed (Gamble and Lewis, 1996; Zeger et al., 2000; Brauer et al., 2008; Sarnat et al., 2006). The characterization of exposures in an epidemiology study may be improved by the use of high-resolution air pollution models as the basic input for human exposure models, along with integration of human factor data (Burke et al., 2001; Ott et al., 1988, Zartarian et al., 2000). There has been a large number of studies that have characterized empirically intra-urban spatial gradients in urban air pollution using saturation sampling and descriptive statistical models (e.g., Henderson, et al., 2007). These approaches have been necessitated by emissions and meteorology data that are not well resolved spatially and by the limitations of deterministic models.

In their review of models used to determine air pollution exposures, Jerrett et al. (2005) concluded that integrated dispersion and meteorological models are becoming more widely used to assess health effects related to air pollution. However, because classical Gaussian dispersion models, which often predict imprecise urban concentration patterns, are enshrined in government regulations and policies, they are most widely used for such dispersion-model-based exposure assessments. Jerret et al. describe "unrealistic assumptions about pollutant transport" as a major limitation for health studies based on such models.

Although coupled mesoscale meteorological and chemical transport models such as the CMAQ (Byun and Schere, 2006) deliver more reliable concentration predictions for a wide variety of different species of gaseous and aerosol pollutants, the intra-urban variability of concentrations is often not well represented with such models, as the typical spatial resolution in the smallest grid is 1-4 kilometers. Isakov and Ozkaynak (2008) proposed a hybrid approach in which local impacts of mobile and stationary sources are modeled with the Atmospheric Dispersion Modeling System (AERMOD) (Cimorelli at al., 2005), while the regional transport and background concentrations are simulated with CMAQ.

Application of Weather and Climate Models for Urban Planning

At scales ranging from global to local, models are providing guidance on mitigation and adaptation decisions. Recent studies (Oleson et al., 2010a; Akbari et al., 2009) have presented compelling evidence that increasing the albedo of cities on a global scale can not only reduce summertime temperatures but also offset carbon emissions through reduced power demand. To take advantage of this effect, some cities are deploying large scale greening plans (e.g., MillionTreesNYC; see Chapter 2).

Models are needed to help quantify the expected benefits and identify unintended impacts of these programs. For example, by how much will planting trees and/or creating urban green spaces reduce urban temperatures (Lynn et al., 2009; Zhou and Shepherd, 2009; Solecki et al., 2005)? Better vegetation models are thus required in the current urban canopy models—a need that is not only of relevance for urban planning studies but also for improving urban canopy parameterizations and weather predictions in general. Recent efforts to couple building energy models with urban canopy parameterizations implemented within NWP models (Salamanca et al., 2010, Salamanca and Martilli, 2010) provide better tools to study feedbacks between building energy use and urban climate, as well as to test the impacts of various urban growth scenarios on future urban climate. However, these models require further validations, and the output was shown to be quite sensitive to the details in information about urban structures and morphology (Salamanca et al., 2011).

Coupling of dynamic urban meteorological models with socioeconomic models is important for long-term planning and prevention in areas of high vulnerability. Risk assessment ultimately needs this type of coupling and will allow taking a more proactive approach. The urban modeling community has not inspired confidence among end user groups concerned with sustainability of cities in the ability to accurately model the complex effects impacting quality of life issues in the urban environment—the more complex models considering street, road, and building impacts have not consistently been able to improve on simple model forecasts.

Data Assimilation and Probabilistic Forecasting Techniques

In general, data assimilation and probabilistic forecasting techniques represent clear advancements over the last decade, but their application for urban areas is still largely unknown. These techniques have been used primarily for research applications rather than for end users. This is partly because of the need for greater computing power, but also because end users are not typically educated on how to properly interpret model-generated probabilistic information, and modelers struggle with how best to communicate it.

Data Assimilation

Liu et al. (2006) evaluated a multi-scale, rapid-cycling, real-time, four-dimensional data-assimilation and forecasting system to assimilate high density data collected during the Joint Urban 2003 field project in downtown Oklahoma City. Using a mesoscale modeling framework, they found improved characterization of the boundary layer, atmospheric dynamics, and thermal structure, which led to reduced biases in forecasting wind speeds and a more realistic boundary layer structure. Baklanov et al. (2009) have noted the need for improved assimilation of surface characteristics into urban scale NWP and air quality models. Even though some high-resolution satellite or airborne datasets are available for urban landscapes, a new generation of algorithms for assimilation of surface temperature, albedo, snow, and other key urban variables will be required.

A generation of two-and three-dimensional land information systems (LIS) have emerged that can be used to assimilate urban surface features into appropriate coupled modeling systems. Kumar et al. (2006) have described a land surface modeling framework that "integrates various community land surface models, ground measurements, satellite-based observations, high performance computing, and data management tools." They also use a sequential data assimilation extension of their LIS that uses many land surface models, observational sources, and assimilation techniques. LIS is one of several types of various land data assimilation systems (LDAS) that are emerging for constraining land-atmosphere simulations involving weather and climate models (Ghenta et al., 2011; Jimenez et al., 2011; Bosilovich, 2008; Rodell et al., 2004).

Chen et al. (2007) present an evaluation of the uncoupled high-resolution land data assimilation system (HRLDAS) which was developed to initialize land-state variables of the coupled WRF-land surface model (Noah) for high-resolution applications. An offline approach was chosen because soil moisture spin up (to reach the equilibrium state) can take up to several years, which is difficult to handle within the computationally expensive WRF. For urban applications, HRLDAS is urbanized by running the coupled Noah/urban model in an offline mode, which then provides the initial soil moisture, soil temperature, snow, vegetation, and wall/road/roof temperature profiles (Chen et al., 2011). Ross et al. (2009) have developed a land information system method for assimilating heterogeneous spatial and georeferenced information into three-dimensional urban models.

Many opportunities for enhanced assimilation exist within the air quality forecasting community, such as the NAQFC (described earlier in this chapter). Pagowski et al. (2010) have recently demonstrated the role that assimilation of surface ozone and fine aerosols can have on air quality forecasts. They applied the WRF-CHEM model and Grid-point Statistical Interpolation, a three-dimensional variational (3D-Var) assimilation tool. This relatively simple approach in chemical data assimilation of ozone and fine particulate matter leads to improved skill of the chemical model forecasts. Other studies using the four-dimensional variational data-assimilation framework (4D-Var) and ensemble Kalman filter (EnKF) data-assimilation frameworks and strategies show equal promise for future air quality forecasting (Constantinescu et al., 2007a-d; Elbern and Schmidt, 1999 and 2001; Elbern et al., 1997).

Probabilistic Forecasting

Dabberdt and Miller (2000) illustrated the direction in which probabilistic simulations of air quality can aid the user community. Delle Monache et al. (2006) presented results from ensemble ozone forecasts using both meteorology and emission perturbations. Wilczak et al. (2006) conducted a similar study but used seven different models, with their own meteorology, emissions, and chemical mechanisms, to create the ensembles. While both studies concluded a gain in forecast skill through the ensemble approach, they also identified a number of issues. Delle Monache et al. (2006) concluded that complex relationships between perturbations to ozone precursors and meteorological drivers can result in systematic forecast errors.

A survey of the literature suggests that at the urban scale, many applications of probabilistic forecasting methods are primarily found within the hydrometeorological context (Villarini et al., 2010b; Schellart et al., 2009). A deterministic forecast provides the user with an "illusion of certainty" (Villarini et al., 2010b). In a recent discussion of probabilistic flood forecasts, Villarini et al. (2010b) cited an American Meteorological Society policy statement on flooding, noting that an important research challenge was "quantifying forecast uncertainty by providing probabilistic forecast guidance" (AMS, 2000). A 2008 policy statement addressing probabilistic forecasting (AMS, 2008) noted several challenges that must be overcome before the user community can take advantage of probability forecasting, many of which are directly applicable to the urban meteorology problem.

Advanced Sensing Techniques for the Atmospheric Boundary Layer

Although there have been important recent advances in observation techniques that have resulted in clear improvements of weather forecasts, there is an obvious need for better observations, particularly to obtain high-resolution profiles of atmospheric variables within the atmospheric/urban boundary layer. For the emergency response community, timely, high spatial and temporal information in and above the urban canopy (i.e., within minutes at sub-km horizontal resolution) of meteorological fields impacting transport and dispersion of hazardous contaminants in an urban environment (i.e., vertical shear of winds, temperature, and moisture) is essential.

There are a number of new and emerging sensing techniques, including differential absorption lidars, which provide promise for urban boundary layer/planetary boundary layer (UBL/PBL) profiling of moisture and boundary layer structure at markedly reduced cost (perhaps an order of magnitude lower than previous norms). These lidars are currently being developed at the University of Montana in collaboration with NCAR and also in the commercial sector. Micropulse lidars and ceilometer instruments provide low-cost profiling technologies for aerosol structure within the PBL and can be used to detect the mixed layer height and structure. Studies (Emeis et al., 2005) have been done to successfully demonstrate their value, but they have largely not been used for these purposes in operational settings in the U.S.

Doppler-lidar systems can provide high-resolution planetary boundary layer wind profiles. Sodars, which are quite a bit cheaper, are often of limited use for urban applications due to concerns about noise pollution caused by the instrument and also background noise contamination of the sodar signals. TAMDAR (Tropospheric Airborne Meteorological Data Reporting) and MDCARS (Meteorological Data Collection and Reporting System) aircraft-based samplings are promising ways of obtaining medium-resolution PBL observations in and around urban areas, albeit at nonuniform sampling intervals throughout the day.

Non-Traditional Sensor Networks

The unique form, population density, and attributes of urban environments make them particularly challenging from the standpoint of traditional meteorological observations. However, the same challenges associated with urban environments present opportunities as well. Nontraditional "human or social" monitors may provide critical real-time meteorological, hazard, or emergency response data through media such as Twitter, Facebook, YouTube, and text messaging alerts (RSS [Really Simple Syndication] or SMS [Short Message Service] feeds). Personal contributions to meteorological assessment and prediction are common. For example, the Weather Channel now uses an interactive twitter feed.[3] BreakingNews, an MSNBC.com property, consolidates verified updates from various news sites, wire services and social networks, allowing people to easily log onto one site and see what other traditional and nontraditional news organizations are reporting.[4] Many public meteorological reports consist of input from voice over phone systems, amateur radios, and controlled-access websites (Ferree et al., 2009). Ferree et al. also note the potential value of social media to NWS forecasters or emergency managers; yet they also note key challenges or gaps in effective integration into the assessment and decision making process.

Key questions that the use of nontraditional sensor networks raises include the following: (1) Are there ways to aggregate real-time information from public sources with at least some quality control? If so, then how is this information distributed in a timely manner to official sources for emergency response, the broadcast media, the general public, and back to those using these social media? (2) How is the information filtered, and by whom? (3) What are the roles of the NWS and the private sector in gathering and redistributing such information?

Mass (2011) documented the great value in geotagged information available from social media sites for nowcasting of weather and for providing warnings. Mass also noted the rapid proliferation of smartphone applications ("apps") and potential roles that they play in urban meteorological dissemination and emergency response. He noted that several available or emerging apps leverage Global Positioning System (GPS) and cell phone tower information to determine location specific information. Next-generation apps might deliver site- or condition-specific forecasts or nowcasts.

---

[3] *http://www.weather.com/social/national.*
[4] *http://www.breakingnews.com/.*

These capacities are primarily enabled by smart technologies such as GPS or mobile GIS capabilities, which are fairly ubiquitous in urban regions. Together, the combination of social media and personalized technology (via GPS receivers, smartphones, etc.) has ushered in the potential era of dynamic, ever-evolving "personal sensor webs."

Nontraditional sources, however, are not limited to personal space. Other data sources that could be of value for urban meteorological forecasting, hazard response, or dissemination include commercial aircraft, road vehicles, traffic monitoring systems, electronic reader boards, among others.

Weather is the number one cause of nonrecurrent traffic congestion, which leads to spikes in greenhouse emissions. A relatively new U.S. Department of Transportation initiative on Connected Vehicles offers the promise to obtain atmospheric state information (e.g. temperature, pressure) from state, fleet, and possibly private citizen passenger vehicles (Mahoney et al., 2010; Drobot et al., 2010). With roughly 250 million vehicles on the nation's roads, most of which are in urban areas, this system could be a paradigm shift in our ability to monitor the surface atmosphere.

REMAINING NEEDS AND FUTURE CHALLENGES

Despite the many emerging meteorological observation and forecasting technologies described here, several key needs, challenges, and opportunities have been identified during the course of this study:

The "Urban" Signal and Climate

There has been inadequate emphasis on providing the necessary observations and modeling activities in the urban environment that are required to meet the needs of a broad cross-section of users of urban meteorology information. In the quest to create unbiased global-scale temperature records, meteorological services around the world routinely adjust the meteorological record to exclude the urban heat signal from climatological records (Karl et al., 1988; Peterson, 2003), and monitoring stations affected by urban development are being relocated to remote rural areas. Given that the type of data required to study and serve the needs of cities is mismatched with what is currently routinely monitored, it is important that the complementary functions of global and urban climate records be recognized. It is also optimal to have quality-controlled long-term urban observations.

In addition, there should be a two-way interaction between broader greenhouse-gas based climate change and urban climate change communities.

Stone et al. (2010) have revealed that large urban regions are warming faster than smaller cities and rural regions. This raises critical questions about whether adaptation and mitigations strategies are properly scaled to address this "hyper-warming" in large cities.

Cities are also poorly characterized (if they are included at all) in GCMs, yet urban footprints and associated aerosol loads are growing as GCM grid size is decreasing. Früh et al. (2010) have recently explored mechanisms to downscale GCM data to the urban scale using a cuboid method. In their method, urban heat load and the frequency of air temperature threshold exceedances were simulated using eight microscale urban climate runs for each appropriate wind direction as well as the time series of daily meteorological parameters either from regional climate projections or observation. While experimental, this methodology rightly notes the need to "downscale" climate impacts onto the "urban climate" signal. It is also essential to address how the urban climate signal scales up to impact regional to global climate in terms of temperature, precipitation, and cloud systems.

Integration of Research Knowledge into Operational Framework

Although the problem of converting what is learned in research into on-the-ground applications is common (i.e. the research to operations "valley of death" problem), the committee recognizes some opportunities within the urban meteorological community. For example, research has established that the shape and size of a city and the prevailing wind can affect the orientation of the UHI signal (Basara et al., 2010). With such knowledge, forecasters could provide very detailed minimum temperature forecasts, for example, around a city. Likewise, the literature has clearly established that precipitation and convective activity may be affected by urban regions. Most operational organizations are not aware of this research or may be skeptical, even though an emerging consensus is developing (Shepherd et al., 2011) on urban rainfall effects. This is complicated by uncertainty on the sign of the effect and under what conditions the effects are most evident prompting the need for further research.

Dynamics of Cities

Cities evolve constantly, and modeling and monitoring systems need to be flexible enough to adjust to these changes and input parameters need to be constantly updated. Challenges for the future will be (1) how to address current deficiencies in model frameworks, physics, and dynamics while avoiding a plethora of poorly validated models that are not compatible or easily implemented in operational settings because of their complexity and the number and type of input parameters needed, (2) advancing air chemistry models and better coupling with weather models to improve predictions of particulates and other harmful atmospheric pollutants, and (3) implementing end-to-end physical social models with appropriate feedbacks and error characterization.

4

Future Directions

As Chapter 3 shows, there is considerable physical science knowledge and effort toward monitoring and forecasting weather in the urban environment—a product of decades of research. On the other hand, Chapter 2 is a more general, high-level, largely anecdotal summary of end users and their needs. The Committee believes that the uneven nature of the information in these two chapters is a testament to the richness of our knowledge about monitoring and forecasting weather versus the needs, understanding, perceptions, and uses of weather information by end users.

As noted earlier, information needs of users remain unmet, despite recent advances and emerging technologies that offer promise to improve urban meteorology prediction and monitoring. This chapter focuses on those unmet needs and on future directions in urban meteorology and monitoring. It examines short-term needs, which might be addressed with small investments but promise large, quick returns, and then explores future challenges that stand to require significant efforts and investments. Note that while short-term needs may be easily attainable, they are not just for short-term attention; instead, their full potential can be reached through long-term sustained efforts only.

Since urban areas are part of the land surface component in weather and climate models, key lessons from the history of land surface modeling, observations, and understanding can provide some guidance on the near-term opportunities and future challenges in urban meteorology.

- Land model details evolve with the treatment of other atmospheric processes (e.g., Manabe, 1969; Deardorff, 1978; Pielke, 1984; Dickinson et al., 1986; Sellers et al., 1986).
- Land model development benefits from model intercomparison (e.g., Henderson-Sellers et al., 1993).

- Land model development benefits from and motivates coordinated field experiments (e.g., Sellers et al., 1992).
- These developments help the establishment of a variety of important international research programs, such as the Global Energy and Water Cycle Experiment (GEWEX), the (earlier) Biospheric Aspects of the Hydrological Cycle (Kabat et al., 2004), and (the successor to GEWEX) the integrated Land Ecosystem-Atmosphere Process Study (iLEAPS).[1]
- These programs, in turn, substantially accelerate the progress in coordinated field experiments over different continents, covering all major ecosystems; land model development, including the explicit consideration of vegetation stomatal resistance and photosynthesis as well as the land atmosphere exchanges of energy, water, and trace gases (e.g., carbon, nitrogen); and improved understanding of land-atmosphere coupling (e.g., Koster et al., 2006; Zeng et al., 2010).

SHORT-TERM NEEDS

There are four clear short-term needs related to urban meteorology:

1. maximize observational data in different categories from diverse sources,
2. regularly update metadata of the urban observations using standardized urban protocols,
3. continue and expand international urban model intercomparisons over urban areas, and
4. develop and apply best practices to strengthen the dialog between urban meteorologists and end user communities.

The second and third short-term needs are related to research needs; the fourth one is related to the need for translating established science to practical applications for end users, while the first one is related to both research and translation needs.

Observational Data

One significant need in urban meteorology is for improved high spatial and temporal resolution observational data. To help address this need, short-term field experiment and long-term monitoring data would consist of

[1] *http://www.ileaps.org*

- forcing data for urban meteorological models (or land surface models in urban areas), such as near-surface air temperature, humidity, wind, precipitation, solar and longwave radiation;
- observational data to characterize urban areas and determine urban model parameters (e.g., roughness length, impermeable areas) and urban sources/sinks (e.g., anthropogenic heating);
- observational data for urban model validation; and
- long-term observational data for end users.

A variety of data in each category are available from different communities. The best source of forcing data in the urban boundary layer likely would come from previous field experiments in urban areas. The down-scaling from 32 km regional atmospheric reanalysis over North America (Mesinger et al., 2006) and coarser resolution (from 0.5 to 2.5 deg or about 50 to 250 km) global reanalysis (e.g., Decker et al., 2011) provides another possibility.

For the urban characterization and source/sink data, the necessary spatial coverage is provided by satellite and aircraft data, such as the Landsat 30 m land cover data, the MODIS (Moderate Resolution Imaging Spectrometer) suite of land surface data (e.g., land cover, vegetation index, surface skin temperature) at 250 m to 1 km resolution, high spatial resolution aircraft lidar digital elevation data, and survey and field experimental data for urban sources/sinks.

Model validation data are primarily from field experiments and surveys. Polar-orbiting and geostationary satellite data (e.g., surface skin temperature) are also crucial. The geostationary data can be available at 4 km and hourly resolutions. They are available up to about 60 degree of latitude; however, the spatial resolution decreases at higher latitudes.

Much work has been done in attempting to remove the urban effect in the long-term climate data record (such as the 2m air temperature) (e.g., Kalnay and Cai, 2003). To avoid urban contamination, only sites far away from current and expected future urban areas are selected by the U.S. Climate Reference Network. However, for urban studies, urban effects need to be included, and long-term urban data need to be developed from the Global Historical Climate Network (GHCN; Peterson and Vose, 1997).

Short-term need #1: maximum access to observational data in different categories from diverse sources, by

- **securing access to existing data sets from previous urban campaigns (e.g., through central archives for existing urban data sets and corresponding metadata),**

- **assuring that long-term monitoring networks will serve needs of both the global and urban climate communities, and**
- **integrating data sets from various monitoring networks (e.g., from the National Oceanic and Atmospheric Administration [NOAA], the Environmental Protection Agency [EPA], the Department of Transportation [DOT], etc) into central data archives (e.g., at major cities) that can be easily accessed by the broader science and end user communities.**

Urban Metadata

Compared with observations over natural vegetation, the representativeness of observational data over urban areas is a much more challenging issue. Observational data have maximum value only if they are accompanied by comprehensive metadata. Without detailed metadata, observational data over the heterogeneous urban areas could be easily misused by the urban meteorology community and others. Considering the heterogeneous nature of urban areas, the site selection (including measurement height) of individual instruments and comprehensive stations with multiple instruments needs to follow flexible guiding principles as discussed in the World Meteorological Organization (WMO) manual on urban observations (WMO, 2008). Quality assurance and management are also crucial. Additional examples of metadata are discussed in NRC (2009).

The network-of-networks study (NRC, 2009) has demonstrated that while a plethora of surface monitoring sites often exist in urban areas, metadata are typically lacking for these sites, data access is not easily available, and data quality may be questionable. Given the importance of this weather and climate data to end users, it is crucial to assess the suitability of these sites, and to collect and document metadata where appropriate.

Furthermore, because the urban environment evolves rapidly as development proceeds (e.g., in almost all major cities in China in the past 30 years, as well as in U.S. urban areas with rapid population growth, such as Las Vegas and Phoenix), metadata for these urban stations need to be regularly updated. For the same reason, rural stations would become urbanized, and their siting needs to be reassessed according to the guiding principle in WMO (2008).

Short-term need #2: regularly updated metadata of the urban observations using standardized urban protocols.

Model Intercomparisons

There have been numerous model intercomparison projects in the past three decades, such as the intercomparison of global atmosphere-land coupled models, regional atmosphere-land coupled models, land surface models, atmosphere-ocean-land coupled models, and paleoclimate models. In general, initial intercomparisons help in the discovery of major model deficiencies, such as the lack of energy and water balance in some land surface models, and identification of the importance of certain major processes, such as the role of vegetation in land modeling). These intercomparisons can be done using comprehensive observations or a combination of limited observational data with model output. They may also include sensitivity tests on hypothetical situations (such as the atmosphere-land coupled model sensitivity to a uniform increase or decrease of global sea surface temperature). Intercomparisons at a later stage usually provide a baseline for understanding model prediction and projection and associated uncertainties instead of focusing on model improvements. For instance, the land/atmosphere coupled global modeling project in Koster et al. (2006) documented the coupling strength of each model and identified the land/atmosphere coupling hot spots.

Although the characterization of a natural vegetation type (e.g., evergreen needle leaf tree) does not change with horizontal scales beyond individual trees, urban characterization changes significantly with scale. For global weather and climate models with a typical grid spacing of ~30 km and ~100 km respectively, most of the urban areas in the world occupy a small fraction of a model grid cell, and only the gross features of urban areas can be considered (e.g., Oleson et al., 2010b). For continental and regional weather and climate models with typical grid sizes from ~2 km to ~30 km, more detailed urban models are needed. For local models over specific urban areas with grid sizes from tens to hundreds of meters, urban models need to consider different urban climate zones. For specific applications over buildings or a neighborhood (e.g., air pollutant dispersion) with a grid size of meters, urban models should take into account details of individual buildings.

Initial urban model intercomparisons have been done in recent years based on a dataset containing net solar and longwave radiation, sensible heat, and latent heat flux observations for an industrial area in Vancouver, Canada (Grimmond et al., 2010a). No model performed best or worst for all fluxes, however, some classes of models performed better for individual fluxes. Based on all statistical measures, the simpler models performed as well as the more complex models, suggesting that we currently lack the physical understanding to develop complex urban environment models. The subsequent intercomparison involved four stages in which participants were given increasingly detailed information about an urban site for which urban fluxes were directly observed (Grimmond et al., 2011). Similar to the initial intercomparison, no individual model performed best for all fluxes. In general, a model will perform better when additional information about the surface is provided. Nevertheless, it is clear that poor choice of parameter values can cause a significant drop in performance for models that otherwise perform well (Grimmond et al., 2011).

The community is still in the stage of capacity building (i.e., developing the urban model for weather and climate models) and cannot yet systematically evaluate the urban model impacts. Therefore, it is not yet possible to present specific examples of deficiencies in current modeling abilities or to provide products that separate near-real-time forecasting from modeling for long-range planning. Operational weather forecasting centers have not separated forecasting evaluations over urban versus nonurban areas. This is a challenge for almost all countries. Even countries with urbanized weather and climate models do not consider urban versus nonurban areas in model evaluation and validation metrics.

