ABSTRACT

The 10th Prospectus Development Team (PDT-10) of the U.S. Weather Research Program was charged with identifying research needs and opportunities related to the short-term prediction of weather and air quality in urban forecast zones. Weather has special and significant impacts on large numbers of the U.S. population who live in major urban areas. It is recognized that urban users have different weather information needs than do their rural counterparts. Further, large urban areas can impact local weather and hydrologic processes in various ways. The recommendations of the team emphasize that human life and well-being in urban areas can be protected and enjoyed to a significantly greater degree. In particular, PDT-10 supports the need for 1) improved access to real-time weather information, 2) improved tailoring of weather data to the specific needs of individual user groups, and 3) more user-specific forecasts of weather and air quality. Specific recommendations fall within nine thematic areas: 1) development of a user-oriented weather database; 2) focused research on the impacts of visibility and icing on transportation; 3) improved understanding and forecasting of winter storms; 4) improved understanding and forecasting of convective storms; 5) improved forecasting of intense/severe lightning; 6) further research into the impacts of large urban areas on the location and intensity of urban convection; 7) focused research on the application of mesoscale forecasting in support of emergency response and air quality; 8) quantification and reduction of uncertainty in hydrological, meteorological, and air quality modeling; and 9) the need for improved observing systems. An overarching recommendation of PDT-10 is that research into understanding and predicting weather impacts in urban areas should receive increased emphasis by the atmospheric science community at large, and that urban weather should be a focal point of the U.S. Weather Research Program.

1. Introduction

a. Background

Prospectus development teams (PDTs) are small groups of experts who are convened by the U.S. Weather Research Program (USWRP) on a one-time basis to discuss critical issues and research opportunities, and to provide advice related to future directions of the program. The recommendations of the PDTs are a principal source of information used to establish re-
search priorities and resource commitments by the USWRP’s Science Steering Committee and the Interagency Working Group. Other expert groups have met to explore research and user needs in such areas as observing systems and strategies, modeling and predictability, weather in coastal and mountain regions, hurricanes at landfall, societal impacts, hydrology, and quantitative precipitation forecasting. The 10th Prospectus Development Team (PDT-10) focused on issues pertaining to weather in the urban forecast zone. The team met 24–26 August 1998, on the campus of the University of California, Los Angeles. This document serves to summarize the deliberation and considerations of PDT-10, and to present recommendations that form the basis for a research prospectus on urban weather.

Prospectus Development Team 10 was specifically charged to “identify and delineate critical issues related to the short-term prediction of weather in urban forecast zones.” In this context, “prediction” included depiction and communication of present weather information and its extrapolation, in addition to numerical weather prediction on timescales up to 24 h. “Weather” includes precipitation, floods, winds, humidity, temperature, clouds, lightning, and visibility, especially as these exert high impact on activities in urban areas. Weather was also taken to include the urban boundary layer as it affects the transport and diffusion, but not the chemical evolution, of airborne toxic emissions and air quality criteria pollutants.

“High impact” refers to conditions that alter routine behavior of the general public and sector activities, including aviation, water management, electric power, surface transportation, public events, broadcasting, and emergency management. PDT-10 was also asked to identify the need, if any, for workshops or other activities that are deemed necessary for the development of a research plan related to urban zone prediction.

b. The urban forecast problem

The urban weather problem is multidimensional in scope. Weather has special and significant impacts on a large fraction of the U.S. population who live in large urban areas. Conversely, large urban areas can impact the local weather and hydrologic processes in various ways. It is important to recognize that urban users have different needs for weather information than do their rural counterparts. Data from the 1990 U.S. census (http://www.census.gov/geo/www/index.html) serve to quantify the large fraction of the population living in urban areas. Of the nearly 250 million people living in the United States in 1990, Carbone (2000) indicates that almost two-thirds (64%) live in urbanized areas occupying less than 2% of the U.S. landmass. The population density in these urbanized areas exceeds 1000 km\(^{-2}\) (2600 mi\(^{-2}\)). Carbone questions the current National Weather Service (NWS) practice of “uniformity of service,” which commonly equates to one forecast per forecast zone (usually a county) and a relatively uniform geographical distribution of observing systems. He suggests that an alternative view “might argue for a per capita level of forecast service (100 times that experienced in rural zones) in urban areas . . . Perhaps a more meaningful definition might take into account the level of disruption to the functions of society caused by weather in urban and rural forecast zones and seek ‘uniformity’ based on comparable minimization of disruptions as measured by loss of life and preventable economic losses.”