Although initial intercomparisons have focused on the energy, water, and momentum fluxes that are needed for atmospheric models, possible future intercomparison could include trace gas fluxes (e.g., carbon dioxide) and aerosols (e.g., for air quality modeling, cloud microphysics modeling). Different urban areas (e.g., coastal, mountainous, tropical, etc.) could also be covered in future intercomparisons as well as urban areas in both developed and developing countries. Intercomparison efforts need to continue with comprehensive data or, when such data are not available, a combination of limited observations with model outputs.

Short-term need #3: continued and expanded international urban model intercomparisons over urban areas.

Communication

There are diverse end user groups with different needs in urban meteorology. There is a lack of communication within urban meteorology (e.g., between modelers and experimentalists), between different end user groups, and most importantly, between urban meteorologists and end users (Oke, 2006). One participant of the workshop (Appendix C), an experienced end user in the department of transportation at a major city in the U.S., specifically mentioned that only half of the presentations by urban meteorology experts during the workshop were comprehensible. There are several reasons for this, such as the lack of communication experiences and the lack of understanding of each other's needs, practices, and capabilities.

Although some end users only need to know the most likely outcome among different options (which is similar to a patient seeking advice from a doctor on a particular treatment), most users require probabilistic urban meteorological information that convey the uncertainty, or likelihood that an event will occur. There are uncertainties associated with any weather and climate prediction due to the uncertainties in initial conditions, boundary conditions, model parameters, model parameterizations of physical, chemical, and biological processes, and the chaotic nature of the atmosphere. Even with the same atmospheric conditions, different urban models may yield different results (e.g., due to different representations of vegetation and hydrology). Furthermore, given that numerous urban models do not perform well across all fluxes, they should be applied with caution, and users should be aware of the implications for decision making (Grimmond et al., 2011). There is also general difficulty in the weather and climate community (as well as the scientific community at large) in characterizing and communicating probabilistic information to end users (NRC, 2006). It is important to note that even though improved communication of probabilistic information is crucial, it is only one piece of the bigger picture. Working collaboratively with communication scientists can help bridge the gap between end users and urban meteorologists.

Short-term need #4: development and application of best practices to strengthen the dialog between urban meteorologists and end user communities.

Note that discussions here are mostly related to communication practices. Communication is also a social scientific field of study with many subfields. Subfields relevant to urban meteorology and end users include risk communication, science communication, organizational communication, and mass communication. There is an essential role of communication science (and other social science disciplines) in helping the meteorological community (urban or otherwise) understand the complex roles of people's perceptions, attitudes, behaviors, and experiences in their using weather information for decision-making. For instance, communicating weather forecast uncertainty information is indeed important, but it is only one piece of a much bigger picture of communication that involves how people process information, their past experiences, the channels through which they get information, the influence of what other people around them think and do, and so on. Fully integrating communication science (and other social science disciplines) in bridging the gap between urban meteorologists and end users requires significant efforts and investments.

CHALLENGES

Although there are some clear short-term and relatively straightforward steps that could be taken, other potentially valuable advances would require significant efforts and investments and would therefore likely be challenging to implement. The value of such activities would need to be weighed against costs, such as through socioeconomic analysis. For instance, to estimate the economic effects of weather variability in the United States, Lazo et al. (2011) defined and measured weather sensitivity as the variability in economic output that is attributable to weather variability, accounting for changes in technology and changes in levels of economic inputs (i.e., capital, labor, and energy). Eleven nongovernmental sectors of the U.S. economy were found to have statistically significant sensitivity to weather variability (as represented by temperature and precipitation), and the U.S. economic output is found to vary by up to $485 billion per year of 2008 gross domestic product, or about 3.4 percent, owing to weather variability. At the state level, the percentage can be above 10 percent (e.g., in California), as shown in Figure 4.1.

Socioeconomic research and capacity related to weather (including urban meteorology) were the focus of the earlier Board on Atmospheric Sciences and Climate (BASC) Summer Study Workshop in 2009 and the subsequent NRC (2010a) report, and hence are not included here. However, the point remains valid that through collaboration, the urban meteorology community and social scientists could develop a core interdisciplinary capacity for urban meteorology-society research and transitioning research to operations. They could start with three priority areas: "estimating the societal and economic value of weather information; understanding the interpretation and use of weather information; and applying this knowledge to improve communication, use, and value" (NRC, 2010a).

Through information gathering (including the workshop), deliberations, and expert judgment, the committee concludes there are three significant long-term challenges related to urban meteorology.

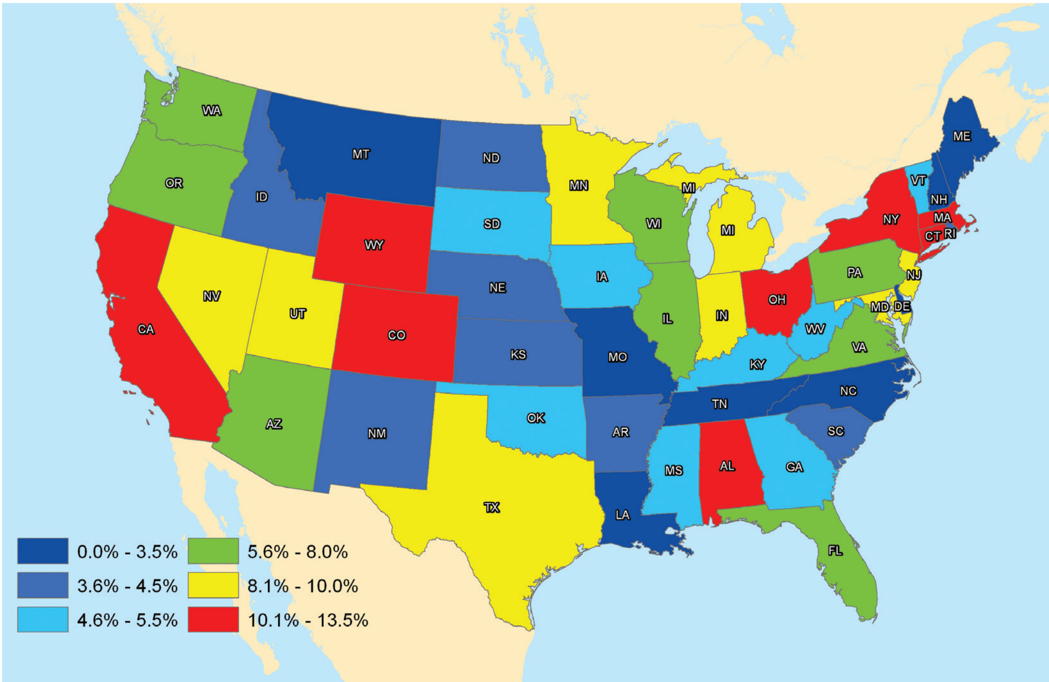


FIGURE 4.1 State sensitivity to weather variability as a percentage of total gross state product. SOURCE: Lazo et al., 2011. (c)American Meteorological Society. Reprinted with permission.

- How can new capabilities for urban observations be developed and implemented?
- How can weather and climate models be urbanized, and how can urban areas be included in the model prediction evaluation and validation metrics?
- How will the capability for integrated urban meteorology-decision support systems be developed?

New Capabilities for Urban Observations

Because it is challenging to obtain representative measurements from individual sites over urban areas, there is a strong need to develop new capabilities in two categories. First, technologies are needed to integrate the information that may be available from the network of personal digital assistants (PDAs), including smartphones that are connected to the internet. Several available or emerging smartphone applications leverage input from the Global Positioning System (GPS) and cell phone towers to determine location-specific information, which could be useful for reporting and evaluating weather events. Next-generation apps may have the capability to deliver site- or condition-specific forecasts and nowcasts. Similarly, a network of vehicles with GPS capability (e.g., from the U.S. Post Office, United Parcel Service [UPS], Federal Express, and possibly taxi services) would be valuable in urban measurements (e.g., for temperature and pressure measurements). To have such networks, inexpensive sensors would need to be developed.

Secondly, given that urbanization affects the physical and dynamical structure of the planetary boundary layer (PBL)—roughly the lowest one kilometer of the atmosphere—new technologies for critical measurements within this layer are essential. The PBL influences both local weather and the concentration and residence time of pollutants in the atmosphere, which in turn impact air quality. Measurements in the PBL are also important for dispersion applications. The PBL is also the most understudied and undersampled layer in the urban atmosphere, in large part because of the difficulty of access over some parts of cities.

Existing and emerging measurement technologies are also discussed in the extended abstract of W.F. Dabberdt in Appendix A. One way to integrate data from various sources is through the urban reanalysis (Box 4.1).

Challenge #1: How can new capabilities for urban observations be developed and implemented, particularly using the network of PDAs (including smartphones), vehicles, and new technologies for measurements in the whole planetary boundary layer?

Urbanization of Weather and Climate Models

As the horizontal resolution in weather and climate models continues to increase due to advances in the models, urban areas can occupy a whole model grid cell or a large fraction of grid cell. The treatment of urban areas can be divided into three categories: (a) not considering urban areas by assuming the areas are covered by the dominant vegetation type in the grid cell; (b) considering urban area as a specific land cover type with specified parameters which can occupy a fraction of grid cell or a whole grid cell; and (c) urbanizing the land model in weather and climate models by considering more detailed urban processes (e.g., anthropogenic heat sources, impervious surface fraction). For the third category, urban model intercomparison has been done recently (Grimmond et al., 2010a, 2011). An urbanized land model has been used in some weather and climate models, such as the UK Met Office Unified Model for weather prediction (Best, 2005) and the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM; Oleson et al., 2010b).

In the United States, urban areas as a land cover type are considered in the NCEP nonhydrostatic mesoscale model based on the Weather and Research Forecasts (WRF-NMM) over North America, with a horizontal grid spacing of 4 km at present. Urban areas are treated in more detail in the NCEP pollutant dispersion prediction. Urban areas, however, are not yet considered in the NCEP global forecast system (GFS) and climate forecast system (CFS). This may be related to the NWS policy of uniformity of service (i.e., weather service distributed without consideration of population density). In addition, because observing systems are more or less uniformly distributed, particularly where terrain is not an obstacle, the NWP evaluation and validation metrics do not consider urban areas explicitly.

The National Weather Service (NWS) has begun to shift to digital gridded forecasts. In particular, NWS just released the Weather-Ready Nation initiative, partly in response to 14 separate disasters (including hurricane Irene), each with an economic loss of $1 billion or more in 2011 (Figure 1.3).[2]

Challenge #2: How can weather and climate models be urbanized and how can urban areas be included in model prediction evaluation and validation metrics?

Only after addressing this challenge can the crucial question that is relevant to end users be addressed: how effective are these forecasting models over urban versus non-urban areas (including the spatial scales of such forecasting and associated error probability distribution)? Such models will also help address another question from end users: as cities grow, does the urban effect (e.g., on temperature, air pollution, precipitation) change continuously or abruptly?

Integrated Urban Meteorology and Decision Support Systems

It can be a challenge for scientists to understand one another, even scientists in different subfields of the same discipline (e.g., between modelers and experimentalists in atmospheric science). Therefore it is not surprising that there is a lack of mutual understanding between meteorologists and the

[2]See *http://www.noaa.gov/extreme2011/index.html* and *http://www.noaanews.noaa.gov/stories2011/20110817_weatherready.html*.

BOX 4.1
Urban Reanalysis

There are observational data from diverse sources for weather forecasting every day. These data are assimilated into the operational model to represent the four-dimensional state of the atmosphere (i.e., three-dimensional in space and one-dimensional in time) for the initial condition (i.e., the best estimate of the initial state of the atmosphere) in numerical weather prediction (NWP) and for model evaluations. These data are referred to as the "analysis" fields.

However, NWP models and the associated data assimilation system have been improved over time; thus the differences in the analysis fields from year to year can be attributed to the model upgrades. Furthermore, due to the computation-related time constraints associated with NWP, many data are not available for real-time data assimilation. Therefore, reanalysis—analyzing data using the same data assimilation system to integrate data from diverse sources—has been done in the past two decades. The first reanalysis came from the National Centers for Environmental Prediction (NCEP) and covers the period from 1948 to present (Kalnay et al., 1996).

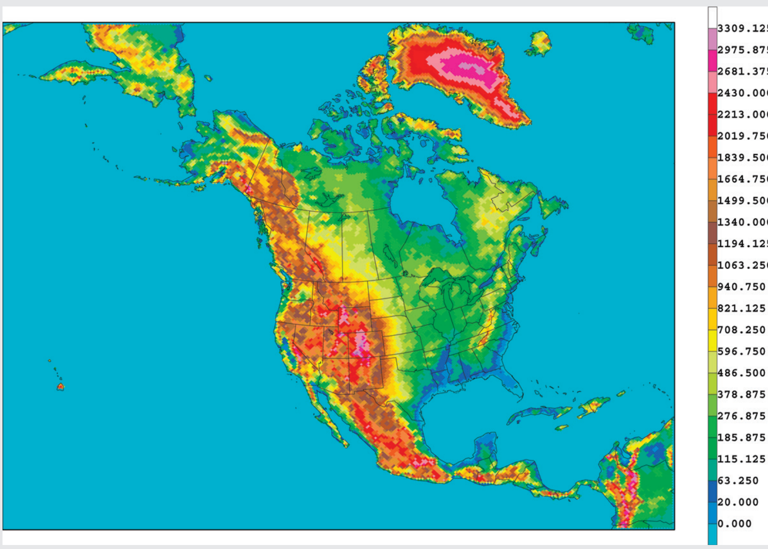
Since then, other weather forecasting centers (European Centre for Medium-range Weather Forecasts [ECMWF] and Japanese Meteorological Agency [JMA]) as well as the NASA Global Modeling and Assimilation Office (GMAO) have released their reanalysis products. At the same time, NCEP has also released the regional reanalysis over North America with a higher horizontal resolution (32 km), which includes the direct assimilation of precipitation observations (see figure below). Furthermore, NCEP released the first atmosphere-ocean-land coupled reanalysis, in contrast to atmosphere-land coupled reanalyses that have resulted from other reanalysis projects. Today, reanalysis is widely regarded as a great success in atmospheric science (with the Kalnay et al. (1996) being the most cited paper in all geosciences).

While the 2m air temperature and humidity are assimilated during the warm seasons to adjust soil moisture in the ECMWF reanalysis, and surface precipitation is assimilated in the NCEP regional reanalysis, most of the land surface data (such as surface skin temperature, 2-m air temperature and humidity, 10m wind speed and direction, and precipitation) are not explicitly assimilated in various reanalysis projects. Therefore the land surface (or urban) reanalysis process involves

- adjusting the near-surface atmospheric fields (temperature, humidity, wind, precipitation, downward solar and longwave radiation) from reanalysis using surface observations;
- running the land surface models (or urban models) forced by these atmospheric fields; and
- obtaining land surface fields such as surface skin temperature, sensible and latent heat fluxes, upward solar and longwave radiation, soil temperature and moisture, and soil heat flux.

Prior land surface reanalysis efforts include the Global Soil Wetness Project (GSWP) (Dirmeyer et al., 1999) and North American and Global Land Data Assimilation System (NLDAS; Mitchell et al., 2004, and GLDAS; Rodell et al., 2004), both of which are produced by particular instances of the Land Information System (LIS) software framework for high-performance land-surface modeling and data assimilation (Kumar et al., 2006).

Following these successful efforts, it is important to develop local reanalysis over selected urban areas. Community efforts are still needed to address several relevant issues: What is the adequate spatial resolution based on end user needs and data availability? How can we downscale coarse-resolution data to obtain atmospheric forcing data and surface data to characterize urban areas? What urban land models should be used? What period should we focus on (e.g., the modern satellite era from 1979 to present)?



The NCEP Regional Reanalysis domain and its 32 km topography. Terrain elevation (m) is indicated by the color scale at the right. SOURCE: Mesinger et al., 2006. (c)American Meteorological Society. Reprinted with permission.

diverse end users found in urban areas. On one hand, meteorologists need to better understand how individuals and organizations interpret forecast information and integrate it with other inputs, such as socioeconomic, political, and cultural factors, in decision-making processes. On the other hand, end users need to better understand how observational data and models generate forecasts and associated uncertainties. Given that by the end of this century most people will be living in cities, this mutual understanding is crucial because of the two-way effects of urban development on local climate and local climate on urban development. This is even more challenging in a nonstationary world (Box 4.2).

BOX 4.2
Challenge in a Nonstationary World

With the global warming of the past century and the expected warming in the coming decades, the assumption of stationarity in weather and climate is widely recognized to be incorrect (Milly et al., 2008). This nonstationarity of events (e.g., fewer cold waves, more heat waves; drought periods followed by extreme precipitation and flooding) presents a major challenge for planning and engineering activities that have a time scale of decades or longer.

Improving modeling capability in a nonstationary world requires scientists to further improve modeling and observations of natural and anthropogenic processes over urban areas. Nonstationarity, however, also implies that good modeling skills in the past and at present do not guarantee those skills for the future. In other words, prediction uncertainties will be larger.

Therefore, there is a strong need for decision makers to learn to manage uncertainties associated with climate projections and projections of human activities. One way to do this is to use climate model sensitivity tests to identify potential vulnerabilities of proposed adaptation strategies. This would allow decision makers to systematically examine the performance of their adaptation strategies over a wide range of possible scenarios which are driven by uncertainties about future climate and several other economic, political, and cultural factors (Pielke, 2009). This urban meteorology-decision support process can then be iterated to develop a strategy that is sufficiently robust across various alterative future scenarios. A similar iterative risk management framework has been emphasized in NRC (2011).

For instance, today's 100-year flood zone in a coastal city (such as New York City) based on historical data cannot be used for urban planning and climate change adaptation in the future. With rising sea level in the next few decades due to global warming, a 100-year flood would inundate a far greater area of this city, and the frequency of flooding and the impacts of storm surge would also be significantly increased. Therefore, urban planning and climate change adaptation (e.g., building storm-surge barriers) need to operate knowing that nonstationarity is the new norm, and planning should involve iterative interaction between scientists (working on climate projections) and urban and regional planners.

To meet this challenge of mutual understanding between users and meteorologists, a combination of complementary approaches is required. These approaches include urban testbeds, applied science projects that involve meteorologists and end users, and joint urban meteorology-decision support exercises (e.g., emergency response, climate change-urban planning).

The idea of an urban meteorology testbed was proposed in Dabberdt et al. (2005) and NRC (2010a): "a testbed is a working relationship in a quasi-operational framework among measurement specialists, forecasters, researchers, private-sector, and government agencies aimed at solving operational and practical regional problems with a strong connection to the end users."

Testbeds typically result in more effective observing systems, better use of data in forecasts, improved services and products, and economic/public safety benefits, and in the end, more effective decision making by users. The translation of R&D findings into better operations, services, and decision-making is accelerated by testbeds.

There are ongoing efforts in a number of cities such as New York City (Reynolds et al., 2004; Arend, 2010; see Chapter 2) and Oklahoma City (Basara et al., 2010) to establish urban observation networks that provide long-term observations (see Box 4.3 for more examples). Combining a suite of in situ and remote sensing instruments to provide a detailed picture of the urban atmosphere in all three dimensions, as well as integrating observations and modeling in an urban testbed with strong stakeholder involvement, remain challenges that have not yet been met in any U.S. city.

The establishment of several urban testbeds across the country and worldwide was commended by several workshop participants as a move in the right direction. However, there is still a lot of work to be done. In addition to identifying additional observations needed for ideal coverage of the urban PBL and developing strategies for simultaneously advancing modeling tools, additional end user communities (e.g., on the business and urban planning side) need to be brought on board.

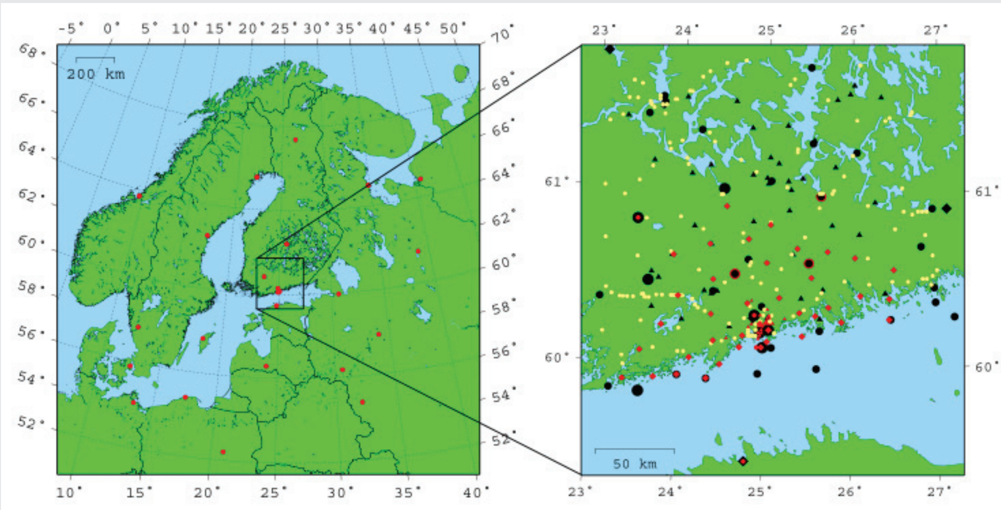
Discussions at the workshop further highlighted that criteria and methodologies for the design of three-dimensional urban networks are still not well established. The World Meteorological Organization guidelines for urban surface monitoring sites (WMO, 2008) are an important first step toward urban network design. In addition, studies are needed to identify crucially important data as well as ideal sensor deployment, which would not only facilitate long-term urban records but also improved urban forecasts. Observing System Simulation Experiments (OSSE), which have been successfully tested for radar networks (Xue et al., 2006), should be developed for urban monitoring networks.

BOX 4.3
Urban Testbeds

One good example of an urban testbed is the Helsinki testbed in Finland (Koskinen et al., 2011). It has been established and maintained since 2005 by the Finnish Meteorological Institute and Vaisala. It is an open research and quasi-operational program designed to advance observing systems and strategies, understanding of mesoscale weather phenomena, urban and regional modeling, and applications in a high-latitude coastal environment (see figure below).

Another good example is Shanghai, which is also actively pursuing development of an urban testbed that includes developing advanced observed systems for advanced models and providing actionable information that addresses user needs. Shanghai also has a multi-hazard early warning system; and information is shared between various agencies.

The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) and the North Central Texas Council of Governments (NCTCOG) are in the process of establishing the Dallas-Fort Worth (DFW) Urban Demonstration Network (Appendix B). Users will include NWS and River Forecasting Center (RFC) forecasters and emergency managers, while users from other sectors such as transportation, utilities, regional airports, arenas, and the media will be added later. This effort will also develop the business models for federal/municipal/private partnerships that will sustain the network.



No.	**Sites in Helsinki Testbed domain**	
46	FMI weather stations	●
34	FMI precipitation stations	▲
13	Off-line temperature loggers in greater Helsinki area	▲ (red)
8	Weather transmitters in greater Helsinki area	▲ (red)
191	Road weather stations	● (yellow)
292	**Surface weather stations, total**	
42	Pairs of weather transmitters in masts	◆ (red)
5	Optical backscatter profilers (new ceilometers)	● (red)
6	FMI ceilometers	●
4	C-band Doppler radars	◆
1	Dual polarization Doppler radar	◆ (red)
4	RAOB sounding stations	● (red)
1	UHF wind profiler	▲ (red)
-	Total lightning network	-

Observing sites in the domain of the Helsinki Testbed (right), and larger area model domain with nearby RAOB sounding stations (left). SOURCE: The Finnish Meteorological Institute, *http://testbed.fmi.fi/Stations.en.html*.

Finding funding and infrastructure mechanisms to establish and maintain urban testbeds will be challenging, especially given the need to integrate existing and new monitoring networks with modeling techniques and provide long-term urban climate data records and validated modeling output tuned for various end users. Databases of urban building structures and transportation networks should also be integrated and continuously updated.

Challenge #3: How will the capability for integrated urban meteorology-decision support systems be developed through the integration of

- support for future intensive urban research projects that integrate modeling and observations and focus on improving the fundamental knowledge of physics and dynamics in the urban atmosphere,
- increased dialogue between urban meteorologists and end users, and
- urban meteorology testbeds?

FINAL THOUGHTS

The field of urban meteorology has grown considerably in the past 50 years, and with the increased growth of cities worldwide, including the United States, there is a pressing need for continued scientific advances within the field. As the capabilities within urban meteorology have improved, the uses for urban weather information and its value to decision makers have increased. Users of urban meteorology information need it to be available in a wide variety of formats, within time constraints set by users' decision processes. In order to help meteorologists provide this tailored information, there is a need for more direct interaction with key end user communities who can help identify their information needs. By advancing the science and technology related to urban meteorology with input from key end user communities, meteorologists will be better able to meet the needs of diverse end users.

References

Akbari, H., S. Menon, and A. Rosenfeld. 2009. Global cooling: increasing world-wide urban albedos to offset CO_2. *Climatic Change* 94:275-286.

Allwine, K. J., J. H. Shinn, G. E. Streit, K. L. Clawson, and M. Brown. 2002. Overview of urban 2000: A multiscale field study of dispersion through an urban environment. *Bulletin of the American Meteorological Society* 83:521-536.

Allwine, K. J. 2004. Overview of joint urban 2003: An atmospheric dispersion study in Oklahoma City. Joint session between the 8th Symposium on Integrated Observing and Assimilation Systems in the Atmosphere, Oceans and Land Surface and the Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone, Seattle, WA, American Meteorological Society.

AMS (American Meteorological Society). 2000. AMS, Policy statement: prediction and mitigation of flash floods. *Bulletin of the American Meteorological Society* 81:1338-1340.

AMS. 2008. AMS, Policy statement: Enhancing Weather Information with Probability Forecasts. *Bulletin of the American Meteorological Society* 89. *http://www.ametsoc.org/policy/2008 enhancingweatherinformation_amsstatement.html*. Accessed November 7, 2011.

AMS. 2011. Realizing the Potential of Vehicle-Based Observations. A Report from the Annual Partnership Topic (APT) Committee on Mobile Observations, under the Board on Enterprise Planning of the Commission on the Weather and Climate Enterprise. *http://www.ametsoc.org/boardpges/cwce/docs/BEP/Mobile-Obs/2011-08-16-Committee-Report.pdf*. Accessed November 7, 2011.

Anderson, T. L., R. J. Charlson, N. Bellouin, O. Boucher, M. Chin, S. A. Christopher, J. Haywood, Y. J. Kaufman, S. Kinne, J. A. Ogren, L. A. Remer, T. Takemura, D. Tanre, O. Torres, C. R. Trepte, B. A. Wielicki, D. M. Winker, and H. Yu. 2005. An "A-Train" strategy for quantifying direct climate forcing by anthropogenic aerosols. *Bulletin of the American Meteorological Society* 86:1795-1809, doi:10.1175/BAMS-86-12-1795.

Arend, M., B. Gross, F. Moshary, Y. Wu, and S. Ahmed. Inter-comparison of vertical profiling instruments for boundary layer measurements in an urban setting. 15th Symposium on Meteorological Observation and Instrumentation. AMS Annual Meeting, Atlanta, GA, January 2010.

Arnfield, A. J. 2003. Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology* 23:1-26.

Arnold, S. J., H. ApSimon, J. Barlow, S. Belcher, M. Bell, D. Boddy, R. Britter, H. Cheng, R. Clark, R. Colvile, S. Dimitroulopoulou, A. Dobre, B. Greally, S. Kaur, A. Knights, T. Lawton, A. Makepeace, D. Martin, M. Neophytou, S. Neville, M. Nieuwenhuijsen, G. Nickless, C. Price, A. Robins, D. Shallcross, P. Simmonds, R. Smalley, J. Tate, A. Tomlin, H. Wang, P. Walsh. 2004. Dispersion of Air Pollution & Penetration into the Local Environment—DAPPLE. *Science of the Total Environment* 332:139-153.

Ashley, W., M. Bentley, and J. Stallins. 2011. Urban-induced thunderstorm modification in the southeast United States. *Climatic Change*, doi:10.1007/s10584-011-0324-1.

Baklanov, A., C. S. B. Grimmond, A. Mahura, and M. Athanassiadou, editors. 2009. Meteorological and air quality models for urban areas. Berlin: Springer Berlin-Heidelberg.

Basara, J., H. Basara, B. Illston, and K. C. Crawford. 2010. The Impact of the Urban Heat Island during an Intense Heat Wave in Oklahoma City. *Advances in Meteorology* 2010:1-11, doi:10.1155/2010/230365.

Beniston, M. 2004. The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. *Geophysical Research Letters* 31:2022-2026.

Best, M. 2005. Representing urban areas within operational numerical weather prediction models. *Boundary-Layer Meteorology* 114:91-109.

Best, M., C. Grimmond, and M. Villani. 2006. Evaluation of the urban tile in MOSES using surface energy balance observations. *Boundary-Layer Meteorology* 118:503-525.

Bhaduri, B., M. Minner, S. Tatalovich, and J. Harbor. 2001. Long-term hydrologic impact of urbanization: a tale of two models. *Journal of Water Resources Planning and Management* 127:13-19.

Boris, J., G. Patnaik, and K. Obenschain. 2011. The how and why of Nomografs for CT-Analyst. Washington, DC: Naval Research Laboratory. NRL/MR/6440-11-9326.

Bornstein R., and Q. L. Lin. 2000. Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. *Atmospheric Environment* 34(3):507-516.

Bosilovich, M. G. 2008. NASA's modern era retrospective analysis for research and applications: Integrating Earth observations. *Earthzine*. *http://www.earthzine.org/2008/09/26/nasas-modern-era-retrospective-analysis/*. Accessed November 7, 2011.

Brauer, M, C. Lencar, L. Tamburic, M. Koehoorn, P. Demers, and C. Karr. 2008. A Cohort Study of Traffic-Related Air Pollution Impacts on Birth Outcomes. *Environmental Health Perspectives* 116(5):680-686, doi:10.1289/ehp.10952.

Britter, R. E., and S. R. Hanna, S. 2003. Flow and dispersion in urban areas. *Annual Review of Fluid Mechanics* 35:469ñ496, doi:10.1146/annurev.fluid.35.101101.161147.

Burke, J., J. Xue, H. Özkaynak. 2001. Population exposures to particulate matter: A comparison of exposure model predictions and measurement data. Presented at 11th Annual Meeting of the International Society of Exposure Analysis, Charleston, SC, November 4-8, 2001.

Byun, D., and K. Schere. 2006. Review of the governing equations, computational algorithms, and other components of the models-3 Community Multiscale Air Quality (CMAQ) modeling system. *Applied Mechanics Reviews* 59:51-77.

Carter, W. M., J. M. Shepherd, S. Burian, and I. Jeyachandran. 2011. Integration of lidar data into a coupled mesoscale-land surface model: A theoretical assessment of sensitivity of urban-coastal mesoscale circulations to urban canopy. *Journal of Atmospheric and Oceanic Technology* (In Press).

Changnon, S. 2004. Climate atlas: Freezing rain and ice storms. Champaign, IL: Printec Press Incorporated.

Changnon, S. A., R. G. Semonin, A. H. Auer, R. R. Braham, and J. Hales. 1981. METROMEX: A Review and Summary. *Meteorological Monographs* 40(18). 181 pp.

Changnon, S. A., K. E. Kunkel, and B. C. Reinke. 1996. Impacts and responses to the 1995 heat wave: A call to action. *Bulletin of the American Meteorological Society* 77:1497-1506.

Chen, F., K. W. Manning, M. A. LeMone, S. B. Trier, J. G. Alfieri, R. Roberts, M. Tewari, D. Niyogi, T. W. Horst, S. P. Oncley, J. B. Basara, and P. D. Blanken. 2007. Description and evaluation of the characteristics of the NCAR high-resolution land data assimilation system. *Journal of Applied Meteorology and Climatology* 46:694-713.

Chen, F., H. Kusaka, R. Bornstain, J. Ching, C.S.B. Grimmond, S. Grossman-Clarke, T. Loridan, K. Manning, A. Martilli, S. Miao, D. Sailor, F. Salamanca, H. Taha, M. Tewari, X. Wang, A. Wyszogrodzki, and C. Zhang. 2011. The integrated WRF/urban modeling system: development, evaluation, and applications to urban environmental problems. *International Journal of Climatology* 31:273-288, doi: 10.1002/joc.2158.

Ching, J., A. Hanna, F. Chen, S. Burian, and T. Hultgren. 2009a. Facilitating advanced urban meteorology and air quality modeling capabilities with high resolution urban database and access portal tools. Chapter 1, pp. 3-9 in *Urbanization of Meteorological and Air Quality Models*, A. Baklanov, C. S. B. Grimmond, A. Mahura, and M. Athanassiadou, editors. Berlin: Springer Berlin-Heidelberg.

Ching, J., M. Brown, S. Burian, F. Chen, R. Cionco, A. Hanna, T. Hultgren, T. McPherson, D. Sailor, H. Taha, and D. Williams. 2009b. National Urban Database and Access Portal Tool. *Bulletin of the American Meteorological Society* 90:1157-1168.

Christen, A., E. van Gorsel, and R. Vogt. 2007. Coherent structures in urban roughness sublayer turbulence. *International Journal of Climatology* 27:1955-1968.

Cimorelli, A. J., S. G. Perry, A. Venkatram, J. C. Weil, R. Paine, R. B. Wilson, R. F. Lee, W. D. Peters, and R. W. Brode. 2005. AERMOD: A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization. *Journal of Applied Meteorology* 44:682-693.

Constantinescu, E. M., A. Sandu, T. Chai, G. R. Carmichael. 2007a. Assessment of ensemble-based chemical data assimilation in an idealized setting. *Atmospheric Environment* 41:18-36.

Constantinescu, E. M., A. Sandu, T. Chai, G. R. Carmichael. 2007b. Autoregressive models of background errors for chemical data assimilation. *Journal of Geophysical Research Atmospheres* 112:D12309. doi: 10.1029/2006JD008103.

Constantinescu, E. M., A. Sandu, T. Chai, G. R. Carmichael. 2007c. Ensemble based chemical data assimilation. I: General approach. *Quarterly Journal of the Royal Meteorological Society* 133:1229-1243.

Constantinescu, E. M., A. Sandu, T. Chai, G. R. Carmichael. 2007d. Ensemble based chemical data assimilation. II: Covariance localization. *Quarterly Journal of the Royal Meteorological Society* 133:1245-1256.

Coon, W. F., and J. E. Reddy. 2008. Hydrologic and Water-quality Characterization and Modeling of the Onondaga Lake Basin, Onondaga County, New York. U.S. Geological Survey Scientific Investigations Report 2008-5013. 85 pp. *http://pubs.usgs.gov/sir/2008/5013/SIR2008-5013.pdf*. Accessed March 30, 2012.

Crossett, K. M., T. .J. Culliton, P. C. Wiley, and T. R. Goodspeed. 2004. Population trends along the coastal United States: 1980-2008. Coastal Trends Report. Silver Spring, MD: NOAA, National Ocean Service. 54 pp.

Dabberdt, W. F., Jeremy Hales, S. Zubrick, A. Crook, W. Krajewski, K. 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* 81:2047-2064, doi:10.1175/15200477(2000)081<2047:FIITUZ>2.3.CO;2.

Dabberdt, W., and E. Miller. 2000. Uncertainty, ensembles and air quality dispersion modeling: applications and challenges. *Atmospheric Environment* 34:4667-4673, ISSN 1352-2310, doi: 10.1016/S1352-2310(00)00141-2.

Dabberdt, W., M. A. Carroll, D. Baumgardner, G. Carmichael, R. Cohen, T. Dye, J. Ellis, G. Grell, S. Grommond, 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 of 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 X. Zou. 2005. Multifunctional mesoscale observing networks. *Bulletin of the American Meteorological Society* 86(7):961-982.

Deardorff, J. W. 1978. Efficient prediction of ground surface temperature and moisture, with an inclusion of a layer of vegetation. *Journal of Geophysical Research* 83:1889-1903.

Decker, M., M. Brunke, Z. Wang, K. Sakaguchi, X. Zeng, and M.G. Bosilovich. 2011. Evaluation of the Reanalysis Products from GSFC, NCEP, and ECMWF Using Flux Tower Observations. *Journal of Climate*, doi:http://dx.doi.org/10.1175/JCLI-D-11-00004.1.

Delle Monache, L., J. Hacker, Y. Zhou, X. Deng, and R. Stull. 2006. Probabilistic aspects of meteorological and ozone regional ensemble forecasts. *Journal of Geophysical Research-Atmospheres* 111: D24307, doi:10.1029/2005JD006917.

Dickinson, R. E., A. Henderson-Sellers, P. J. Kennedy, and M. F. Wilson. 1986. Biosphere-atmosphere transfer scheme (BATS) for the NCAR Community Climate Model. Boulder, CO: National Center for Atmospheric Research. NCAR/TN-387+STR.

Dirmeyer, P. A., A. J. Dolman and N. Sato. 1999. The pilot phase of the Global Soil Wetness Project. *Bulletin of the American Meteorological Society* 80(5):851-878.

Dodman, D. 2009. Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environment and Urbanization* 21:185-201.

Drobot, S. D., M. Chapman, P. A. Pisano, and B. B. McKeever. 2010. Using Vehicles as Mobile Weather Platforms. *Advances in Intelligent and Soft Computing* 81:203-213.

Drobot, S. D. 2011. Personal communication with EMS and freight operators.

Eder, B., D. Kang, R. Mathur, S. Yu, and K. Schere. 2006. An operational evaluation of the Eta-CMAQ quality forecast model. *Atmospheric Environment* 40:4894-4905.

Eder, B., D. Kang, R. Mathur, J. Pleim, S. Yu, T. Otte, and G. Pouliot. 2009. A performance evaluation of the National Air Quality Forecast Capability for the summer of 2007. *Atmospheric Environment* 43:2312-2320.

Elbern, H., H. Schmidt, A. Ebel. 1997. Variational data assimilation for tropospheric chemistry modeling. *Journal of Geophysical Research* 102:15967-15985.

Elbern, H., and H. Schmidt. 1999. A four-dimensional variational chemistry data assimilation scheme for Eulerian chemistry transport modelling. *Journal of Geophysical Research* 104:18583-18598.

Elbern, H., and H. Schmidt. 2001. Ozone episode analysis by four-dimensional variational chemistry data assimilation. *Journal of Geological Research* 106:3569-3590.

Emeis, S., C. Munkel, and K. Schafer. 2005. Remote sensing of stratification and height of the atmospheric mixing-layer by acoustic and optical methods. *Gefahrstoffe Reinhaltung Der Luft* 65:247-250.

Emeis, S. 2011. Surface-Based Remote Sensing of the Atmospheric Boundary Layer. *Atmospheric and Oceanographic Studies Library* 40, doi:10.1007/978-90-481-9340-0.

EPA (Environmental Protection Agency). "Counties Designated 'Nonattainment'." Last modified March 30, 2012. *http://www.epa.gov/oaqps001/greenbk/mapnpoll.html.*

Fenger, J. 2009. Air pollution in the last 50 years: From local to global. *Atmospheric Environment* 43:13-22.

Ferree, J. T., J. Demuth, G. M. Eosco, and N. S. Johnson. 2009. The increasing role of social media during high impact weather events. 37th AMS Conference on Broadcast Meteorology. *http://ams.confex.com/ams/37Broadcast/techprogram/paper_154007.htm*. Accessed October 28, 2011.

FHWA (Federal Highway Administration). 2011. How do weather events impact roads? *http://ops.fhwa.dot.gov/weather/q1_roadimpact.htm*. Accessed November 28, 2011.

Früh, B., H. Feldmann, H.-J. Panitz, G. Schädler, D. Jacob, P. Lorenz, and K. Keuler. 2010. Determination of precipitation return values in complex terrain and their evaluation. *Journal of Climate* 23:2257-2274.

Gaffin, S. R., M. Imhoff, C. Rosenzweig, R. Khanbilvardi, A. Pasqualini, A. Y. Y. Kong, D. Grillo, A. Freed, D. Hillel, and E. Hartung. 2012. Bright is the new black: Multi-year performance of high-albedo roofs in an urban climate. *Environmental Research Letters* 7(014029), doi:10.1088/1748-9326/7/1/014029.

Gamble, J. F. and R. J. Lewis. 1996. Health and fespirable particulate (PM_{10}) air pollution: A causal or statistical association? *Environmental Health Perspectives* 104(8):838-850.

Ghenta, D., J. Kaduka, J. Remediosb, and H. Balztera. 2011. Data assimilation into land surface models: the implications for climate feedbacks. *International Journal of Remote Sensing* 32(3):617-632, doi:10.1080/01431161.2010.517794.

Godschalk, D. R. 1991. Disaster mitigation and hazard management. Pp. 131-160 in: *Emergency Management: Principles and Practices for Local Government,* T. E. Drabek and G. J. Hoetmer, editors. Washington, DC: International City Management Association.

Grell, G., S. Peckham, R. Schmitz, S. McKeen, G. Frost, W. Skamarock, and B. Eder. 2005. Fully coupled "online" chemistry within the WRF model. *Atmospheric Environment* 39:6957-6975.

Grimm, N. B., S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs. 2008. Global Change and the Ecology of Cities. *Science* 319(756):756-760.

Grimmond, C. S. B. 2006. Progress in measuring and observing the urban atmosphere. *Theoretical and Applied Climatology* 84:3-22.

Grimmond, C. S. B., and T. R. Oke. 1999. Heat storage in urban areas: observations and evaluation of a simple model. *Journal of Applied Meteorology* 38:922-940.

Grimmond, C., and T. Oke. 2002. Turbulent heat fluxes in urban areas: Observations and a local-scale urban meteorological parameterization scheme (LUMPS). *Journal of Applied Meteorology* 41:792-810.

Grimmond, C. S. B., T. R. Oke, and H. A. Cleugh. 1993. The role of "rural" in comparisons of observed suburban-rural flux differences. Exchange processes at the land surface for a range of space and time scales. *International Association of Hydrological Sciences Publication* 212:165-174.

Grimmond, C. S. B., M. Best, J. Barlow, A. J. Arnfield, J.-J. Baik, S. Belcher, M. Bruse, I. Calmet, F. Chen, P. Clark, A. Dandou, E. Erell, K. Fortuniak, R. Hamdi, M. Kanda, T. Kawai, H. Kondo, S. Krayenhoff, S. H. Lee, S.-B. Limor, A. Martilli, V. Masson, S. Miao, G. Mills, R. Moriwaki, K. Oleson, A. Porson, U. Sievers, M. Tombrou, J. Voogt, T. Williamson. 2009. Urban surface energy balance models: Model characteristics and methodology for a comparison study. Pp. 97-123 in: *Urbanization of Meteorological and Air Quality Models*. Baklanov, A., C. S. B. Grimmond, A. Mahura, and M. Athanassiadou, editors. Dordrecht: Springer.

Grimmond, C. S. B., M. Blackett, M. Best, J. Barlow, J. J. Baik, S. Belcher, S. I. Bohnenstengel, I. Calmet, F. Chen, A. Dandou, K. Fortuniak, M. L. Gouvea, R. Hamdi, M. Hendry, T. Kawai, Y. Kawamoto, H. Kondo, E. S. Krayenhoff, S. H. Lee, T. Loridan, A. Martilli, V. Masson, S. Miao, K. Oleson, G. Pigeon, A. Porson, Y. H. Ryu, F. Salamanca, and L. Shashua. 2010a. The International Urban Energy Balance Models Comparison Project: First Results from Phase 1. *Journal of Applied Meteorology and Climatology* 49:1268-1292, doi:10.1175/2010JAMC2354.1.

Grimmond, C. S. B., M. Roth, T. R. Oke, Y. C. Au, M. Best, R. Betts, G. Carmichael, H. Cleugh, W. Dabberdt, R. Emmanuel, E. Freitas, K. Fortuniak, S. Hanna, P. Klein, L. S. Kalkstein, C. H. Liu, A. Nickson, D. Pearlmutter, D. Sailor, J. Voogt. 2010b. Climate and More Sustainable Cities: Climate Information for Improved Planning & Management of Cities (Producers/Capabilities Perspective). *Procedia Environmental Science* 1:247-274.

Grimmond, C. S. B., M. Blackett, M. J. Best, J.-J. Baik, S. E. Belcher, J. Beringer, S. I. Bohnenstengel, I. Calmet, F. Chen, A. Coutts, A. Dandou, K. Fortuniak, M. L. Gouvea, R. Hamdi, M. Hendry, M. Kanda, T. Kawai, Y. Kawamoto, H. Kondo, E. S. Krayenhoff, S.-H. Lee, T. Loridan, A. Martilli, V. Masson, S. Miao, K. Oleson, R. Ooka, G. Pigeon, A. Porson, Y.-H. Ryu, F. Salamanca, G.-J. Steeneveld, M. Tombrou, J. A. Voogt, D. Young, N. Zhang. 2011. Initial Results from Phase 2 of the International Urban Energy Balance Comparison Project. *International Journal of Climatology* 31:244-272, doi: 10.1002/joc.2227.

Hand, L., and J. M. Shepherd. 2009. An investigation of warm season spatial rainfall variability in Oklahoma City: Possible linkages to urbanization and prevailing wind. *Journal of Applied Meteorology and Climatology.* 48:251-269.

Hanna, S. 2007. A review of uncertainty and sensitivity analyses of atmospheric transport and dispersion models. Pp. 331-351 in *Developments in Environmental Science 6, Air Pollution Modeling and Its Application XVIII*, C. Borrega and E. Renner, Editors. New York: Elsevier Publishing Company.

Hanna, S., and E. Baja. 2009. A simple urban dispersion model tested with tracer data from Oklahoma City and Manhattan. *Atmospheric Environment* 43:778-786.

Hanna, S., J. White, and Y. Zhou. 2007. Observed winds, turbulence, and dispersion in built-up downtown areas of Oklahoma City and Manhattan. *Boundary-Layer Meteorology* 125:441-468.

Hanna, S., J. White, J. Troiler, R. Vernot, M. Brown, H. Kaplan, Y. Alexander, J. Moussafir, Y. Wang, C. Williamson, J. Hannan, and E. Hendrick. 2011. Comparisons of JU2003 observations with four diagnostic urban wind flow and Lagrangian particle dispersion models. *Atmospheric Environment* 45:4073-4081.

Hembury, N., and R. Holle. 2011. Vaisala LS200, Technological Advancements for VHF total lightning mapping. Presented at the Southern Thunder Conference, National Weather Center, Norman, OK . July 11-14, 2011.

Henderson, S. B., B. Beckerman, M. Jerrett, and M. Brauer. 2007. Application of land use regression to estimate long-term concentrations of traffic-related nitrogen oxides and fine particulate matter. *Environmental Science and Technology* 41(7):2422-2428, doi:10.1021/es0606780.

Henderson-Sellers, A., Z.-L. Yang, and R. E. Dickinson. The Project for Intercomparison of Land-surface Parameterization Schemes. 1993. *Bulletin of the American Meteorological Society* 74:1335-1351.

Herwehe, J. A., T. L. Otte, R. Mathur, and S. T. Rao. 2011. Diagnostic analysis of ozone concentrations simulated by two regional-scale air quality models. *Atmospheric Environment* 45:5957-5969.

Hidalgo, J., V. Masson, A. Baklanov, G. Pigeon, and L. Gimeno. 2008. Advances in Urban Climate Modeling. *Trends and Directions in Climate Research* 1146:354-374.

Holloway, T., A. Fiore, and M. G. Hastings. 2003. Intercontinental Transport of air pollution: Will emerging science lead to a new hemispheric treaty? *Environmental Science & Technology* 37:4535-4542.

Holt, T., and J. Pullen. 2007. Urban Canopy Modeling of the New York City Metropolitan Area: A Comparison and Validation of Single- and Multilayer Parameterizations. *Monthly Weather Review* 135:1906-1930.

Holt, T., J. Pullen, and C. H. Bishop. 2009. Urban and ocean ensembles for improved meteorological and dispersion modeling of the coastal zone. *Tellus* 61A:232-249.

Hunt, J. C. R., M. Maslin, T. Killeen, P. Backlund, and H. J. Schellnhuber. 2007. Introduction. Climate change and urban areas: research dialogue in a policy framework. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* 365:2615-2629.

Imhoff, M. L, W. T. Lawrence, C. D. Elvidge, T. Paul, E. Levine, M. V. Privalsky, and V. Brown. 1997. Using nighttime DMSP/OLS images of city lights to estimate the impact of urban land use on soil resources in the United States. *Remote Sensing of Environment* 59(1):105-117, doi:10.1016/S0034-4257(96)00110-1.

Imhoff, M. L., P. Zhang, R. E. Wolfe, and L. Bounoua. 2010. Remote sensing of the urban heat island effect across biomes in the continental USA. *Remote Sensing of Environment* 114:504-513.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Pachauri, R.K and Reisinger, A., editors. IPCC, Geneva, Switzerland, 104 pp.

Isakov, V., Özkaynak, H. 2008. A Modeling Methodology to Support Evaluation of Public Health Impacts of Air Pollution Reduction Programs. Pp. 616-624 in *Air Pollution Modeling and its Applications XIX*. Borrego, C., A. I. Miranda, editors. Dordrecht: Springer Science & Business Media B.V.

Jacobson, C. 2011. Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review. *Journal of Environmental Management*. 92(6):1438-1448, doi:10.1016/j.jenvman.2011.01.018.

Jacobson, M. 2010. Enhancement of Local Air Pollution by Urban CO_2 Domes. *Environmental Science & Technology* 44:2497-2502.
Jerrett et al. 2005. Spatial Analysis of Air Pollution and Mortality in Los Angeles. *Epidemiology* 16:727-736.
Jeyachandran, I., S. Stetson, and S. Burian. 2010. Estimating urban canopy parameters using synthetic aperture radar data. *Journal of Applied Meteorology and Climatology* 49(4): 732-747.
Jimenez, C., C. Prigent, B. Mueller, S. I. Seneviratne, M. F. McCabe, E.F. Wood, W. B. Rossow, G. Balsamo, A. K. Betts, P. A. Dirmeyer, J. B. Fisher, M. Jung, M. Kanamitsu, R. H. Reichle, M. Reichstein, M. Rodell, J. Sheffield, K. Tu, and K. Wang. 2011. Global intercomparison of selected 1993-1995 monthly averaged land surface heat fluxes. *Journal of Geophysical Research* 116:D02102, doi:10.1029/2010JD014545.
Jin, M., and J. M. Shepherd. 2005. On including urban landscape in land surface model—how can satellite data help? *Bulletin of the American Meteorological Society* 86:681-689.
Jin, M., and J. M. Shepherd. 2008. Aerosol relationships to warm season clouds and rainfall at monthly scales over east China: urban land versus ocean. *Journal of Geophysical Research* 113:D24S90. doi:10.1029/2008JD010276.
Jin, M., J. M. Shepherd, and C. Peters-Lidard. 2007. Development of a parameterization for simulating the urban temperature hazard using satellite observations in climate model. *Natural Hazards* 43:257-271.
Jin, M., J.M. Shepherd, and W. Zheng, 2011. Urban Surface Temperature Reduction via the Urban Aerosol Direct Effect: A Remote Sensing and WRF Model Sensitivity Study. *Advances in Meteorology*, doi:10.1155/2010/681587.
Kabat, P., M. Claussen, P. A. Dirmeyer, J. H. C. Gash, L. Bravo de Guenni, M. Meybeck, R. Pielke, C. J. Vorosmarty, R. W. A. Hutjes, and S. Lutkemeier. 2004. *Vegetation, Water, Humans and the Climate*. New York: Springer.
Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W.Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, D. Joseph. The NCEP/NCAR 40-Year Reanalysis Project. 1996. *Bulletin of the American Meteorological Society* 77(3):437-471.
Kalnay, E., and M. Cai. 2003. Impact of urbanization and land-use change on climate. *Nature* 423:528-531.
Karl, T. R., H. F. Diaz, G. Kukla. 1988. Urbanization: its detection and effect in the United States climate record. *Journal of Climate* 1:1099-1123, doi:10.1175/1520-0442(1988)001<1099:UIDAEI>2.0.CO;2.
Kastner-Klein, P., and M. W. Rotach. 2004. Mean flow and turbulence characteristics in an urban roughness sublayer. *Boundary-Layer Meteorology* 111:55-84.
Kaufman, Y. J., T. Didier, and B. Olivier. 2005. A satellite view of aerosols in the climate system. *Nature* 419:215-223.
Klein, P., and J. V. Clarke. 2007. Flow Variability in a North American Downtown Street Canyon. *Journal of Applied Meteorology and Climatology* 46:851-877, doi:10.1175/JAM2494.
Klein, P., B. Leitl, and M. Schatzmann. 2007. Driving physical mechanisms of flow and dispersion in urban canopies. *International Journal of Climatology* 24(7):1887-1907, doi:10.1002/joc.1581.
Koskinen, J. T., J. Poutiainen, D. M. Schultz, S. Joffre, J. Koistinen, E. Saltikoff, E. Gregow, H. Turtiainen, W. F. Dabberdt, J.i Damski, N. Eresmaa, S. Göke, O. Hyvärinen, L. Järvi, A. Karppinen, J. Kotro, T. Kuitunen, J. Kukkonen, M. Kulmala, D. Moisseev, P. Nurmi, H. Pohjola, P. Pylkkö, T. Vesala, and Y. Viisanen. 2011. The Helsinki Testbed: A Mesoscale Measurement, Research and Service Platform. *Bulletin of the American Meteorological Society* 32:325-342.

Koster, R. D., Y. C. Sud, Z. Guo, P. A. Dirmeyer, G. Bonan, K. W. Oleson, E. Chan, D. Verseghy, P. Cox, H. Davies, E. Kowalczyk, C. T. Gordon, S. Kanae, D. Lawrence, P. Liu, D. Mocko, C.-H. Lu, K. Mitchell, S. Malyshev, B. McAvaney, T. Oki, T. Yamada, A. Pitman, C. M. Taylor, R. Vasic, Y. Xue. 2006. GLACE: The Global Land-Atmosphere Coupling Experiment. Part I: Overview. *Journal of Hydrometeorology* 7:590-610.

Kumar, S. V., C. Peterslidard, Y. Tian, P. Houser, J. Geiger, S. Olden, L. Lighty, J. Eastman, B. Doty, and P. Dirmeyer. 2006. Land Information System: An interoperable framework for high resolution land surface modeling. *Environmental Modelling and Software* 21:1402-1415.

Lamptey, B. 2010. An analytical framework for estimating the urban effect on climate. *International Journal of Climatology* 30:72-88.

Lazo, J. K., M. Lawson, P. H. Larsen and D. M. Waldman. 2011. U.S. Economic Sensitivity to Weather Variability. *Bulletin of the American Meteorological Society* 92(6):709-720.

Lemonsu, A., S. Belair, and J. Mailhot. 2009. The New Canadian Urban Modelling System: Evaluation for Two Cases from the Joint Urban 2003 Oklahoma City Experiment. *Boundary-Layer Meteorology* 133:47-70.

Lindberg, F., and C. S. B. Grimmond. 2010. Continuous sky view factor from high resolution urban digital elevation models**.** *Climate Research* 42:177-183, doi:10.3354/cr00882.

Lindberg, F., and C. S. B. Grimmond. 2011. Nature of vegetation and building morphology characteristics across a city: influence on shadow patterns and mean radiant temperatures in London. *Urban Ecosystems*, doi:10.1007/s11252-011-0184-5.

Liu, Y., F. Chen, T. Warner, and J. Basara. 2006. Verification of a mesoscale data-assimilation and forecasting system for the Oklahoma City area during the Joint Urban 2003 field project. *Journal of Applied Meteorology and Climatology* 45:912-929.

Loridan, T., C. Grimmond, B. Offerle, D. Young, T. Smith, L. Jarvi, and F. Lindberg. 2011. Local-Scale Urban Meteorological Parameterization Scheme (LUMPS): Longwave Radiation Parameterization and Seasonality-Related Developments. *Journal of Applied Meteorology and Climatology* 50:185-202.

Lynn, B.H., T. Carlson, C. Rosenzweig, R. Goldberg, L. Druyan, et al. 2009. A modification to the NOAH LSM to simulate heat mitigation strategies in the New York City metropolitan area. *Journal of Applied Meteorology and Climatology* 48:199-216, doi: 10.1175/2008JAMC1774.1.

Mahoney, Bill, Sheldon Drobot, Paul Pisano, Ben McKeever, and Jim O'Sullivan. 2010. Vehicles as Mobile Weather Observation Systems. *Bulletin of the American Meteorological Society* 91:1179-1182, doi:10.1175/2010BAMS2954.1.

Maktav, D., F. S. Erbek and C. Jurgens. 2005. Remote Sensing of Urban Areas. *International Journal of Remote Sensing* 26:655-659.

Mailhot, J., S. Bélair, A. Lemonsu, L. Tong, A. Leroux, N. Benbouta, M. Benjamin, F. Chagnon, G. Morneau, and R. Hogue. 2006. Urban modeling at the Meteorological Service of Canada. *CMOS Bulletin SCMO* 34:110-114.

Manabe, S., and K. Bryan. 1969. Climate and ocean circulation. I. The atmospheric circulation and the hydrology of the earth's surface. *Monthly Weather Review* 97:739-744.

Martilli, A., A. Clappier, and M. Rotach. 2002. An urban surface exchange parameterisation for mesoscale models. *Boundary-Layer Meteorology* 104:261-304.

Martilli, A., Y. Roulet, M. Junier, F. Kirchner, M. Rotach, and A. Clappier. 2003. On the impact of urban surface exchange parameterisations on air quality simulations: the Athens case. *Atmospheric Environment* 37:4217-4231.

Martilli, A. 2007. Current research and future challenges in urban mesoscale modelling. *International Journal of Climatology* 27:1909-1918.

Martilli, A. 2009. On the Derivation of Input Parameters for Urban Canopy Models from Urban Morphological Datasets. *Boundary-Layer Meteorology* 130:301-306.

Mass, C. 2011. Nowcasting: The Next Revolution in Weather Prediction. *Bulletin of the American Meteorological Society*. Submitted. *http://www.atmos.washington.edu/~cliff/BAMSNowcast7.11.pdf*. Accessed November 9, 2011.

Masson, V. 2000. A physically-based scheme for the urban energy budget in atmospheric models. *Boundary-Layer Meteorology* 94:357-397.

Masson, V. 2006. Urban surface modelling and the meso-scale impact of cities. *Theoretical and Applied Climatology* 84:35-45.

Mathur, R., J. E. Pleim, D. C. Wong, T. L. Otte, R. C. Gilliam, S. J. Roselle, J. O. Young, F. S. Binkowski, and A. Xiu. 2010. The WRF CMAQ integrated on-line modeling system: development, testing, and initial applications. In: *Air Pollution Modeling and Its Application XX*. D. G. Steyn, and S. T. Rao, editors. Netherlands: Springer.

McCarthy, M. P., M. J. Best, and R. A. Betts. 2010. Climate change in cities due to global warming and urban effects. *Geophysical Research Letters* 37(9).

McClellan, T., P. Boone, and M.A. Coleman. 2010. Maintenance Decision Support System (MDSS): Indiana Department of Transportation (INDOT) Statewide Implementation. Final Report for FY09. *www.in.gov/indot/files/MDSSReportWinter08-09.pdf*. Accessed November 9, 2011.

McLaughlin, D., D. Pepyne, V. Chandrasekar, B. Philips, J. Kurose, M. Zink, K. Droegemeier, S. Cruz-Pol, F. Junyent, J. Brotzge, D. Westbrook, N. Bharadwaj, Y. Wang, E. Lyons, K. Hondl, Y. Liu, E. Knapp, M. Xue, A. Hopf, K. Kloesel, A. DeFonzo, P. Kollias, K. Brewster, R. Contreras, T. Djaferis, E. Insanic, S. Frasier, F. Carr. 2009. Short-wavelength technology and the potential for distributed networks of small radar systems. *Bulletin of the American Meteorological Society* 90(12):1797-1817.

Meehl, G.A., F. Zwiers, J. Evans, T. Knutson, L. Mearns, and P. Whetton. 2000. Trends in extreme weather and climate events: issues related to modeling extremes in projections of future climate change. *Bulletin of the American Meteorological Society* 81:427-436.

Menne, B. The health impacts of 2003 summer heat-waves. Briefing note for the delegations of the fifty third session of the WHO regional Committee for Europe. WHO Europe, September 8, 2003.

Mesinger, F., G. Dimego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi. 2006. North American regional reanalysis. *Bulletin of the American Meteorological Society* 87:343-360.

Mestayer, P. G., and S. Anquetin. 1995. Climatology of Cities. Pp. 165-189 in: *Diffusion and Transport of Pollutants in Atmospheric Mesoscale Flow Fields*. Norwell, MA: Kluwer Academic Publishers.

Mestayer, P. G., P. Durand, P. Augustin, S. Bastin, J.-M. Bonnefond, B. Benech, B. Campistron, A. Coppalle, H. Delbarre, B. Dousset, P. Drobinski, A. Druilhet, E. Frejafon, C. S. B. Grimmond, D. Groleau, M. Irvine, C. Kergomard, S. Kermadi, J.-P. Lagouarde, A. Lemonsu, F. Lohou, N. Long, V. Masson, C. Moppert, J. Noilhan, B. Offerle, T. R. Oke, G. Pigeon, V. Puygrenier, S. Roberts, J.-M. Rosant, F. Said, J. Salmond, M. Talbaut, and J. Voogt. 2005. The urban boundary-layer field campaign in Marseille (UBL/CLU-ESCOMPTE): Set-up and first results. *Boundary-Layer Meteorology* 114:315-365.

Metzger, K. B., K. Ito, K., and T. D. Matte. 2010. Summer heat and mortality in New York City: How hot is too hot? *Environmental Health Perspectives* 118(1):80-86, doi:10.1289/ehp.0900906.

Mills, G., H. Cleugh, R. Emmanuel, W. Endlicher, E. Erell, G. McGranahan, E. Ng, A. Nickson, J. Rosenthal and K. Steemer. 2010. Climate Information for Improved Planning and Management of Mega Cities (needs perspective). *Procedia Environmental Sciences* 1:228-246.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead: Whither water management? *Science* 319:573-574.

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):1-32.

Mitra, C., T. Jordan, and M. Shepherd. 2011. Growth of Kolkata, India-Past, present, and future: a synergistic analysis using cartographic, GIS, remote sensing, and cellular automata modeling. *Professional Geographer* (Conditionally Accepted).

Moore, R. J. 2007. The PDM rainfall-runoff model. *Hydrology and Earth System Science* 11:483-499.

Morss, R. E., and F. M. Ralph. 2007. Use of information by National Weather Service forecasters and emergency managers during CALJET and PACJET-2001. *Weather and Forecasting* 22:539-555, doi:10.1175/WAF1001.1.

Morss, R. E., Wilhelmi, O. V., Downton, M. W., and E. Gruntfest. 2005. Flood risk, uncertainty, and scientific information for decision-making: Lessons from an interdisciplinary project. *Bulletin of the American Meteorological Society* 86:1593-1601.

NASA, EPA, NOAA. 2011. "Infusing satellite data into environmental applications." Last modified August 2, 2011. *http://www.star.nesdis.noaa.gov/smcd/spb/aq/*.

NCDC (National Climatic Data Center). 2011. Billion Dollar U.S. Weather/Climate Disasters. *http://www.ncdc.noaa.gov/oa/reports/billionz.html*. Accessed on December 13, 2011.

Nelson, M., E. Pardyjak, J. Klewicki, S. Pol, and M. Brown. 2007b. Properties of the wind field within the Oklahoma City Park Avenue street canyon. Part I: Mean flow and turbulence statistics. *Journal of Applied Meteorology and Climatology* 46:2038-2054.

Nelson, M., E. Pardyjak, and P. Klein. 2011. Momentum and Turbulent Kinetic Energy Budgets Within the Park Avenue Street Canyon During the Joint Urban 2003 Field Campaign. *Boundary-Layer Meteorology* 140:143-162.

NRC (National Research Council). 2002. *Weather Radar Technology Beyond NEXRAD*. Washington, DC: National Academy Press.

NRC. 2003a. *Communicating Uncertainties in Weather and Climate Information: A Workshop Summary*. Washington, DC: National Academies Press.

NRC. 2003b: *Tracking and Predicting the Atmospheric Dispersion of Hazardous Material Releases: Implications for Homeland Security.* Washington, DC: National Academies Press.

NRC. 2004. *Where Weather Meets the Road*. Washington, DC: National Academies Press.

NRC. 2005. *Improving the Scientific Foundation for Atmosphere- Land-Ocean Simulations: Report of a Workshop*. Washington, DC: National Academies Press.

NRC. 2006. *Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecast*. Washington, DC: National Academies Press.

NRC. 2007a. *Understanding Multiple Environmental Stresses: Report of a Workshop*. Washington, DC: National Academies Press.

NRC. 2007b: Environmental Data Management at NOAA: Archiving, Stewardship, and Access. Washington, DC: National Academies Press.

NRC. 2008. Observing *Weather and Climate from the Ground Up: A Nationwide Network of Networks*. Washington, DC: National Academies Press.

NRC. 2009. *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks*. Washington, DC: National Academies Press.

NRC. 2010a.*When Weather Matters: Science and Services to Meet Critical Societal Needs*. Washington, DC: National Academies Press.

NRC. 2010b. Advancing the Science of Climate Change. Washington, DC: National Academies Press.

NRC. 2011a. How Communities Can Use Risk Assessment Results: Making Ends Meet: A Summary of the June 3, 2010, Workshop of the Disasters Roundtable. Washington, DC: National Academies Press.

NRC. 2011b. America's Climate Choices. Washington, DC: National Academies Press.

NWCC (National Water and Climate Center). 2009. *SNOTEL And Snow Survey & Water Supply Forecasting*. *http://www.wcc.nrcs.usda.gov/snotel/SNOTEL-brochure.pdf*. Accessed October 19, 2011.

OFCM (Office of the Federal Coordinator for Meteorological Services and Supporting Research). 2004. Urban Meteorology—Meeting Weather Needs in the Urban Community. Washington, DC: OFCM. FCM-R22-2004.

Offerle, B., I. Eliasson, C. S. B. Grimmond, and B. Holmer. 2007. The influence of surface heating on air temperature, wind and turbulence in an urban street canyon. *Boundary Layer Meteorology* 122:273-292, doi:10.1007/s10546-006-9099-8.

Oke, T. R. 1982. The Energetic Basis of the Urban Heat-Island. *Quarterly Journal of the Royal Meteorological Society* 108:1-24.

Oke, T. R. 1987. Boundary Layer Climates. London: Routledge and New York: John Wiley & Sons (co-published).

Oke, T. R. 1997. Urban environments. Pp. 303-327 in: *The Surface Climates of Canada*. W. G. Bailey, T. R. Oke, W. R. Rouse, editors. Montreal, Quebec: McGill-Queen's University Press.

Oke, T. R. 2006. Towards better scientific communication in urban climate. *Theoretical and Applied Climatology* 84(1-3):179-190.

Oke, T. R. 2009. The need to establish protocols in urban heat island work. Paper presented at the T.R. Oke Symposium & Eighth Symposium on Urban Environment, Phoenix, AZ, January 11-15, 2009. http://ams.confex.com/ams/89annual/webprogram/Paper150552.html.

Oleson, K., G. Bonan, J. Feddema, M. Vertenstein, and C. Grimmond. 2008a. An urban parameterization for a global climate model. Part I: Formulation and evaluation for two cities. *Journal of Applied Meteorology and Climatology* 47:1038-1060.

Oleson, K., G. B. Bonan, J. Feddema, and M. Vertenstein. 2008b. An Urban Parameterization for a Global Climate Model. Part II: Sensitivity to Input Parameters and the Simulated Urban Heat Island in Offline Simulations. *Journal of Applied Meteorology and Climatology* 47:1061-1076, doi:10.1175/2007JAMC1598.1.

Oleson, K. W., G. B. Bonan, and J. Feddema. 2010a. Effects of white roofs on urban temperature in a global climate model. *Geophysical Research Letters* 37(L03701), doi:10.1029/2009GL042194.

Oleson, K. W., G. B. Bonan, J. Feddema, and T. Jackson. 2010b. An examination of urban heat island characteristics in a global climate model. *International Journal of Climatology* 31(12):1848-1865, doi:10.1002/joc.2201.

Orville, R. E. 2008. Development of the National Lightning Detection Network. *Bulletin of the American Meteorological Society* 89(2):180-190.

Ott, W., Thomas, J., Mage, D., and L. Wallace. 1988. Validation of the Simulation of Human Activity and Pollutant Exposure (SHAPE) model using paired days from the Denver, CO, carbon monoxide field study. *Atmospheric Environment* 22(10):2101–2113.

Otte, T. 2005. Linking the Eta Model with the Community Multiscale Air Quality (CMAQ) Modeling System to build a National Air Quality Forecasting System. *Weather and Forecasting* 20:367-384.

Özkaynak et al. 2008. Summary and findings of the EPA and CDC symposium on air pollution exposure and health. *Journal of Exposure Science and Environmental Epidemiology* 19:19-29, doi:10.1038/jes.2008.34.

Pagowski, M., G. A. Grell, S. A. McKeen, et al. 2010. Three dimensional variational data assimilation of ozone and fine particulate matter observations. Some results using the Weather Research and Forecasting-Chemistry model and Gridpoint Statistical Interpolation. *Quarterly Journal of the Royal Meteorological Society* 136(653):2013-2024, doi:10.1002/qj.700.

Patnaik, G., J. P. Boris, F. F. Grinstein, and J. P. Iselin. 2005. "Large scale urban simulations with FCT." Pp. 105-130 in: *Flux-Corrected Transport*. D. Kuzmin, R. Löhner, and S. Turek, editors. Berlin: Springer Verlag, doi:10.1007/3-540-27206-2_4.

Patz, J. A., D. Campbell-Lendrum, T. Holloway, J. A. Foley. 2005. Impact of regional climate change on human health. *Nature* 438:310-317.

Peterson, T. C. 2003. Assessment of Urban Versus Rural In situ Surface Temperatures in the Contiguous United States: No Difference Found. *Journal of Climate* 16:2941-2959.

Peterson, T. C., and R. S. Vose. 1997. An Overview of the Global Historical Climatology Network Temperature Database. *Bulletin of the American Meteorological Society* 78(12): 2837-2849.

Pielke, R. A. 1984. *Mesoscale Meteorological Modeling*. New York: Academic Press.

Pielke, R. A. 2009. Collateral Damage from the Death of Stationarity. *GEWEX News* May 2009:5-7.

Poelmans, L., A.V. Rompaey, and O. Batelaan. 2010. Coupling urban expansion models and hydrological models: How important are spatial patterns? *Land Use Policy* 27:965-975, doi:10.1016/j.landusepol.2009.12.010.

Pope, V. D., Gallani, M. L., Rowntree, P. R., and R. A. Stratton. 2000. The impact of new physical parametrizations in the Hadley Centre climate model: HadAM3. *Climate Dynamics* 16(2-3):123-146, doi: 10.1007/s003820050009.

Raupach, M. R., R. A. Antonia, and S. Rajagopalan. 1991. Rough-Wall Turbulent Boundary Layers *Applied Mechanics Reviews* 44(1):1-25, doi:10.1115/1.3119492.

Reynolds, R. M., R. D. Bornstein, S. R. Hanna, T. Oke, B. B. Hicks, and H.-N. Lee. 2004. "The New York City Urban Atmospheric Observatory-An Overview." Paper presented at the AMS Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone, Seattle, Washington, January 10-15, 2004.

Reynolds, S., S. Burian, J. M. Shepherd, and M. Manyin. 2008. "Chapter 7: Urban induced rainfall modifications on urban hydrologic response." Pp. 92-122 in: *Reliable Modeling of Urban Water Systems*, W. James, K. N. Irvine, E. A. McBean, R. E. Pitt, and S. J. Wright, editors. Guelph, Ontario: Computational Hydraulics International.

Rodell, M., P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D. Toll. 2004. The Global Land Data Assimilation System. *Bulletin of the American Meteorological Society* 85(3):381-394, doi:10.1175/BAMS-85-3-381.

Rose, L. S., J. A. Stallins, and M. L. Bentley. 2008. Concurrent Cloud-to-Ground Lightning and Precipitation Enhancement in the Atlanta, Georgia (United States), Urban Region. *Earth Interactions* 12(11):1-30.

Rosenfeld D., U. Lohmann, G.B. Raga, C.D. O'Dowd, M. Kulmala et al. 2008. Flood or drought: How do aerosols affect precipitation? *Science* 321(5894):1309-1313, doi:10.1126/science.1160606.

Ross, L., J. Bolling, J. Dollner and B. Kleinschmit. 2009. Enhancing 3D City Models with Heterogeneous Spatial Information: Towards 3D Land Information Systems. *Advances in GIScience* 113-133, doi:10.1007/978-3-642-00318-9.

Rotach, M. W. 1999. On the influence of the urban roughness sublayer on turbulence and dispersion. *Atmospheric Environment* 33(24-25):4001-4008.

Rotach, M. W., R. Vogt, C. Bernhofer, E. Batchvarova, et al. 2005. BUBBLE: An Urban Boundary Layer Meteorology Project. *Theoretical and Applied Climatology* 81:231-261, doi:10.1007/s00704-004-0117-9.

Roth, M. 2007. Review of urban climate research in (sub)tropical regions. *International Journal of Climatology* 27(14):1859-1873, doi:10.1002/joc.1591.

Sakaki, T. M. Okazaki, and Y. Matsuo. 2010. Earthquake Shakes Twitter Users: Real-time Event Detection by Social Sensors. *Proceedings of the 19th International Conference on World Wide Web (WWW2010)* 851-860, doi:10.1145/1772690.1772777.

Salamanca, F., A. Krpo, A. Martilli, and A. Clappier. 2010. A new building energy model coupled with an urban canopy parameterization for urban climate simulations-part I. formulation, verification, and sensitivity analysis of the model. *Theoretical and Applied Climatology* 99(3-4):331-344, doi:10.1007/s00704-009-0142-9.

Salamanca, F., and A. Martilli. 2010. A new Building Energy Model coupled with an Urban Canopy Parameterization for urban climate simulations-part II. Validation with one dimension off-line simulations. *Theoretical and Applied Climatology* 99(3-4):345-356, doi:10.1007/s00704-009-0143-8.

Salamanca, F., A. Martilli, M. Tewari, and F. Chen. 2011. A study of the urban boundary layer using different urban parameterizations and high-resolution urban canopy parameters with WRF. *Journal of Applied Meteorology and Climatology* 50(5)1107-1128, doi:10.1175/2010JAMC2538.1.

Sano, I., Y. Okada, M. Mukai, and S. Mukai. 2009. Retrieval algorithm based on combined use of POLDER and GLI data for biomass aerosols. *Journal of the Remote Sensing Society of Japan* 29(1):54-59.

Sarnat, J. A., J. Schwartz, P. J. Catalano, and H. Suh. 2001. The role of gaseous pollutants in particulate matter epidemiology: confounder or surrogate. *Environmental Health Perspectives* 109(10):1053-1062.

Sarnat, S. E., H. H. Suh, B. A. Coull, J. Schwartz, P. H. Stone, and D. R. Gold. 2006. Ambient particulate air pollution and cardiac arrhythmia in a panel of older adults in Steubenville, Ohio. *Occupational and Environmental Medicine* 63:700-706.

Schellart, A.N.A., M.A. Rico-Ramirez, S. Liguori, and A. J. Saul. 2009. Quantitative Precipitation Forecasting for a Small Urban Area: Use of Radar Nowcasting. *Proceedings of the 8th International Workshop on Precipitation in Urban Areas*, St. Moritz, Switzerland, December 10-13.

Sellers, P. J., Y. Mintz, Y. C. Sud, and A. Dalcher. 1986. A simple biosphere model (SIB) for use within general calculation models. *Journal of Atmospheric Science* 43(6):505-531.

Sellers, P. J., F. G. Hall, G. Asrar, D. E. Strebel, and R. E. Murphy. 1992. An Overview of the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE). *Journal of Geophysical Research* 97(D17):18345-18371, doi:10.1029/92JD02111.

Seto, K., and J. M. Shepherd. 2009. Global urban land-use trends and climate impacts. *Current Opinion in Environmental Sustainability* 1:89-95, doi:10.1016/j.cosust.2009.07.012.

Shepherd, J. M. 2005. A Review of Current Investigations of Urban-Induced Rainfall and Recommendations for the Future. *Earth Interactions* 9:1-27, doi:http://dx.doi.org/10.1175/EI156.1.

Shepherd, J. M., H. Pierce, and A. J. Negri. 2002. On rainfall modification by major urban areas: Observations from space-borne radar on TRMM. *Journal of Applied Meteorology* 41:689-701.

Shepherd, J. M., J. A. Stallins, M. Jin, and T. L. Mote. 2010. "Urbanization: Impacts on Clouds, Precipitation, and Lightning." Pp. 1-28 in *Urban Ecosystem Ecology*. J. Aitkenhead-Peterson and A. Volder, editors. Madison, WI: American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc.

Shepherd, M., T. Mote, J. Dowd, M. Roden, P. Knox, S. C. McCutcheon, and S. E. Nelson. 2011. An Overview of Synoptic and Mesoscale Factors Contributing to the Disastrous Atlanta Flood of 2009. *Bulletin of the American Meteorological Society* 92:861-870, doi:http://dx.doi.org/10.1175/2010BAMS3003.1.

Smith, R., P. D. Batesa, and C. Hayes. 2012. Evaluation of a coastal flood inundation model using hard and soft data. *Environmental Modelling & Software* 30:35-46, doi:http://dx.doi.org/10.1016/j.envsoft.2011.11.008

Solecki, W. D, C. Rosenzweig, L. Parshall, G. Pope, M. Clark, J. Cox, and M. Wiencke. 2005. Mitigation of the heat island effect in urban New Jersey. *Global Environmental Change Part B: Environmental Hazards* 6(1):39-49, doi:10.1016/j.hazards.2004.12.002.

Souch, C., and S. Grimmond. 2006. Applied climatology: urban climate. *Progress in Physical Geography* 30(2):270-279, doi:10.1191/0309133306pp484pr.

SPU (Seattle Public Utilities). 2006. Water Shortage Contingency Plan. Seattle, WA: Seattle Public Utilities. *http://www.cityofseattle.net/util/stellent/groups/public/@spu/@rmb/@resplan/@plancip/documents/webcontent/watershor_200312021018123.pdf*. Accessed October 19, 2011.

SPU. 2011. Services of Seattle Public Utilities. *http://www.seattle.gov/util/Services/index.asp*. Accessed October 19, 2011.

Stewart, I. D. 2011. A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology* 31(2):200-217, doi:10.1002/joc.2141.

Stewart, I. D., and T. R. Oke. 2009a. Conference notebook: A new classification system for urban climate sites. *Bulletin of the American Meteorological Society* 90: 922-923.

Stewart, I. D., and T. R. Oke. 2009b. Classifying urban climate field sites by "local climate zones": The case of Nagano, Japan. In: *Preprints, Seventh International Conference on Urban Climate*, Yokohoma, Japan, June 29-July 3, 2009.

Stone, B., J. Hess, and H. Frumkin. 2010. Urban Form and Extreme Heat Events: Are Sprawling Cities more Vulnerable to Climate Change than Compact Cities? *Environmental Health Perspectives* 118(10):1425-1428, doi:10.1289/ehp.0901879.

Studio Ma. 2011. Phoenix Urban Form. *http://studioma.com/*. Accessed October 25, 2011.

Sutton, C. P. 2003. A scale adjusted measure of "Urban Sprawl" using nighttime satellite imagery. *Remote Sensing of Environment* 86(3):353-369, doi:10.1016/S0034-4257(03)00078-6.

Sutton, P. C., T. Cova, and C. D. Elvidge. 2006. Mapping "Exurbia" in the Conterminous United States Using Nighttime Satellite Imagery. *Geocarto International* 21(2):39-45.

Sutton, P. C., R. Goetz, S. Fildes, C. Forster, and T. Ghosh. 2010. Darkness on the Edge of Town: Mapping Urban and Peri-Urban Australia Using Nighttime Satellite Imagery. *The Professional Geographer* 62(1):119-133.

Tewari, M., H. Kusaka, F. Chen, W. Coirier, S. Kim, A. Wyszogrodzki, and T. Warner. 2010. Impact of coupling a microscale computational fluid dynamics model with a mesoscale model on urban scale contaminant transport and dispersion. *Atmospheric Research* 96(4):656-664, doi:10.1016/j.atmosres.2010.01.006.

Thompson, W. T., T. Holt, and J. Pullen. 2007. Investigation of a sea breeze front in an urban environment. *Quarterly Journal of the Royal Meteorological Society* 133:579-594. doi:10.1002/qj.52.

UN (United Nations). 2008. State of the World's Cities 2008/2009. *http://www.unhabitat.org/pmss/listItemDetails.aspx?publicationID=2562*. Accessed November 29, 2011.

USGCRP (United States Global Change Research Program). 2009. Global Climate Change Impacts in the United States. New York: Cambridge University Press.

Usery, E.L, J. Choi, and M.P. Finn. 2010. Modeling Sea-Level Rise and Surge in Low-Lying Urban Areas Using Spatial Data, Geographic Information Systems, and Animation Methods. *Geotechnologies and the Environment* 2(1):11-30, doi:10.1007/978-90-481-2238-7_2.

Usery, E.L, J. Choi, and M.P. Finn. 2010. Office of Air Quality and Planning Standards. 2010. Our Nation's Air: Status and Trends through 2008. *http://epa.gov/airtrends/2010/report/fullreport.pdf*. Accessed November 8, 2011.

Vardoulakis, S., B. E. A. Fisher, K. Pericleous, and N. Gonzalez-Flesca. 2003. Modelling air quality in street canyons: a review. *Atmospheric Environment* 37(2):155-182, doi:10.1016/S1352-2310(02)00857-9.

Villarini, G., J. A. Smith, M. Baeck, P. Rees, and W.F. Krajewski. 2010a. Radar analyses of extreme rainfall and flooding in urban drainage basins. *Journal of Hydrology* 381(3-4):266-286, doi:10.1016/j.jhydrol.2009.11.048.

Villarini, G., W. F. Krajewski, A. Ntelekos, K. Georgakakos, and J. Smith. 2010b. Towards probabilistic forecasting of flash floods: The combined effects of uncertainty in radar-rainfall and flash flood guidance. *Journal of Hydrology* 394(1-2):275-284, doi:10.1016/j.jhydrol.2010.02.014.

Voogt, J. A., and T. R. Oke. 2003. Thermal remote sensing of urban climate. *Remote Sensing of Environment* 86:370-384, doi:10.1016/S0034-4257(03)00079-8.

Wen, G., A. Marshak, R. F. Cahalan, L. A. Remer, and R. G. Kleidman. 2007. 3-D aerosol-cloud radiative interaction observed in collocated MODIS and ASTER images of cumulus cloud fields. *Journal of Geophysical Research* 112:(D13204), doi:10.1029/2006JD008267.

Wilczak, J. M., S. A. McKeen, I. Djalalova, G. A. Grell, S. E. Peckham, W. Gong, V. Bouchet, R. Moffet, J. McHenry, J. McQueen, P. Lee, Y. Tang and G. R. Carmichael. 2006. Bias-corrected ensemble and probabilistic forecasts of surface ozone over eastern North America during the summer of 2004. *Journal of Geophysical Research-Atmospheres* 111(D23):D23S28, doi:10.1029/2006JD007598.

Wilhelmi, O.V., and M. H. Hayden. 2010. Connecting people and place: a new framework for reducing urban vulnerability to extreme heat. *Environmental Research Letters* 5(014021), doi:10.1088/1748-9326/5/1/014021.

WMO (World Meteorological Organization). 2008. Part II, Chapter 11: Urban Observations. In: *Guide to Meteorological Instruments and Methods of Observation, WMO No-8*. Geneva: World Meteorological Organization.

Xue, M., M. Tong, and K. K. Droegemeier. 2006. An OSSE Framework Based on the Ensemble Square Root Kalman Filter for Evaluating the Impact of Data from Radar Networks on Thunderstorm Analysis and Forecasting. *Journal of Atmospheric and Oceanic Technology* 23:46-66, doi:10.1175/JTECH1835.1.

Ye, Z., C. Strong, X. Shi, and S. Conger. 2009. Analysis of Maintenance Decision Support System (MDSS) Benefits & Costs. *http://www.meridian-enviro.com/mdss/pfs/files/WTI-4W1408_Final_Report.pdf*. Accessed March 30, 2012.

Yow, D. M. 2007. Urban heat islands: observations, impacts, and adaptation. *Geography Compass* 1(6):1227-1251, doi:10.1111/j.1749-8198.2007.00063.x.

Yu, H., Y. J. Kaufman, M. Chin, G. Feingold, L. A. Remer, T. L. Anderson, Y. Balkanski, N. Bellouin, O. Boucher, S. Christopher, P. DeCola, R. Kahn, D. Koch, N. Loeb, M. S. Reddy, M. Shulz, T. Takemura, and M. Zhou. 2006. A review of measurement-based assessments of the aerosol direct radiative effect and forcing. *Atmospheric Chemistry and Physics* 6:613-666.

Zartarian, V. G., H. Ozkaynak, J. M. Burke, M. J. Zufall, M. L. Rigas, and E. J. Furtaw, Jr. 2000. A modeling framework for estimating children's residential exposure and dose to chlorpyrifos via dermal residue contact and nondietary ingestion. *Environmental Health Perspectives* 108(6):505-514.

Zeger, S. L., D. Thomas, F. Dominici, J. M. Sarnet, J. Schwartz, D. Dockery, and A. Cohen. 2000. Exposure Measurement Error in Time-Series Studies of Air Pollution: Concepts and Consequences. *Environmental Health Perspectives* 108(5):419-426.

Zeng, X., M. Barlage, C. Castro, and K.Fling. 2010. Comparison of Land-Precipitation Coupling Strength Using Observations and Models. *Journal of Hydrometeorology* 11:979-994, doi:10.1175/2010JHM1226.1.

Zhou, Y. and J. M. Shepherd. 2009. Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. *Natural Hazards* 52(3):639-668, doi:10.1007/s11069-009-9406-z.

Appendixes

Appendix A

Extended Speaker Abstracts

OVERVIEW OF URBAN METEOROLOGY
SUE GRIMMOND, KING'S COLLEGE LONDON

Introduction

Increasing urban populations worldwide has heightened awareness, enhanced interest and focused attention on urban meteorology. The absolute number of people living in cities, the proportion of the world's population this represents, and the land surface cities cover all continue to increase. Concurrently, greater computer capacity has allowed for higher resolution model domains to be used routinely for Numerical Weather Prediction (NWP) which has resulted in urban areas now being a land surface category that models need to account for.

Moreover, urban areas have higher population densities than rural areas. This, combined with the living conditions of many in cities, means that urban dwellers have a greater likelihood of being at risk or vulnerable to meteorological events. Consequently it is critical that we have the ability to forecast urban weather and to provide meteorological data for end user applications that range from dispersion, to thermal comfort, to flooding, energy demand, etc.

Urban areas range from small towns to megacities. Despite their differences in size, common characteristics of urban areas are changes in land cover, morphology (form), and emissions compared to nonurban land surfaces. NWP models need to address these. This paper provides a brief overview of these features.

Urban Surface Characteristics

One of the most distinct characteristics of the urban surface is the amount of vegetated cover relative to the impervious or built cover. Typically this varies across a city, with the largest impervious fraction found in the central business district (CBD), with residential areas more vegetated (Figure A.1). The built fraction consists of paved roads, sidewalks and parking lots as well as actual buildings. The characteristics of buildings also tend to change with distance from the CBD, with the buildings typically becoming shorter. Towards the suburbs, buildings also tend to be of lower density (more widely spaced).

This change in building height (H) and the distance between them (W), impacts wind flow and radiation exchange. In addition, urban building materials have different thermal and radiative characteristics to natural materials which affect heat storage and radiative exchanges.

Taller buildings are also associated with increased anthropogenic heat flux. Additional energy is required for the buildings to operate (e.g. elevators), and the greater density of people results in increased needs for air conditioning, removal of CO_2 enriched air, etc. With a focus of activities, such as in the CBD, there are more emissions from transport, which has implications for both energy and air quality.

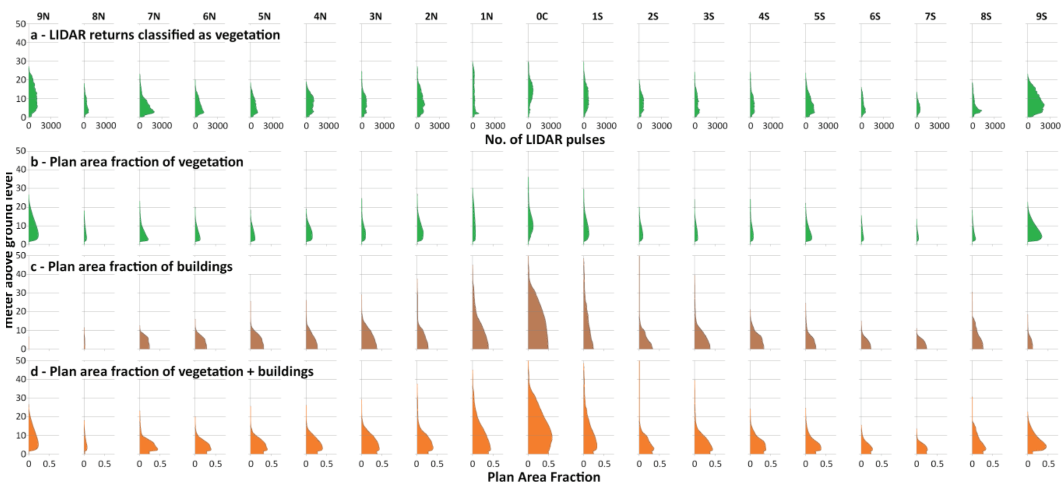


FIGURE A.1 Variation in plan area fraction by height of trees/shrubs and buildings in a North to South transect of London (OC centre of London, although not the tallest building area of London) (Lindberg and Grimmond, 2011)

Scale and Applications

Typically urban meteorological processes are considered to operate at three spatial scales; these relate to spatial units that are relevant for applications and decision making. The micro-scale, which in the vertical dimension relates to the urban canopy layer (from about the mean height of the roughness elements—buildings and trees to the ground), is what is experienced most directly by people. At this scale, there is significant spatial variability because of differences in radiation (e.g. shading/sunlit) and wind flow (blocked, channelled, open) that occur over very short distances. This spatial variability is not resolved in urban land surface parameterizations that are included in NWP. If they need to be resolved, some form of computational fluid dynamics (CFD) modelling is needed (e.g. large eddy simulation, LES).

The local or neighbourhood scale, where the vertical dimension extends from the blending height (minimum of about two times the roughness height) to a height dependent on the nature of the variability of the neighbourhood areas, is what urban land surface models parameterize in NWP models. The urban area is made of a series of such neighbourhoods which may have different characteristics related to urban form, vegetation cover etc. It is at this scale that understanding/modelling of meteorology is required for decision making related to response to flooding, assessing vulnerability to heat waves, response to hazardous dispersion, etc.

The meso- or city scale creates its own urban boundary layer, the height of which is a function of the different neighbourhoods in the city and the characteristics of the surrounding rural area. This city scale is normally an administrative unit for which decisions are made related to large scale meteorological and climatological processes; for example susceptibility to major storms or synoptic events (e.g., hurricanes, snow storms, regional heat waves) or climatological vulnerabilities (e.g., sea level rise).

Features of Urban Environment from a Meteorological Perspective

The most well-known atmospheric feature of the urban environment is the urban heat island (UHI). The original definition of the UHI is related to the canopy layer (UCL)—the air temperature difference between an urban area and the surrounding rural area. However, when considering the UHI, a number of key issues need to be taken into account. The UHI is dynamic, and the size and location of the maximum varies with time of day and with season. This means that few people experience the *maximum* urban warming, rather an urban effect that is less than that. It is also important to keep in mind that the magnitude of the difference is dependent not only on the characteristics of the urban area but also on the rural environment that is being used as a reference (Figure A.2).

Moreover, it is important to distinguish which UHI is being discussed: temperatures observed in the air, of the surface, and in the soil all are different. These all depend on the height/depth of the observation too. The temperature that people experience is more likely to be that of the UCL. Satellites do not observe this, rather features of the surface. Results need to be corrected for the emissivity of the surface materials and are dependent on the field of the view of the instrument and pixel resolution. Thus, the satellite determined temperature product is biased towards roofs and is dependent on clear conditions between the satellite and surface.

Given the large variability of temperature over small distances (e.g. Offerle et al. 2007), in any application it is critically important to understand

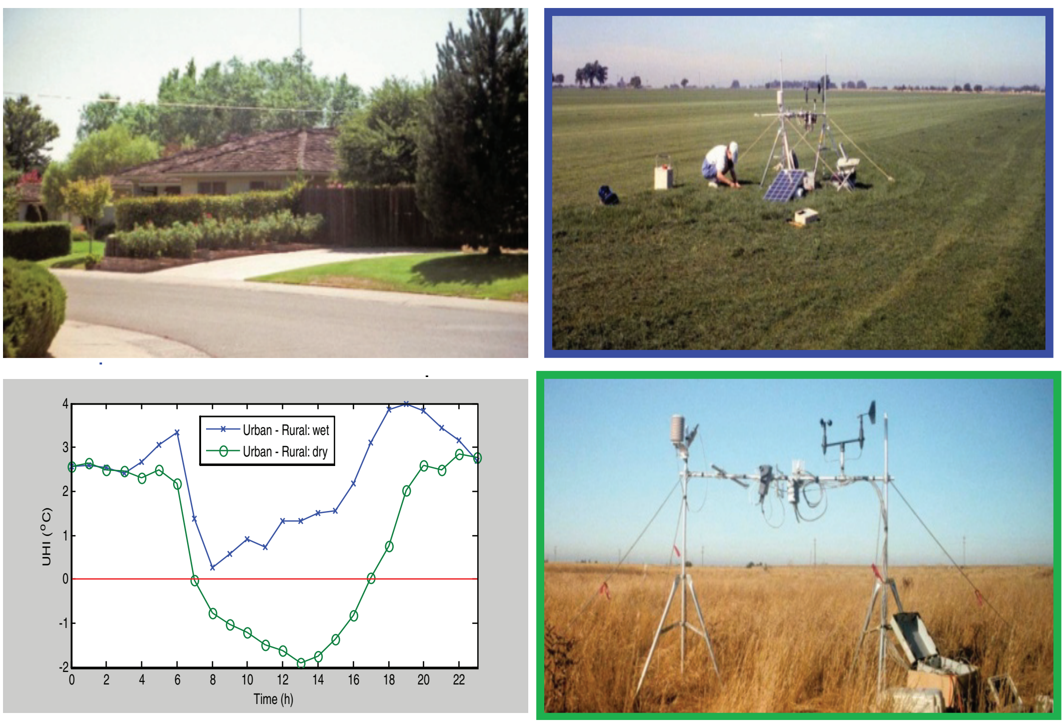


FIGURE A.2 Air temperature differences measured between a suburban site and two rural areas surrounding Sacaramento, CA: one without irrigation (dry) and one with irrigation (wet). Data from Grimmond et al. (1993).

how standard observations will differ from the actual location of interest. This remains an area where much work is needed.

A key feature of the urban environment relates to the trapping of radiation and re-radiation because of the reduced sky view factor (SVF). The standard nonurban meteorological station typically will have a much higher SVF (more open) than the urban area (Figure A.3). The radiation receipt at normal angles (early morning and evening) and enhanced radiative trapping, combined with the large urban mass (buildings and other structures) help generate a large

FIGURE A.3 Sky view factor (SVF) and location of a UK Met Office climate station (SJP, St James's Park) in central London. SJP can be seen to have a much higher SVF than the surrounding urban area. Anotated figure from Lindberg and Grimmond (2010).

storage heat flux (Grimmond and Oke 1999). This flux is normally greater in the evening hours and provides a source of energy into the evening which can be important for maintaining the turbulent sensible heat flux and unstable or neutral conditions. The additional heat from the anthropogenic heat flux also contributes to this. Precipitation processes are influenced by the presence of the large roughness elements of cities, the additional heating, and the additional source of aerosols. However the impact of the urban area is complex and appears to depend on synoptic conditions (Figure A.4).

Urban Land Surface Models (ULSM)

Developers of ULSM, which form the lower boundary condition for NWP models, have taken a wide range of approaches to incorporate what they regard as the essential feature of the urban environment (Grimmond et al. 2009, 2010a). Key differences between these schemes include if vegetation is accounted for; anthropogenic heat flux is accounted for; the surface is treated as flat, an infinitely long canyon, or having intersections; multiple reflections occur; and how many (and where) resistances for heat and moisture transfer are used (Figure A.5).

The recent offline evaluation of more than 30 ULSM by Grimmond et al. (2010a, 2011) found that no single model performs best for all components

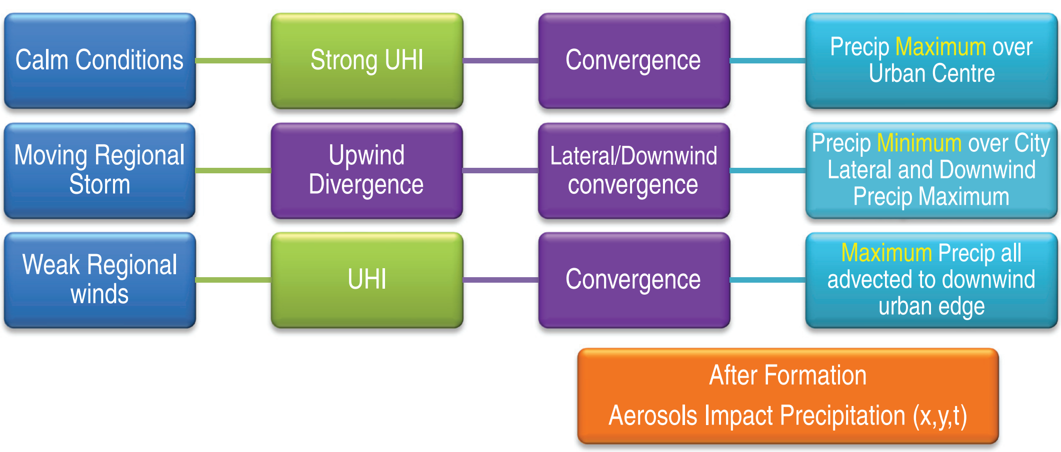


FIGURE A.4 Processes that influence precipitation resulting from summer thunderstorms. Figure created based on presentation by RD Bornstein (2011) Urban impacts on summer thunderstorms. International Workshop on Urban Weather and Climate. Beijing, July 12-15, 2011.

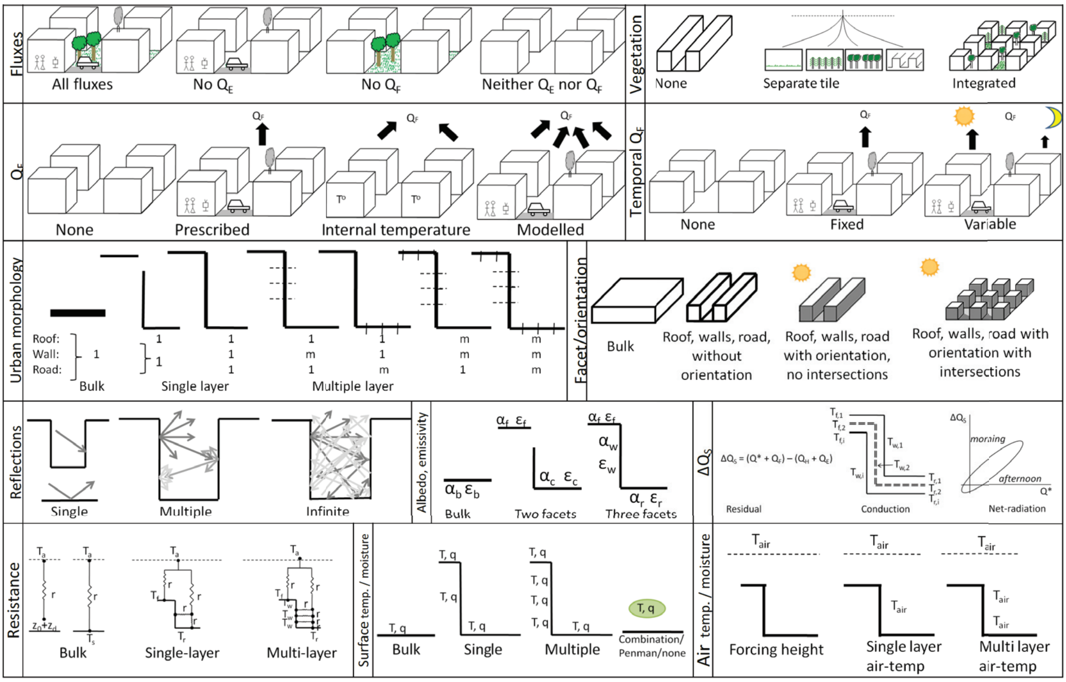


FIGURE A.5 Range of approaches taken to model urban processes in ULSM (modified from Grimmond et al. 2011).

of the urban energy balance and that accounting for evaporation is important. This study makes a number of recommendations for model development and model use (Grimmond et al. 2011).

Recommendations/Final Comments

A recent international review of urban meteorology for the World Climate Congress 3 made a series of recommendations for urban meteorology. In summary (modified from Grimmond et al. 2010b):

1. *Observations:* More operational urban measurement stations and networks within urban areas and upwind. The stations should conform to WMO Urban Guidelines (WMO 2006, Chapter 11). The long-term measurement stations in cities should be preserved. There is a need for vertical profiles of physical and chemical variables.

2. *Data*: International data archive is needed which can be used for historical and current analyses. This would aid with the translation of research findings into applications and for improving meteorological understanding. Development of guidelines for different climate zones and urban land-uses is also needed; and ensuring that there is high quality data of use to a broad range of end users. It is critical that there are good metadata (e.g., description of instruments, site, data quality assurance and control, protocol).

3. *Understanding*: There is a need to develop methods and frameworks to analyse atmospheric data measured above complex urban surfaces. It is necessary to develop methods to distinguish between signals attributable to urban change, regional change, and global change.

4. *Modelling*: There is a need for improved short-range, high-resolution numerical prediction in urban areas of weather, air quality, and chemical dispersion. Improved modelling of biogeophysical features of the urban land surface exchange of heat, moisture, momentum, and radiation with the atmospheric urban boundary layer. Improve (and/or incorporate) data assimilation of meteorological and biogeophysical data from improved observing networks.

5. *Tools*: Develop tools that allow models to accommodate the wide differences in data availability depending on application from research to operational situation (e.g., routine versus research intensive data), probable impacts of proposed sustainable design measures to be assessed and ranked including any unintended consequences of the proposed changes.

6. *Knowledge Exchange*: Ensure widespread training of the meteorological community about urban meteorology. Assist in appreciation of the role of meteorology and hydrology in urban planning and management of sustainable cities of all sizes. Communication across scientific disciplines and spatial and temporal scales must be encouraged.

REFERENCES

Grimmond, C. S. B., and T. R. Oke. 1999: Heat storage in urban areas: observations and evaluation of a simple model. *Journal of Applied Meteorology* 38:922-940.

Grimmond, C. S. B., T. R. Oke, and H. A. Cleugh. 1993. The role of "rural" in comparisons of observed suburban -rural flux differences. Exchange processes at the land surface for a range of space and time scales. *International Association of Hydrological Sciences Publication* 212:165-174.

Grimmond, C. S. B., M. Best, J. Barlow and A. J. Arnfield J.-J. Baik, S. Belcher, M. Bruse, I. Calmet, F. Chen, P. Clark, A. Dandou, E. Erell, K. Fortuniak, R. Hamdi, M. Kanda, T. Kawai, H. Kondo, S. Krayenhoff, S. H. Lee, S.-B. Limor, A. Martilli, V. Masson, S. Miao, G. Mills, R. Moriwaki, K. Oleson, A. Porson, U. Sievers, M. Tombrou, J. Voogt, and T. Williamson. 2009. Urban surface energy balance models: model characteristics and methodology for a comparison study. Pp. 97-123 in *Urbanization of Meteorological and Air Quality Models*, A. Baklanov. C. S. B. Grimmond, A. Mahura, M. Athanassiadou, editors. Dordrecht: Springer-Verlag, 97-123.

Grimmond, C. S. B., M. Blackett, M. Best, J. Barlow, J. J. Baik, S. Belcher, S. I. Bohnenstengel, I. Calmet, F. Chen, A. Dandou, K. Fortuniak, M. L. Gouvea, R. Hamdi, M. Hendry, T. Kawai, Y. Kawamoto, H. Kondo, E. S. Krayenhoff, S. H. Lee, T. Loridan, A. Martilli, V. Masson, S. Miao, K. Oleson, G. Pigeon, A. Porson, Y. H. Ryu, F. Salamanca, G. J. Steeneveld, M. Tombrou, J. Voogt, D. Young, and N. Zhang. 2010a. The International Urban Energy Balance Models Comparison Project: First results from Phase 1. *Journal of Applied Meteorology and Climatology* 49: 1268-1292, doi: 10.1175/2010JAMC2354.1.

Grimmond, C. S. B., M. Roth, T. R. Oke, Y.C. Au, M. Best, R. Betts, G. Carmichael, H. Cleugh, W. Dabberdt, R. Emmanuel, E. Freitas, K. Fortuniak, S. Hanna, P. Klein, L. S. Kalkstein, C. H. Liu, A. Nickson, D. Pearlmutter, D. Sailor, and J. Voogt. 2010b. Climate & More Sustainable Cities: Climate Information for Improved Planning & Management of Cities (Producers/Capabilities Perspective). *Procedia Environmental Science* 1:247-274.

Grimmond, C. S. B., M. Blackett, M. J. Best, J.-J. Baik, S. E. Belcher, J. Beringer, S. I. Bohnenstengel, I. Calmet, F. Chen, A. Coutts, A. Dandou, K. Fortuniak, M. L. Gouvea, R. Hamdi, M. Hendry, M. Kanda, T. Kawai, Y. Kawamoto, H. Kondo, E. S. Krayenhoff, S.-H. Lee, T. Loridan, A. Martilli, V. Masson, S. Miao, K. Oleson, R. Ooka, G. Pigeon, A. Porson, Y.-H. Ryu, F. Salamanca, G.-J. Steeneveld, M. Tombrou, J. A. Voogt, D. Young, and N. Zhang. 2011. Initial Results from Phase 2 of the International Urban Energy Balance Comparison Project. *International Journal of Climatology* 31:244-272 DOI: 10.1002/joc.2227.

Lindberg, F., and C. S. B. Grimmond. 2010. Continuous sky view factor from high resolution urban digital elevation models**,** Climate Research 42:177-183 doi:10.3354/cr00882.

Lindberg, F., and C. S. B. Grimmond. 2011. Nature of vegetation and building morphology characteristics across a city: influence on shadow patterns and mean radiant temperatures in London *Urban Ecosystems* doi: /10.1007/s11252-011-0184-5.

Offerle, B., I. Eliasson, C. S. B. Grimmond, and B. Holmer. 2007. The influence of surface heating on air temperature, wind and turbulence in an urban street canyon. *Boundary Layer Meteorology* 122:273-292, doi: 10.1007/s10546-006-9099-8.

WMO (World Meteorological Organization). 2006. Guide to Meteorological Instruments and Methods of Observation, WMO No-8. Chapter 11: Urban Observations.

URBAN METEOROLOGICAL MEASUREMENTS
WALTER F. DABBERDT, VAISALA GROUP

Introduction—The Urban Challenge

Cities alter the landscape in many different and pronounced ways relative to the neighboring, natural environment. The larger and more densely populated the city, the greater is its impact on atmospheric processes (both meteorological and air quality) within and downwind of its boundaries. The manmade urban landscape alters the thermal, radiative, and aerodynamic characteristics of the land surface and subsurface (e.g., Dabberdt and Davis, 1978), thereby modifying the local atmospheric and hydrologic environment. In addition, waste heat and particulate and gaseous emissions further alter the atmospheric state and composition. As a result, the atmospheric environment differs in many ways from conditions immediately upwind with significant changes in temperature, winds, humidity, cloud cover, precipitation, visibility, and air quality. The urban heat island is but one manifestation of these changes. Table A.1 is a subjective summary developed by Oke (1997) of the kinds and magnitudes of these changes. In the face of these effects, there is a pressing challenge to properly measure the state of the atmosphere in a way that enables both the quantification of the atmospheric state at any time and the prediction of changes in time using numerical models and other techniques (e.g., nowcasting).

This note addresses the urban measurement challenge in terms of identifying the *operational* needs for meteorological and air quality observations. End-user groups are identified along with their respective atmospheric information needs and data requirements (temporal and spatial resolution, and latency). These needs ultimately define the requisite atmospheric observing

TABLE A.1 Estimated Urban Meteorological Effects for a Mid-Latitude City with about 1 Million Inhabitants

Variable	Change	Magnitude/Comments[a]
Turbulence intensity	Greater	10-50%
Wind speed	Decreased	5-30% @ 10m in strong flow
	Increased	In weak flows with heat island
Wind direction	Altered	1-10deg
UV radiation	Much less	25-90%
Solar radiation	Less	1-25%
Infrared input	Greater	5-40%
Visibility	Reduced	Na
Evaporation	Less	About 50%
Convective heat flux	Greater	About 50%
Heat storage	Greater	About 200%
Air temperature	Warmer	1-3C per 100yr; 1-3C annual mean; up to 12C hourly mean
Humidity	Drier	Summer daytime
	More moist	Summer night; all day winter
Cloud	More haze	In and downwind of city
	More cloud	Especially in lee of city
Fog	More or less	Depends on aerosol and surroundings
Precipitation		
Snow	Less	Some turns to rain
Total	More?	To the lee rather than in city
Thunderstorms	More	
Tornadoes	Less	

[a] Values for summer unless otherwise noted
SOURCE: Oke, 1997

systems and the design of the observing network. Lastly, a few technological challenges are introduced. Research needs for specialized measurements and instrumentation options are outside the scope of this note although virtually all operational measurements are useful for research purposes as well.

Users, Applications and Needs

There is a wide range of urban end users of atmospheric information. Some are public institutions and agencies charged with protecting life and property, while many others are private organizations and businesses that use atmospheric information to enhance their operations or mitigate damages. By sheer numbers, the largest user group is the general public whose citizens use meteorological and air quality information to make a myriad of decisions in their daily lives; these range, for example, from decisions on proper clothing for the day to selecting the timing and routing of their commutes to avoiding or minimizing the deleterious effects of elevated levels of ozone or particulate matter. As useful as meteorological or air quality information alone may be, users invariably use this information to make decisions based on information about specific impacts to them; this involves blending meteorological information with various risk factors that are a specific function of the users' applications.

As a result, specifying the meteorological measurement needs for an urban area first requires deep understanding of the users and the derivative information required for their applications along with the necessary accuracy, precision, and temporal and spatial resolution of that information. It also requires knowledge of how numerical meteorological and air quality prediction models and data assimilation models use these measurements to make predictions of the future atmospheric state as well as to provide detailed analyses of the current atmospheric state. In this way, end users may either make use of the measured atmospheric data directly or they may rely on output data generated by numerical models (which, in turn, assimilate the observational data).

A subjective summary of the range of typical users and their characteristic data needs is presented in Table A.2. Thirteen types of urban applications are listed along with the different user groups that deal with the various applications. Their data needs are then characterized according to four sets of features. First, the table lists the type(s) of atmospheric data needed to aid in their decision-making. Second, the required spatial resolution is categorized as falling into one of three categories: fine-scale (at the block or street level), neighborhood scale, or city scale. Third, the temporal resolution is typed as

TABLE A.2 Examples of some common urban applications of atmospheric information and their respective user groups, with a subjective assessment of their data requirements.

			Characteristic User Data Requirements			
Application Type	End User Group	User Sector	Atmospheric Data	Spatial Resolution	Temporal Resolution	Forecast Period
Electric power	Power producers	Private	T, L, CC	city	≤1	NC, Sh, Md, Ln
	Grid operators	Private	I	neighborhood (equiv.)	—	—
	Local utilities	Private and Public	T, pp, V	neighborhood	≤1	NC, Sh, Md, Ln
Building systems management	Building managers	Private	T, L	block	1-3	Sh, Md
Transportation management	Highway departments	Public	T, I, pp, V, VSBY	neighborhood	≤1	Sh, Md
	Railroads	Private	T, I, pp, V, VSBY	city	≤1, 1-3	Sh, Md
	Airports	Public	T, I, pp, V, VSBY, CC	neighborhood	≤1	NC, Sh, Md, Ln
	Harbor and river masters	Public	T, I, pp, V, VSBY	neighborhood	≤1, 1-3	NC, Sh, Md
Public health and safety	Health departments and emergency mangers	Public	T, U, pp, L, V, CC	neighborhood	≤1	Md
Air quality	Air quality management and public safety officials	Public	AQ, T, U	block, neighborhood	1-3	Md
Emergency response	Public and industrial safety officials	Public and Private	T, U, pp, V, AQ	block, neighborhood	≤1	NC, Sh
Flood control	Municipal officials	Public	pp, T	block, neighborhood	1-3	NC, Sh
Insurance	Company officials	Private	pp, T, I, L, V	block, neighborhood	≤1	Md, Ln
Retail sales management	Company officials	Private	pp, T	neighborhood, city	>3	Ln
Research	Basic and applied researchers	Academic, Public, Private	VSBY CC	block, neighborhood, city	≤1, 1-3, >3	NC, Sh, Md, Ln
Urban planning	Municipal officials	Public	T, U, V, AQ	neighborhood	1-3, >3	(climate averages)
Tourism	Public visitor bureaus and private service providers	Public and Private	T, U, V, pp, L, AQ, VSBY, CC	city	1-3	Md
Personal decision support	General public (local)	Public	T, U, V, pp, I, L, AQ, VSBY, CC	neighborhood	1-3	Sh, Md, Ln

KEY: Atmospheric Data: AQ=pollution concentrations; CC=cloud cover; I=icing; L=lightning; pp=precipitation; T=temperature; U=humidity; V=wind; VSBY=visibility. Forecast Period: NC(nowcast)=≤2h; Sh=2-12h; Md=12-48h; Ln=>48h.

either high resolution (≤ 1h), moderate resolution (1-3 h) or low resolution (> 3h). And lastly, the forecast lead time requirements are stratified into four categories: current state and nowcasts (≤ 2h), short-range forecasts (2-12h), mid-range forecasts (12-48h) and longer range forecasts (> 48h). It is clear from the table that the data requirements of the different user groups have many commonalities but also some significant differences. For example, public health and safety organizations charged with warning the public of the hazards of impending heat waves or cold spells have far different requirements than does the renewable energy industry looking to balance energy production with demand or the construction industry that simply needs to know if the wind speed will permit safe (and sometimes legal) operation of a building crane.

Observing System Needs and Measurement Options

Measurement needs differ significantly according to the latency requirements of the application. Applications that depend on the current state of the atmosphere largely depend directly on local observations near the ground and aloft. Very short-range forecasts ("nowcasts")—out to 60 min or so—use increasingly sophisticated heuristic methods that extrapolate current conditions. Beyond a few hours, mesoscale numerical prediction models are initialized with upper-air data from ground-based and space-based profiling and volumetric sampling devices together with boundary conditions provided by smaller-scale (larger domain) models while data assimilation methods optimize the use of these data in the forecast continuum (resulting in significant improvements in NWP performance). The forecast domain between nowcasts and mesoscale forecasts is sometimes filled by blending the two although this temporal gap continues to shrink as the latency of mesoscale prediction models decreases.

The current state of atmospheric measurement networks is mixed. The need for dense networks of near-surface meteorological observations is largely being addressed (NRC, 2009) through a viral effort among state and local authorities although much remains to be accomplished to merge these into a truly nationwide network (of networks). Representative measurements within cities remain a challenge and much remains to be done. Proper siting of automated surface weather stations is inconsistent among existing stations, although Oke (2006) has produced a comprehensive set of guidelines that should assist in improving the siting and characterization of surface meteorological stations in urban areas.

In a recent report of the National Research Council (NRC, 2009), the need for new and improved measurements of various atmospheric and soil properties was considered in great detail. Table A.3 summarizes some of the findings from that study in the left-hand column and introduces a number of measurement technology options (right-hand column) that can be used to satisfy some or all of the respective data needs. Four of the measurement needs from the NRC study were identified as "highest priority;" these included PBL height; soil moisture and temperature (to a depth of 2m); high-resolution lower-tropospheric profiles of absolute humidity; and air quality concentrations of ozone, particulate matter, carbon monoxide and sulfur dioxide above the atmospheric surface layer (roughly 10% of the PBL height). These four priority needs are included in the upper part of Table A.3. The study also identified a number of needs that are "just below the … highest priorities;" these are shown in the lower half of Table A.3 and include solar radiation, lower-tropospheric (LT) profiles of wind and temperature, surface icing, and surface-layer turbulence. Corresponding measurement technology options are briefly described below (N.B. exemplary references are included throughout although the discussion is neither an inclusive nor definitive review or assessment of the state of the art in measurement technologies).

Radar wind profilers (Carter et al., 1995, Clifford et al., 1994) transmit a short pulse of radio-frequency electromagnetic energy into the atmosphere, where a small fraction is scattered from refractive-index irregularities in the

TABLE A.3 Priority Measurement Needs (NRC, 2009) and Associated Measurement Technology Options

Priority Measurement Needs[a]	Measurement Technology Options
Height (and structure) of the PBL	Radiosondes; backscatter lidar; radar wind profilers; sodar; commercial aircraft
Soil moisture and soil temperature profiles (to 2m depth)	Neutron sensor -cosmic ray absorption
High-resolution LT vertical profiles of atmospheric humidity	DIAL and Raman lidar; radiosondes; microwave radiometric profilers; commercial aircraft
Air quality concentrations (above the atmospheric surface layer)	DIAL and Raman lidar; tall towers with in situ monitors
Solar radiation (direct and diffuse)	Radiometers
Vertical LT profiles of wind	Radiosondes; radar wind profilers, Doppler lidar; sodar; commercial aircraft
Icing at the ground surface	Lidar (spectral)
Vertical LT profiles of temperature	Radiosondes; commercial aircraft
Surface turbulence parameters	Sonic anemometry

NOTE: LT = lower tropospheric; PBL = planetary boundary layer
[a]First-priority needs are above the double line

atmosphere back to the profiler's antenna. The irregularities are transported with the wind and so act as tracers of air movement. As a result, the frequency of the returned signal undergoes a Doppler shift in proportion to the speed of the wind along the pointing (radial) direction of the transmitted electromagnetic pulse. By alternately pointing the transmitted beam in various directions, the three-dimensional wind vector can be resolved over successive height intervals (ranges). The higher-frequency UHF (~1 GHz) wind profilers can resolve the wind within height intervals ≥ 60 m up to heights of several kilometers. Lower-frequency devices have greater ranges but coarser range resolution. Radar wind profilers operate in all weather conditions. They are also able to estimate the height of the mixing layer and the planetary boundary layer (Cohn and Angevine, 2000) from changes with height in the vertical profiles of the refractive index structure function, the spectral width of the received signals, and the vertical component of velocity.

Sodar (sonic or sound detection and ranging; see Coulter and Kallistratova, 2004) is a radar-like device that emits pulses of acoustic energy, which is scattered back from the atmosphere to a receiver on the ground by means of thermal irregularities in the air. As these thermal irregularities are transported by the wind, sodar can measure the vertical profile of the wind from the Doppler shift of the received acoustic energy. Sodar systems can also estimate the height of the mixing layer from changes with height in the temperature structure function and the vertical component of velocity. So-called mini-sodars have ranges up to a few hundred meters with range-resolution of a few tens of meters while higher-powered systems may profile up to a few kilometers with coarser range resolution.

Atmospheric lidar (light detection and ranging; see Killinger and Menyuk, 1987) refers to a family of profiling devices that emit short pulses of visible, ultraviolet or infrared beams of electromagnetic energy to obtain height-resolved profiles of winds, gaseous molecules or fine particles, depending on the design of the system.

Aerosol (or elastic backscatter) lidars are the simplest type of atmospheric lidar and are typically used to detect cloud properties as well as aerosols in the clear air and in plumes from certain pollution sources. Lidar detects constituents that are equal to and greater than the laser wavelength. In these systems, the backscattered wavelength is the same as the transmitted wavelength. The magnitude of the received signal depends on the backscatter coefficient of the scatterers at a given range and the extinction caused by the scatterers along the path to that range, where the latter is typically the quantity of interest. So-called **micropulse lidars** (Spinhirne, 1993) utilize narrow-band solid-state lasers in the visible spectrum with very high pulse repetition rates (several thousand per second) at micro Joule-level pulse energies. They have excellent range resolution (≥5 m) and long range (up to 25km). Another type of backscatter lidar is the **ceilometer** (Münkel et al., 2006), which was originally developed to measure meteorological ceiling (cloud base height). These systems use low-power wide-band diode lasers that operate at near-infrared wavelengths (~900nm) and high pulse repetition rates (~6.5kHz). Ceilometers can measure cloud base heights up to about 13km and aerosol profiles in urban areas to several kilometers with range resolution ≥ 10m and measurement cycles ≥ 6s.

Profiles of water vapor and trace gases (e.g. ozone, sulfur dioxide, water vapor) can be measured with either of two classes of advanced lidars: differential absorption lidars (DIAL) and Raman scattering lidars. The **DIAL** technique generally uses two laser wavelengths—typically in the near-infrared spectrum—to determine the range-resolved profile of atmospheric trace molecular species. One wavelength is tuned to an absorption line of the molecular species of interest while the other is tuned to a nearby ("off-line") wavelength that is weakly (or not) absorbed by the species of interest. The lidar return from the off-line wavelength provides a reference signal for the atmospheric scattering from molecules and aerosols and for any slowly varying ambient absorption that may be common to both wavelengths. Molecular absorption along the "on-line" path attenuates the lidar signal to yield the range-resolved profile of the species. Aerosol profiles are also obtained at the same time from both lidar wavelengths. **Raman lidar** (Grant, 1991; Whiteman et al., 1992) is also used for measuring the range-resolved concentration of atmospheric gases, and can profile aerosols as well. Raman lidar uses inelastic scattering to single out the gas of interest from other atmospheric constituents. A small portion of the energy of the transmitted ultraviolet light is retained by the gas during the scattering process, which then shifts the scattered light to a longer wavelength according to the gaseous molecule of interest. The magnitude of the backscattered signal is proportional to the concentration of the gas. As with DIAL systems, the Raman technique uses the difference between the transmitted wavelength and the much weaker Raman scattered wavelength to obtain the concentration profile.

The ground-based microwave radiometric profiler (**MWRP**) is a passive, multi-channel, all-weather instrument (Westwater et al., 2005) that can provide profiles of atmospheric temperature, water vapor (relative humidity), and cloud liquid water; some MWRPs are also flown on satellites and research aircraft. The MWRP observes radiation intensity (brightness temperature) at various microwave frequencies, along with zenith infrared and surface meteorological measurements. State-of-the-art MWRPs have up to 14 V-band (51 to 59 GHz) microwave channels to retrieve temperature profiles and up to 21 K-band (22 to 30 GHz) microwave channels to measure water vapor. Historical radiosonde and neural network or regression methods are then used to retrieve near-continuous meteorological profiles to heights ≤ 10km (range resolution decreases as range increases).

Radiosondes are balloon-borne devices used operationally to provide twice-daily profiles (soundings) of winds, temperature, humidity, and pressure from the ground surface to pressure altitudes up to 10hPa at nearly 100 sites in the U.S. The radiosonde (Dabberdt et al., 2002; Durre et al., 2006) consists of an expendable unit containing sensors, electronics, and a radio transmitter to telemeter the measurements back to a receiver at the launch station. Data are transmitted at 1Hz (equivalent to 5-8m height differential at launch). Winds are determined from the movement of the radiosonde suspended beneath the balloon using one of several methods: optical tracking, radio tracking, radar tracking, and GPS locating. Pressure, temperature and relative humidity are measured with in situ sensors on the radiosonde.

Commercial aircraft provide tropospheric soundings (Benjamin et al., 2008; Moninger et al., 2010) of winds, pressure, temperature and humidity, as well as aircraft aeronautical data. Two systems—MDCRS and TAMDAR—are in use in the U.S. MDCRS (meteorological data collection and reporting system) was first developed for the Federal Aviation Administration (FAA) and the National Weather Service (NWS) in 1991. MDCRS collects and organizes up to 100,000 real-time, automated position and weather reports (en route, departure and approach) per day from 1500 participating aircraft (typically B757 aircraft). On takeoff, MDCRS data are obtained every 6s for the first 90s, which equates to several hundred meters in the lower troposphere. Unfortunately, MDCRS data in the PBL are often missing. TAMDAR (tropospheric airborne meteorological data reporting) is a commercial system inaugurated in 2004 that uses several hundred regional aircraft (e.g. Saab 340, ERJ, CRJ). During ascent and descent, observations are made at 10 hPa (~100m) pressure intervals up to 200 hPa (1800m). Observations above 200 hPa are made at 25 hPa intervals.

Soil moisture is a key variable in understanding and predicting atmospheric processes, yet representative measurements are difficult to obtain and not widely available. A new measurement method (Zreda et al., 2008) offers much promise; it is based on a technique that uses a Helium-3 neutron detector to measure the absorption of fast neutrons generated in the ground by bombardment from ambient cosmic rays. The amount of absorption is proportional to the moisture in the environment and allows for the measurement of water content in soil and the water equivalent depth of snow.

The method is passive and can yield soil moisture measurements on a scale about 300m radius and 0.5m depth.

Some Additional Considerations

In addition to the users' information needs and the need for additional and improved surface-based measurements described above, there are at least four other requirements needing attention in the urban zone. These include improved radar and lightning observations, appropriate metadata for all observing systems, effective network-design tools, and urban-regional prototype networks to evaluate and refine observing network designs and predictive models.

The national WSR-88D (or, NEXRAD) S-band Doppler weather radar network (Crum and Alberty, 1993) is a very effective system for storm-scale monitoring for many applications. But it also has limitations (NRC, 2002): it is unable to view precipitation within about three-fourths of the PBL and its scan rate is too slow and its range resolution too coarse for many applications. The multi-university Collaborative Adaptive Sensing of the Atmosphere (CASA) project has been evaluating the effectiveness of small x-band (3cm) radars in a four-node testbed in west-central Oklahoma (McLaughlin et al., 2009). CASA has developed adaptive scanning technologies that are designed to intelligently seek meteorological targets of interest and to optimize their sampling close to the surface. CASA has also demonstrated the value of assimilating these radar observations in NWP models (Xue et al. , 2006). Eventually, perhaps thousands of such radars could be placed on buildings and communications towers throughout the nation. At the present time, CASA is planning to expand and move (2012) its Oklahoma testbed to the greater Dallas-Ft. Worth metropolitan area in order to address urban-specific needs and applications (see Appendix B).

In the same way that the existing radar network is not optimal for fine-scale urban needs, neither is the U.S. National Lightning Detection Network (Orville, 2008). The NLDN measures cloud-to-ground (CG) lightning with excellent temporal and spatial resolution but it does not effectively detect in-cloud (IC) lightning, which is typically a very useful antecedent of subsequent hazardous CG strokes and precipitation. Commercial off-the-shelf total (CG + IC) lightning detection systems (Hembury and Holle, 2011) are now available and operating in some locations.

At the present time, there are no full-scale three-dimensional operational or research meteorological measurement networks in existence, although plans are beginning to emerge to establish one or two in the U.S. and China.

These early adaptors (prototypes) will be important for several reasons. They will be great resources for developing the tools to properly and effectively design future measurement networks, including decisions on the optimal mix of observing systems and their geographical distribution. They will also enable rigorous testing of urban-scale predictive models (NWP and nowcasting models alike) and facilitate their improvement. And, perhaps most importantly, they will demonstrate their societal and economic value in terms of better understanding users' needs for atmospheric information and how best to address them.

References

Benjamin, S. B. D. Jamison, W. R. Moninger, B. Schwartz, and T.W. Schlatter. 2008. Relative forecast impact from aircraft, profiler, rawinsonde, VAD, GPS-PW, METAR and mesonet observations for hourly assimilation in the RUC. 12th Conference on IOAS-AOLS, New Orleans, LA. American Meteorological Society. (January).

Carter, D. A., K. S. Gage, W. L. Ecklund, W. M. Angevine, P. E. Johnston, A. C. Riddle, J. Wilson and C. R. Williams. 1995. Developments in UHF lower tropospheric wind profiling at NOAA's Aeronomy Laboratory. *Radio Science* 30(4):977-1001.

Clifford, S. F, C. Kaimal, R. J. Lataitas and R. G. Strauch. 1994. Ground-Based Remote Profiling in Atmospheric Studies: An Overview. *Proceedings of the IEEE* 82(3).

Cohn, S. A. and W. M. Angevine. 2000. Boundary layer height and entrainment zone thickness measured by lidars and wind-profiling radars. *Journal of Applied Meteorology* 39(8):1233-1247.

Coulter, R. L., and M. A. Kallistratova. 2004. Two decades of progress in sodar techniques: a review of 11 ISARS proceedings. *Meteorology and Atmospheric Physics* 85(1-3):3-19.

Crum, T. D., and R. L. Alberty. 1993. The WSR-88D and the WSR-88D operational support facility. *Bulletin of the American Meteorological Society* 74(9): 1669-1687.

Dabberdt, W. F., and P. A. Davis. 1978. Determination of energetic characteristics of urban-rural surfaces in the greater St. Louis area. *Boundary-Layer Meteorology* 14:105-121.

Dabberdt, W. F., H. Cole, A. Paukkunen, J. Horhammer, V. Antikainen and R. Shellhorn. 2002. Radiosondes. Pp. 1900-1913 in *Encyclopedia of Atmospheric Sciences,* Vol. 6, J. R. Holton, J. Pyle, and J. A. Curry, editors. New York: Elsevier Science/Academic Press.

Durre, I., R. S. Vose, and D. B. Wuertz. 2006. Overview of the Integrated Global Radiosonde Archive. *Journal of Climate* 19(1):53-68.

Grant, W. B. 1991. Differential absorption and Raman lidar for water vapor profile measurements: a review. *Optical Engineering* 30(1):40-48.

Hembury, N. and R. Holle. 2011. Vaisala LS200: Technological Advancements for VHF total lightning mapping. Southern Thunder Conference, National Weather Center, Norman, OK, July 11-14, 2011. *http://www.goes-r.gov/downloads/southern-thunder/2011/session_2/hembury.pdf*.

Killinger, D. K., and N. Menyuk. 1987. Laser Remote Sensing of the Atmosphere. *Science* 235:37-45.

McLaughlin, D., D. Pepyne, B. Philips, J. Kurose, M. Zink, D. Westbrook, E. Lyons, E. Knapp, A. Hopf, A. Defonzo, R. Contreras, T. Djaferis, E. Insanic, S. Frasier, V. Chandrasekar, F. Junyent, N. Bharadwaj, Y. Wang, Y. Liu, B. Dolan, K. Droegemeier, J. Brotzge, M. Xue, K. Kloesel, K. Brewster, F. Carr, S. Cruz-Pol, K. Hondl, and P. Kollias. 2009. Short-Wavelength Technology and the Potential For Distributed Networks of Small Radar Systems. *Bulletin of the American Meteorological Society* 90 (12):1797-1817.

Moninger, W. M., S. Benjamin, B. Jamison, T. L. Smith, and T. Schlatter. 2010. TAMDAR and MDCRS Impact on RUC forecasts. *http://amdar.noaa.gov/docs/TAMDAR_MDCRS_GSD_4Mar10.pdf*.

Münkel, C., N. Eresmaa, J. Räsänen and A. Karppinen. 2006. Retrieval of mixing height and dust concentration with lidar ceilometers. *Boundary-Layer Meteorology* 124:117-128.

NRC (National Research Council). 2002. *Weather Radar Technology Beyond NEXRAD*. Washington, DC: National Academies Press.

NRC. 2009. *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks*. Washington, DC: National Academies Press.

Oke, T. R. 1997. Urban climates and environmental global change. Pp. 273-287 in *Applied Climatology: Principles and Practice*, R. D. Thompson and A. H. Perry, editors. London: Routledge.

Oke, T. R. 2006. *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites*. Report No. 81, WMO/TD-No. 1250. Geneva, Switzerland: World Meteorological Organization.

Orville, R. E. 2008. Development of the National Lightning Detection Network. *Bulletin of the American Meteorological Society* 89(2):180-190.

Spinhirne, J. D. 1993. Micro pulse lidar. *IEEE Transactions on Geoscience and Remote Sensing* 31(1).

Westwater, E., S. Crewell and C. Mätzler. 2005. Surface-based microwave and millimeter wave radiometric remote sensing of the troposphere: A tutorial. *IEEE Geoscience and Remote Sensing Society Newsletter*. March:16-33.

Whiteman, D. N., S. H. Melfi, and R. A. Ferrare. 1992. Raman lidar system for the measurement of water vapor and aerosols in the Earth's atmosphere. *Applied Optics* 31:3068-3082.

Xue, M., M. Tong and K. K. Droegemeier. 2006. An OSSE framework based on the ensemble square root kalman filter for evaluating the impact of data from radar networks on thunderstorm analysis and forecasting. *Journal of Atmospheric and Oceanic Technology* 23(1):46-66.

Zreda, M., D. Desilets, T. P. A. Ferré and R. Scott. 2008. Measuring soil moisture content noninvasively at intermediate spatial scale using cosmic-ray neutrons. *Geophysical Research Letters* 35(21):0012-0016.

CLIMATE CHANGE AND CITIES OF THE FUTURE
BRIAN STONE, GEORGIA INSTITUTE OF TECHNOLOGY

This presentation covers four principal topics related to climate change and the future of cities. These topics include the characterization of urban heat island (UHI) formation as regional climate change, the significance of land use change to urban climate, the significance of metropolitan spatial structure to the incidence of extreme heat events, and physical design strategies that can be employed to enhance the climate resilience of cities. What follows in this abstract is an overview of each of these four topics.

Heat island Formation as Climate Change

The adoption of alternative definitions of the climate change problem by the international climate science and policy communities has created an important discontinuity between climate change management at the global and regional levels. Unrecognized by the U.N. Framework Convention on Climate Change definition of human-driven climate change, land surface drivers of regional-scale climate change, such as the urban heat island effect, are not characterized as potential mechanisms for climate change mitigation. The implications of this definitional issue for cities are multifold. Chief among these is a tendency to focus more aggressively on emissions-related mitigation in cities rather than on land-surface drivers of climate change (e.g., reduced albedo and energy balance shifts), which are shown through this presentation to be the dominant driver of warming trends in large U.S. cities over the past half century.

Land Use Change in Cities as a Driver of Regional-Scale Climate Change

To assess the extent to which regional drivers of climate change, such as UHI, are contributing to warming trends in cities, this presentation reports findings from a study on urban and rural temperatures trends in proximity to 50 of the most populous U.S. cities. Employing data from urban and rural meteorological stations meeting a set of selection criteria, this study derives decadal UHI change trends over the period of 1961 to 2010. The results of this analysis support three conclusions: (1). Land use change is a more owerful driver of observed warming trends than are rising concentrations of greenhouse gases over the last five decades; (2) Urban temperatures are not only higher than proximate rural areas, on average, they are increasing over time at a higher rate; and (3) The extent to which urban areas are amplifying background, global warming trends has accelerated over the last decade. In most large cities of the U.S. urban temperatures are rising at twice the rate of global temperatures, with heat island-related drivers playing the dominant role at this scale.

Land Use Change and the Frequency of Extreme Heat Events

Urbanization is not only driving the extent to which cities are warming in excess of their rural surroundings, it is contributing to a rapid rise in the number of extreme heat events (EHEs) over time. Defined as any day in which the minimum or maximum temperature exceeds the 85th percentile of a long-term average (1961-1990), extreme heat events provide a basis to assess the potential health effects of rising temperatures that accounts for regional population acclimatization to different seasonal temperature ranges.

Previous work has found the 85th percentile of the long-term temperature distribution to be associated with an increase in heat-related health effects.

An assessment of minimum temperature EHEs across 50 large U.S. cities between 1956 and 2005 shows the frequency of extreme heat to be increasing rapidly. During this period, the average number of extreme heat events per year more than doubled, rising from an average of 9 per year to 19 per city. Importantly, the rate of increase in EHEs was found to vary significantly with metropolitan spatial structure. Employing a standard sprawl index, metropolitan regions included in the study were ranked by population density, street connectivity, regional centeredness of land development, and land use mix. Based on these rankings, the frequency of EHEs in the most sprawling cities was found to be increasing at a rate almost three times greater than the most compact cities. Significant correlations between regional rates of deforestation, sprawl rankings, and EHE frequency are suggestive of a linkage between metropolitan land use change and the rising frequency of extreme heat.

Enhancing Urban Climate Resilience

Trends in heat island growth and the frequency of extreme heat in the largest U.S. cities clearly demonstrate the rising threat of climate change to urban populations. Three classes of strategies to manage rising levels of ambient heat in cities are supported by this work and the literature on urban climate change. The first of these entails "sunscreening" strategies, which are intended to abate the radiant and sensible heat load on cities through an increase in vegetative cover, enhancing the latent heat flux, or an increase in the reflectivity of urban surfaces (albedo enhancement). The incorporation of such sunscreening approaches into municipal land development codes is needed to account for climate change management at each stage in the development process. "Green area ratios," requiring all development and redevelopment projects to meet minimum standards of vegetative cover and/or albedo, provide a promising planning tool for urban heat management. A second set of strategies focuses on the implications of regional land cover for the pace of warming trends throughout a metropolitan region. Characterized as "greenbelting," such strategies focus on protecting and regenerating natural land covers in proximity to urban centers to address the influence of regional deforestation on heat island formation. Urban growth boundaries and "redfield to greenfield" initiatives—programs focused on the acquisition and conversion of defunct development projects to greenspace—provide viable policy approaches to increasing greenspace in proximity to urban centers. A final component of urban climate resilience entails the energy conservation and efficiency strategies effective in reducing waste heat emissions from fuel combustion and building climate control. Characterized as "carbon cooling" due to the potential for energy reduction programs to address both the local and global drivers of climate change, such strategies are the most common approach to climate management at the urban scale today. Carbon cooling strategies prioritize emission control techniques that carry the associated benefits of climate change adaptation in cities. Such "adaptive mitigation" projects represent a critical linkage between climate management policy at the regional and global levels.

In response to the organizing theme of the meeting, a number of meteorological data needs are suggested by the presentation. The first and most pressing of these is the need for a more dense array of first-order meteorological stations in and in proximity to urban areas. Data on heat island trends is unavailable for many large metropolitan regions due to the absence of a continuous and reliable temperature record at a minimum number of rural sites in proximity to urban centers.

A second data need and one related to the first are improved methods for assessing the extent to which rural meteorological stations are subject to the impacts of local land use change. Nonstandard siting of instrumentation and significant changes to rural land cover, such as resulting from nearby deforestation or agricultural activities, have been found to be a significant influence on rural temperature trends used for baseline development in heat island research. Enhanced evaluation and enforcement of siting requirements across all meteorological stations is needed to improve the reliability of urban and rural climate trends that are increasingly significant to public health.

Finally, higher resolution modeling tools are needed to assess the combined impacts of global and micro-scale climate drivers on extreme heat in cities. At present, downscaling methods employed with global circulation models support a maximum resolution that is often too coarse for integration with meso and microscale climate models that are most responsive to urban land use conditions.

Appendix B

The Dallas-Fort Worth Urban Testbed

FRED CARR,[1] JERRY BROTZGE,[1] AND BRENDA PHILIPS[2]

One current effort to establish an urban testbed as described in this and earlier NRC reports is being carried out by an NSF Engineering Research Center on Collaborative Adaptive Sensing of the Atmosphere (CASA) in the Dallas-Fort Worth (DFW) metropolitan area. The mission of CASA is to develop and deploy networks of low-cost, X-band, dual-polarimetric Doppler radars dedicated to enhance our ability to observe, understand, predict, and respond to hazardous weather events. The close spacing of these radars gives them the ability to scan low to the ground with very high spatial and temporal resolution (McLaughlin et al., 2009). The project, known as the Dallas-Fort Worth Urban Demonstration Network, is an end-to-end testbed that has the primary goal of improving the detection, prediction, and warning of hazardous weather including flash flooding, severe winds, and tornadoes in a densely populated urban environment. Additional goals include very-high resolution analysis/modeling to resolve street level weather and urban canyon wind flow, improved transport and dispersion forecasts of pollutants, improved understanding of the effects of an urban area on its surroundings, and the evaluation of various observing systems for potential national deployment.

The DFW testbed is a joint venture between the University of Massachusetts, Colorado State University, and the University of Oklahoma, and includes local stakeholders, such as the North Central Texas Council of Governments, the emergency management community, and regional forecast offices. It will embrace the vision of the Network of Networks report (NRC, 2009)—to deploy and/or access a wide array of sensors, including WSR-88D, TDWR, and CASA radars, local surface networks, profilers, aircraft and satellite data that will be used for the creation of added-value products and assimilated for model prediction. Regional

[1] The University of Oklahoma.
[2] University of Massachusetts.

analysis and forecast products will be operated in real time and made available to partner stakeholders. Initially, 8 X-band radars from the CASA partners will supplement the existing WSR-88D and two TDWR radars (see Figure B.1), with the first 4 being moved to the DFW area from the CASA IP1 testbed in southwestern Oklahoma by late Fall 2011. It is expected that other observing assets will be provided or financed by other federal, state, and metropolitan agencies that will benefit from a densely observed urban complex. Additional partners may include instrument vendors and numerous local industries such as the transportation, media, defense, and energy sectors.

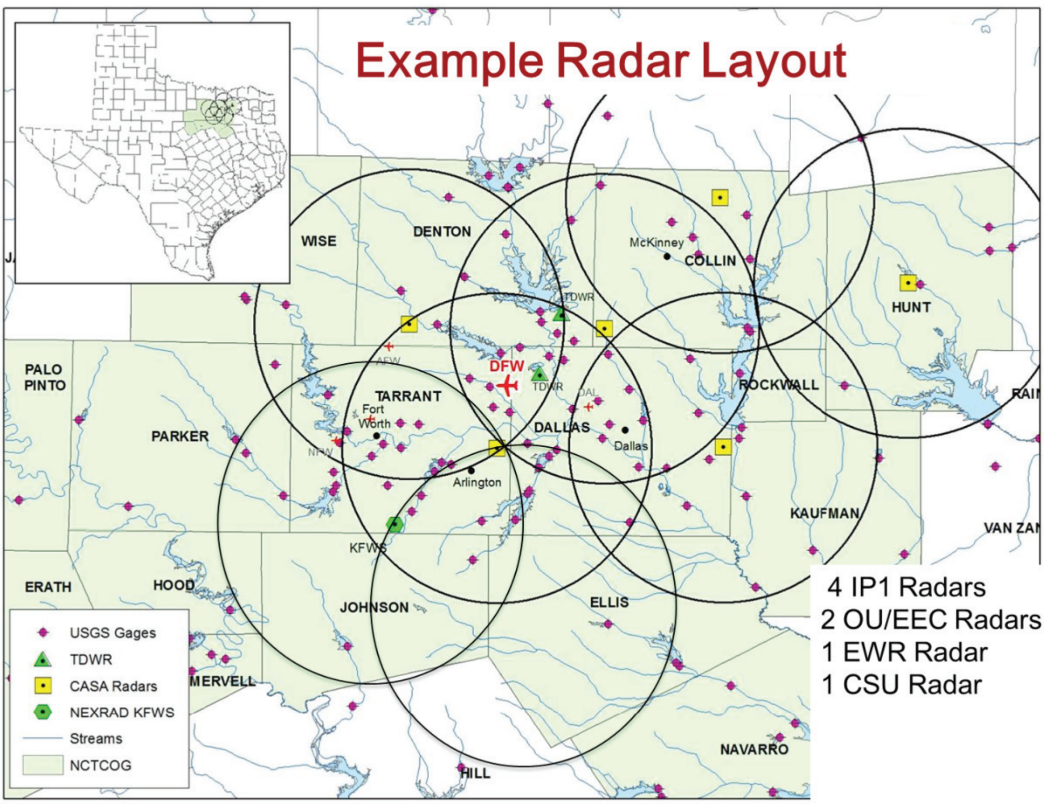


FIGURE B.1 An example radar layout for the Dallas-Ft. Worth Urban Demonstration Network.

The Dallas-Fort Worth Metroplex is an ideal location for such a demonstration testbed. The DFW area population is over 6.5 million, the 4th largest in the U.S., and is the fastest growing major metropolitan area in the country, adding nearly 1.3 million since 2000. Dallas-Fort Worth is home to two major airports, including DFW, the third busiest airport in the world, numerous regional airports, several major interstates and many large sports complexes. Its Gross Metro Product is near $400B, which is attractive for commercial partners seeking markets for value-added products. It experiences a wide range of hazardous weather and air quality in all four seasons, and is also vulnerable to local flooding. Its area of 9,286 square miles gives it a spatial dimension important for numerical weather prediction capability.

The Urban Demonstration Network will be funded and operated by a consortium of local and federal government and private sector partners. CASA is the lead institution and is investing over $2.5 million into the initial radar systems, deployment, and real-time operations. The North Central Texas Council of Governments will take the lead locally, providing operational support and recruiting area partners. Other partners include government agencies such as the National Weather Service, specifically its Southern Region and Fort Worth Forecast Office, and local universities such as the University of Texas at Arlington. Additional partners will include those mentioned above who may enhance the observing networks.

In addition to providing high-spatial, high-temporal radar and other data to users in real time for warning operations, the DFW testbed is expected to be the ideal research platform, with major research thrusts including convective initiation, quantitative precipitation estimation (QPE)/quantitative precipitation forecasting (QPF), fusion of, for example, satellite and radar data, urban hydrology, and urban-scale numerical modeling and data assimilation. This research will also help the NWS achieve its warn-on-forecast vision (NRC, 2010). It is hoped that the DFW Urban Demonstration Network, through its multi-university, cross-disciplinary partnerships and university-government-private sector collaborations, will provide a model for how other metropolitan areas can invest in observational consortiums for operational and research missions that benefit public safety and economic security.

REFERENCES

McLaughlin, D., D. Pepyne, V. Chandrasekar, B. Philips, J. Kurose, M. Zink, K. Droegemeier, S. Cruz-Pol, F. Junyent, J. Brotzge, D. Westbrook, N. Bharadwaj, Y. Wang, E. Lyons, K. Hondl, Y. Liu, E. Knapp, M. Xue, A. Hopf, K. Kloesel, A. DeFonzo, P. Kollias, K. Brewster, R. Contreras, T. Djaferis, E. Insanic, S. Frasier, and F. Carr. 2009. Short-wavelength technology and the potential for distributed networks of small radar systems. *Bulletin of the American Meteorological Society* 90(12):1797-1817. Figure courtesy of Cedar League, Colorado State University.

NRC (National Research Council). 2009. *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks*. Washington, DC: National Academies Press.

NRC. 2010. *When Weather Matters: Science and Services to Meet Critical Societal Needs*. Washington, DC: National Academies Press.

Appendix C

Workshop Information

Board on Atmospheric Sciences and Climate

URBAN METEOROLOGY: SCOPING THE PROBLEM, DEFINING THE NEEDS

Committee Meeting and Summer 2011 Community Workshop

Final Meeting Agenda
July 27-29, 2011

National Academies Jonsson Center
314 Quissett
Woods Hole, MA 02543

Workshop Goals

The field of urban meteorology has grown considerably in the past few decades, and a number of recent publications have helped pinpoint pressing needs for scientific advances. To date, however, most assessments of R&D priorities have come from discussions within the scientific community. There is a need for more direct interaction with key 'end user' communities, who can help identify their needs. The goal of the workshop is to facilitate a dialog between the research community and the users of urban meteorology information by bringing together scientific experts with representatives from select end user communities.

Wednesday July 27, 2011

7:00 -7:45 A.M. Shuttle Bus Service from Hotel to Jonsson Center
(Shuttle Departs every 10-15 minutes)

OPEN SESSION: 8:00 A.M. -5:30 P.M.: Carriage House

8:00 A.M. Breakfast in Main House

8:30 A.M. Welcome, Introduction, Purpose of Workshop
Chris Elfring, BASC Director
John Snow, University of Oklahoma
Xubin Zeng, University of Arizona

8:45 A.M. Overview of Urban Meteorology
Sue Grimmond, King's College London

Morning Panel Discussion on End-Users: *Panelists will each have 10 minutes to speak followed by 20 minutes of general discussion.*

Questions to be addressed in the morning panel discussions:
What are user needs?
What needs are not being met, and what are the reasons?
If your needs are not being met, how do we address them?

9:15 A.M. **Perspective from the Federal Agencies**

Moderator: Ellis Stanley

EPA: S.T. Rao
FEMA: Sandra Knight
DDOT: Terry Bellamy
CDC: George Luber

10:15 A.M. *Break*

10:30 A.M **End User Perspectives**

Moderator: Stefanie Sarnat

Air Quality: Paula Davidson, NOAA/NWS
Urban Vulnerability: Olga Wilhelmi, NCAR
Emergency: Ellis Stanley, Dewberry
Security: Gayle Sugiyama, Lawrence Livermore National Laboratory
Utilities: James Rufo Hill, Seattle Public Utilities
Urban Planning: Stuart Gaffin, Columbia University

12:00 P.M. Continued Discussion over ***LUNCH*** in the Main House

1:00 P.M. Observations and Modeling of the Urban Environment
Walt Dabberdt, Vaisala

Afternoon Panel Discussion on End-Users: *Panelists will each have 10 minutes to speak followed by 20 minutes of general discussion.*

Questions to be addressed in the afternoon panel discussions:
What are the new capabilities and products needed to better serve users?
How can these capabilties and products be effectively communicated to users?

1:30 P.M. **Federal Agency Perspectives: Science and Technology Challenges**

Moderator: Marshall Shepherd

NWS: Andy Edman
NASA: Marc Imhoff
NOAA/OFCM: Sam Williamson
DOE: Nancy Brown
USGS: Sue Cannon

2:50 P.M. *Break*

3:05 P.M. **Research Community Perspectives: Science and Technology**

Moderator: Petra Klein

Urban Observations: Marshall Shepherd, University of Georgia

Urban Modeling: Teddy R. Holt, Naval Research Laboratory
Urbanization of Mesoscale Models and their Operational Use: Martin Best, UK Met Office
Urban Meteorology: Tim Oke, University of British Columbia

4:15 P.M. Assignment for Working Groups and Charges
**see Charge to the Working Groups document* (p. 162)
John Snow and Xubin Zeng

WG1a
End Users/Applications
Chair: Stefanie Sarnat
Rapporteur: Mark Arend
NRC staff: Maggie Walser
Room: TBA

WG1b
End Users/Applications
Chair: Ellis Stanley
Rapporteur: George Schewe
NRC staff: Laurie Geller
Room: TBA

WG2a
Observations and modeling
Chair: Marshall Shepherd
Rapporteur: Dev Niyogi
NRC staff: Chris Elfring
Room: TBA

WG2b
Observations and modeling
Chair: Petra Klein
Rapporteur: James Voogt
NRC staff: Lauren Brown
Room: TBA

5:00 P.M. Working Groups: Meet briefly for introduction and discussions

6:00 P.M. Continued Discussion over **DINNER:** Main House/Grounds

Thursday, July 28, 2011

7:00 -7:45 A.M. Shuttle Bus Service from Hotel to Jonsson Center (Shuttle Departs every 10-15 minutes)

8:00 A.M. Breakfast in Main House

OPEN SESSION: 8:30 A.M.-5:00 P.M.: Carriage House

8:30 A.M	**Cities of the Future:** Brian Stone, Georgia Institute of Technology
9.00 A.M.	Working Groups Convene to Address Their Charge
12:00 P.M.	Continue discussion over ***LUNCH*** in the Main House
1:00 P.M	***Plenary: All Participants Reconvene*** *Each Working Group Rapporteur will present their respective group's "findings." The Rapporteurs will each have 15 minutes to present followed by 5 minutes of Q&A.*
2:30 P.M.	General Discussions Reflections on key issues/questions Next steps
3:15 P.M.	*Break*
3:45 P.M.	Working Groups reconvene: • Finalize their findings based on the discussions • Draft outline • Assignment and plan to complete any further input to study committee
5:00 P.M.	Workshop Adjourns
5:30 P.M.	Optional **DINNER**: Main House/Grounds

PARTICIPANT LIST

Urban Meteorology: Scoping the Problem, Defining the Needs
BASC Summer Study-Participant List
July 27-28, 2011
Woods Hole, MA

BASC Board and Staff

Antonio J. Busalacchi, Jr., BASC Chair, University of Maryland
Richard E. (Rit) Carbone, NCAR Earth Observing Laboratory
Chris Elfring, Board Director, BASC
Katie Thomas, Study Director, BASC
Rita Gaskins, Administrative Coordinator, BASC
Elizabeth Finkelman, Program Assistant, BASC
Lauren Brown, Research Associate, BASC
Laurie Geller, Senior Program Officer, BASC
Maggie Walser, Program Officer, BASC

Committee

John T. Snow (cochair), BASC member, University of Oklahoma
Xubin Zeng (cochair), BASC member, University of Arizona
Ellis Stanley, Dewberry
Petra Klein, University of Oklahoma
Stefanie Sarnat, Emory University
Marshall Shepherd, University of Georgia

Participants

Mark Arend, The City College of New York, CUNY
Terry Bellamy, District Department of Transportation, Washington, DC
Martin Best, Met Office, United Kingdom
Kelley Brookins, Chicago Transit Authority
Nancy Brown, Lawrence Berkeley National Laboratory (LBL)
Susan H. Cannon, U.S. Geological Survey (USGS)
Walt Dabberdt, Vaisala
Paula Davidson, National Oceanic and Atmospheric Administration (NOAA)
Sheldon Drobot, National Center for Atmospheric Research (NCAR)
Andy Edman, National Oceanic and Atmospheric Administration (NOAA)

Stuart Gaffin, Columbia University
Sue Grimmond, King's College, London
James Rufo Hill, Seattle Public Utilities
Teddy R. Holt, Naval Research Laboratory
Marc L. Imhoff, Goddard Space Flight Center, NASA
Paul Kirshen, Battelle Memorial Institute
Kim Klockow, University of Oklahoma
Sandra Knight, Federal Emergency Management Agency (FEMA)
George Luber, Centers for Disease Control and Prevention (CDC)
Thomas Matte, New York City Department of Health
Dev S. Niyogi, Purdue University
Fred Ogden, University of Wyoming
Tim Oke, University of British Columbia
Brenda Philips, University of Massachusetts, Amherst
S. Trivikrama (S.T.) Rao, U.S. Environmental Protection Agency (EPA)
David Sailor, Portland State University
George Schewe, Trinity Consultants
Brian Stone, Jr., Georgia Institute of Technology
Gayle Sugiyama, Lawrence Livermore National Laboratory (LLNL)
James A. Voogt, University of Western Ontario
Olga Wilhelmi, National Center for Atmospheric Research (NCAR)
Samuel P. Williamson, Office of the Federal Coordinator for Meteorology (OFCM), NOAA

CHARGE TO WORKING GROUPS

The challenge for the working groups is to move beyond the Day 1 discussions and provide tangible and substantive input to the Committee, which will consider this input as it writes its final report. The working groups will be asked to discuss the questions below and each group's rapporteur will be asked to prepare slides that summarize the discussion, to present in the plenary session.

Key Questions

1. Briefly describe some of the advances in meteorological forecasting/monitoring in the past decade that have had the most impact on urban areas and why. Were any of these developed specifically for urban uses and, where not, what relationships or synergies led to developments in other areas being found to benefit urban uses?

2. Are there important existing urban-level forecasting/monitoring capabilities that are not being effectively utilized by the relevant end user communities, either due to lack of awareness that such capabilities exist, or failure to provide such information in a usable form?

3. Are there particular needs of specific end user communities that are not being met by current urban-level forecasting/monitoring efforts?

4. Are there emerging technologies in meteorological forecasting/monitoring that would help contribute to urban dwellers' safety and well-being?

5. What are some effective ways to strengthen the interactions between urban meteorology researchers and the different end user communities?

6. What new future needs or challenges might be anticipated in light of the potential additional stresses resulting from to be brought by the impacts of global climate change?

Appendix D

Statement of Task

An ad hoc committee will plan and conduct a public workshop that will facilitate a dialog between the research community and the users of urban meteorology information by bringing together selected scientific experts (potentially including experts from other countries that are making strides in this field) with a wide array of representatives from end user communities. The committee will develop the workshop agenda, select and invite participants who will contribute presentations and take part in plenary and small group discussions, and moderate the discussions. The outcome of this activity will be a consensus report of the committee that builds on workshop presentations and discussions to provide conclusions on the following topics:

1. Briefly describe some of the advances in meteorological forecasting/monitoring in the past decade that have had the most impact on urban areas and why. Were any of these developed specifically for urban uses and, where not, what relationships or synergies led to developments in other areas being found to benefit urban uses?

2. What is the current state of urban level meteorological forecasting/monitoring capabilities?

- Are there important urban-level forecasting/monitoring capabilities that are not being utilized by the relevant end user communities, either due to lack of awareness that such capabilities exist, or failure to provide such information in a useable form?
- What needs for the end user communities are not being met by current urban-level forecasting/monitoring?

3. What is the future of urban level meteorological forecasting/monitoring capabilities?

- Are there emerging technologies in meteorological forecasting/monitoring that would help contribute to urban dwellers' safety and well-being?
- What future needs or challenges might be anticipated in light of the potential additional stresses to be brought by the impacts of climate change?

Appendix E

Acronym List

4D	Var data-assimilation framework—four-dimensional variational data-assimilation framework
AERMOD	Atmospheric Dispersion Modeling System
AMS	American Meteorological Society
AQ	air quality
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BASC	Board on Atmospheric Sciences and Climate
BL	Boundary Layer
CASA	Center for Collaborative Adaptive Sensing of the Atmosphere
CCNY	City College of New York
CDC	Centers for Disease Control
CESM	the NCAR Community Earth System Model
CFD	Computational Fluid Dynamics (Modeling)
CFS	climate forecast system
CG	Cloud to Ground (Lightning)
CIMEL	CIMEL Electronique, Paris, France
CMAQ	Community Multiscale Air Quality model
CMAQ-WRF	Community Multiscale Air Quality Weather Research and Forecasting coupled model
CSAQ	Community Scale Air Quality
DEMS	digital elevation model
DFW	Dallas-Fort Worth
DHS	Department of Homeland Security
DIAL	Differential Absorption Lidar

DMSP OLS	Defense Meteorological Satellite Program Operational Linescan System
DOD	Department of Defense
DOT	Department of Transportation
ECMWF	European Centre for Medium-range Weather Forecasts
EM	Electromagnetic Modeling
EMS	*Emergency Medical Service*
EnKF data-assimilation framework	ensemble Kalman filter data-assimilation framework
EPA	*Environmental Protection Agency*
EPHI	Environmental Public Health Indicators
EPiCC	Environmental Prediction in Canadian Cities Network
FHWA	Federal Highway Administration
FIFE	the First International Satellite Land Surface Climatology Project Field Experiment
GCM	global climate model
GEWEX	the Global Energy and Water Cycle Experiment
GFS	global forecast system
GHCN	Global Historical Climate Network
GHG	Greenhouse Gas (Emissions)
GIS	Geographic Information System
GLDAS	Global Land Data Assimilation System
GMAO	the NASA Global Modeling and Assimilation Office
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GSWP	the Global Soil Wetness Project
HAZMAT	hazardous materials
HRLDAS	high resolution land data assimilations systems
IC	intra-cloud (lightning)
iLEAPS	integrated Land Ecosystem-Atmosphere Process Study
INDOT	Indiana Department of Transportation
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing Satellite
ISA	impervious surface area

ISL	Interstitial Sublayer
ISLSCP	International Satellite Land Surface Climatology Project
JMA	Japanese Meteorological Agency
KML	Keyhole Markup Language
LANDSAT	Derived from Land Satellite
LDAS	land data assimilations systems
LES	Large-Eddy simulation
lidar	Light Detection and Ranging
LIS	land information system
LST	land surface temperature
LUMPS	local-scale urban meteorological parameterization scheme
MDCARS	*Meteorological Data Collection and Reporting System*
MDSS	Maintenance and Decision Support System
MFRSR	*Multi-Filter Rotating Shadowband Radiometer*
MISR	Multi-angle Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MSA	Metropolitan Statistical Area
MWRP	Microwave Radiometric Profilers
NAAQS	National Ambient Air Quality Standards
NAQFC	National Air Quality Forecast Capability
NARAC	National Atmospheric Release Advisory Center
NASA	National Aeronautics and Space Administration
NASA LIS	NASA Land Information System
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCTCOG	the North Central Texas Council of Governments
NEXRAD	Next-Generation Radar
NLDAS	North American Land Data Assimilation System
NLDN	National Lightning Detection Network
NOAA	National Oceanic and Atmospheric Administration
NOAA MADIS	National Oceanographic and Atmospheric Association's Meteorological Assimilation Data Ingest System
NOAA NCDC	National Oceanic and Atmospheric Administration's National Climatic Data Center
NRC	The National Research Council

NUDAPT	National Urban Database and Access Portal Tool
NWCC	The National Wind Coordinating Collaborative
NWP	Numerical Weather Prediction
NWS	National Weather Service
NYC MetNet	New York City Meteorological Network
OFCM	Office of the Federal Coordinator for Meteorology
OSSE	Observing System Simulation Experiments
PBL	planetary boundary layer
PDA	Personal Digital Assistant
PM Samplers	Particulate Matter Samplers
RANS	Reynolds-averaged Navier-Stokes
RAOB	the Universal RAwinsonde OBservation program
RFC	River Forecasting Center
RISA	Regional Integrated Sciences and Assessments (NOAA program)
RSL	Roughness Sublayer
RSS	Really Simple Syndication
SAR	synthetic aperture radar
SEAFM	streamflow forecasting computer model system used and developed by Seattle Public Utilities
SEB	surface energy balance
SMS	Short Message Service
SNOTEL	SNOwpack TELemetry
SPOT	Satellite Pour l'Observation de la Terre
SPU	Seattle Public Utilities
TAMDAR	Tropospheric Airborne Meteorological Data Reporting
T&D	transport and dispersion
TOMS	Total Ozone Mapping Spectrometer
TRMM	Tropical Rainfall Measurement Mission
UBL	Urban Boundary Layer
UBL/PBL	Urban Boundary Layer/Planetary Boundary Layer
UCL	Urban Canopy Layer
UCM	urban canopy model
UHI	Urban Heat Island

UPS	United Parcel Service
USWRP	U.S. Weather Research Program
V-I-S model	Ridds's vegetation-impervious surface-soil model
WMO	World Meteorological Organization
WRF	Weather Research & Forecasting Model
WRF/Chem model	Weather Research and Forecasting/Chemistry model
WRF-NMM	Weather Research and Forecasting-Nonhydrostatic Mesoscale Model
WSR-88D	Weather Surveillance Radar 88 Dop

Appendix F

Committee and Staff Biographical Sketches

COMMITTEE

Dr. John T. Snow (*Co-chair*) is a Regents' Professor of Meteorology and Dean Emeritus of the College of Atmospheric & Geographic Sciences at the University of Oklahoma. He earned both his B.S. and M.S. in Electric Engineering from Rose-Hulman Institute of Technology, and his Ph.D. in Atmospheric Science from Purdue University. Currently, Dr.Snow's professional interests lie in the field of "Earth System Science," merging research in the Earth and Life Sciences to generate a comprehensive explanation for "how the world works." In recent years, Dr. Snow has been involved in a number of local and regional economic development projects and technology transfer efforts. Dr. Snow is involved with a number of professional organizations, serving as an American Meteorological Society(AMS) Fellow, a Royal Meteorological Society Fellow, and a member of the NSF Geosciences Advisory Committee to name a few. The AMS has honored Dr. Snow with the Charles Anderson Award for his efforts in improving education and diversity in the atmospheric sciences, and the Cleveland Abbey Award for his excellent service to both the Society and profession. While his NRC committee membership extends back to the late 1980s, Dr. Snow is currently a member of both BASC and the Panel on Digitization and Communications Science.

Dr. Xubin Zeng (*Co-chair*) is a Professor in the Department of Atmospheric Sciences at the University of Arizona (UA), as well as the Director of the UA Climate Dynamics and Hydrometeorolgy Center (CDHC). He holds a Ph.D. in Atmospheric Science from Colorado State University. Through over 100 peer-reviewed publications, Dr. Zeng's research interests include land-atmosphere-ocean interface processes, climate modeling, hydrometeorology, remote sensing, and nonlinear dynamics. He has given over 80 invited talks at conferences and institutions. His research products (including models, algorithms, and value-added datasets) have been used worldwide by numerous groups (including NCAR, NCEP, ECMWF). In addition to being an elected member of the American Meteorological Society's Executive Committee and Council, he was recently named an AMS Fellow. This year, Dr. Zeng was named a Galileo Circle Fellow, the highest recognition awarded by the UA College of Science. Dr. Zeng served on two NRC Committees before. Since 2008, he has also served as a member of the National Academies' Board on Atmospheric Sciences and Climate (BASC).

Dr. Petra M. Klein is an Associate Professor and Edith Kinney Gaylord Presidential Professor at the University of Oklahoma's School of Meteorology. She earned both her undergraduate degree in Physics and Ph.D. in Civil Engineering from the University of Karlsruhe in Germany. Dr. Klein's research broadly focuses on atmospheric boundary layer research and tropospheric pollution problems. Specific areas of study include urban meteorology, focusing on the modification of the atmospheric boundary layer structure in urban areas; air pollution studies, notably the dispersion of traffic emissions and the long-range transport of Ozone and its precursor pollutants; as well as wind-tunnel modeling of atmospheric flows. Dr. Klein has served as a member and chair of the AMS Board on the Urban Environment, and is currently a Board member of the International Association for Urban Climatology. She is also a member of the Editorial Board of the Journal Environmental Fluid Mechanics, and a reviewer for Atmospheric Environment, Atmospheric Research, Boundary Layer Meteorology, Environmental Fluid Mechanics, Environmental Management, and the Journal of Applied Meteorology.

Dr. Stefanie Ebelt Sarnat is an Assistant Professor in the Department of Environmental Health at Emory University in Atlanta, GA. She earned both her B.S. and M.S. from the University of British Columbia, and her Doctor of Science from Harvard School of Public Health. Dr. Sarnat's research addresses environmental impacts on human health. With a particular interest in the health effects of air pollution, she is conducting population-based studies in several U.S. cities, including Atlanta, Birmingham, Dallas, and St. Louis, in which she investigates the association between air pollution and health care usage for cardiovascular and respiratory diseases. Her studies have also addressed the impact of automobile-related air pollution on asthmatic children and other susceptible populations, as well as the impacts of climate and meteorological conditions on acute morbidity. Dr. Sarnat is a member of the American Thoracic Society, the International Society for Environmental Epidemiology, and the International Society of Exposure Science.

Dr. J. Marshall Shepherd is a Professor in the Department of Geography's Atmospheric Sciences Program at the University of Georgia (UGA). Dr. Shepherd earned his B.S., M.S., and Ph.D. in physical meteorology from Florida State University. Prior to joining the UGA Faculty, Dr. Shepherd spent 12 years as a research meteorologist at NASA Goddard Space Flight Center. During that time, he served as Deputy Project Scientist for the Global Precipitation Measurement Mission. Dr. Sheppard is an AMS/TRW Industry and Dolores Auzene Fellow, and National Achievement Scholar. His research interests include the urban climate, tropical precipitating systems, hydroclimate variability, satellite remote sensing of weather and hydroclimate, as well as the development of innovative outreach strategies and applications for research data. In May 2004, Dr. Shepherd was awarded the Presidential Early Career Award for his work on how urban environments affect precipitation. He has since been elected a Fellow of the American Meteorological Society. Dr. Shepherd has well over 65 scholar publications, and he serves as an Editor for the Journal of Applied Meteorology and Climatology. He served on the National Academies of Science Committee on National Security Implications of Climate Change on U.S. Naval Forces, and presently serves on the NOAA Climate Working Group, the University Space Research Association Earth Science Advisory Committee, and is a Project Associate for the Urbanization and Global Environmental Change project.

Ellis M. Stanley, Sr. is the Vice President of Western Emergency Management Services at Dewberry's office in Los Angeles. Dewberry is a respected professional services firm that serves both the public and private sectors. Mr. Stanley has been directing emergency management programs for over thirty years, including ten years spent as the general manager for the Los Angeles Emergency Preparedness Department. He earned his bachelor's degree in political science from the University of North Carolina, Chapel Hill, and recently received an honorary doctoral degree for public service from the University of Maryland Eastern Shore (UMES). Mr. Stanley is a faculty member at both Harvard University and American University, where he teaches meta-leadership, and senior crisis management, respectively. In addition, he serves on board of directors for the National Institute of Urban Search and Rescue, and the board for the Disaster Recovery Institute International. He also is a member of Operation Hope, Inc. and the American Red Cross of Greater Los Angeles.

NRC Staff

Ms. Katie Thomas is an Associate Program Officer for the Board on Atmospheric Sciences and Climate (BASC). She received her B.S. from the University of Michigan in 2004 and her M.S. in Environmental Science and Policy from Johns Hopkins University in 2009. Since joining the NRC, she has worked on studies related to climate modeling, weather radar, Arctic Sea ice prediction, and advancing climate science.

Ms. Elizabeth Finkelman is a Senior Program Assistant for the Board on Atmospheric Sciences and Climate (BASC). She received her Bachelor of Arts and Science degree from McGill University in 2010, concentrating in molecular biology and political science. Since joining the NRC in March of 2011, she has participated in Board-related projects and studies concerning climate change, urban meteorology, climate modeling, and urban forestry.