Urban needs for specialized weather information derive from the diverse user groups and population sectors found in urban areas. These groups include the following:

- water supply and sewage facilities;
- electric power industry;
- fuel suppliers—natural gas, fuel oil, coal, gasoline;
- transportation sectors—aviation, marine, and surface;
- emergency response agencies;
- public safety agencies;
- insurance industry;
- health care providers;
- recreation facilities; and
- the general public.

Large urban areas impact weather and atmospheric structure in various ways. Urban heat islands result from the combined effects of changed thermal and radiative properties of the surface, anthropogenic emissions of sensible heat, and changes in the exchange of water and the corresponding impact on the radiation budget. Changes in surface roughness in urban areas also affect the exchange of heat, mass, and momentum between the surface and the atmosphere, as well as the depth of the urban mixed layer. Hydrological processes are also altered to a significant degree as a result of buildings and pavement that affect runoff and streamflow. There is also speculation by some (e.g., Bornstein and Lin 1999) that large urban areas may influence the genesis, intensity, and movement of convective storms and frontal boundaries.
Weather impacts urban areas and urban residents in many ways. Heavy rains can cause severe flooding, snow and freezing rain can disrupt transportation systems, severe storms and accompanying lightning and high winds can cause power failures, and so forth. To better understand weather-related fatalities, consider that there are direct and indirect effects attributable to the weather. Direct effects reflect deaths from such causes as heat stroke, lightning strikes, freezing, and so forth. We will come back to direct effects.

First, we focus attention on indirect effects, which are largely those deaths caused by weather-related traffic accidents although other indirect effects also exist, such as falls on ice, avalanches, and so forth. In the case of traffic-related deaths, a study by the U.S. Department of Transportation (USDOT 1998) provides valuable insights. The USDOT has done some rough estimates and come to the conclusion that between 8% and 15% of fatal crashes of highway vehicles may have been weather related. In 1995, for example, that would have implied that between 4500 and 8500 vehicles were involved in fatal crashes that were related to weather conditions. If we assume that there are one-to-two fatalities and two vehicles per accident, then the number of weather-related traffic fatalities is in the range 2250 to 8500 per year, or of order 6000 on average. However, the occurrence of a crash during bad weather does not necessarily mean that the bad weather caused the crash. Conversely, just because 86% of fatal crashes in 1995 occurred in normal weather, we cannot conclude that weather has a marginal effect on highway risk. To conclude, the USDOT states that not much is really known about the effect of weather on highway safety beyond what common sense and personal experience tell us. This is an area where extensive research is needed. For example, fog and ice have not received much attention; most research has focused on rain. And even for rain, the studies have not yielded a consistent, accurate methodology for integrating crash data and weather data locally and nationally to determine the added risk because of rain-induced loss of visibility and wet pavement.

The major direct impact on human mortality results from heat waves, and urban areas are particularly vulnerable because of their high population densities and because urban areas exacerbate conditions that lead to heat stress. Table 1 is from Changnon et al. (1996), who summarize the numbers of deaths in the twentieth century attributed to various weather conditions. Their data clearly show that heat waves cause more deaths, both on an annual average basis and from single events, than all other weather conditions combined! J. Patz (1999, personal communication) discusses in detail the relationship between temperature extremes and mortality in 11 eastern U.S. cities. It was found that the current and the previous day’s temperatures were most strongly indicative of mortality. For cold temperatures, mortality generally decreased as the temperature increased from the coldest days, while for the hottest days, mortality increased abruptly after a critical threshold temperature had been reached.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Annual average</th>
<th>Maximum events</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tornadoes</td>
<td>82–100</td>
<td>739</td>
<td>Mar 1925</td>
</tr>
<tr>
<td></td>
<td></td>
<td>322</td>
<td>Apr 1974</td>
</tr>
<tr>
<td>Heavy rains and floods</td>
<td>100–160</td>
<td>2200</td>
<td>May 1899</td>
</tr>
<tr>
<td></td>
<td></td>
<td>732</td>
<td>Mar 1913</td>
</tr>
<tr>
<td>Hurricanes</td>
<td>38–63</td>
<td>6000</td>
<td>Sep 1900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1836</td>
<td>Sep 1928</td>
</tr>
<tr>
<td>Hail</td>
<td>1</td>
<td>22</td>
<td>May 1981</td>
</tr>
<tr>
<td>Windstorms</td>
<td>60–115</td>
<td>105</td>
<td>Dec 1972</td>
</tr>
<tr>
<td>Lightning</td>
<td>100–156</td>
<td>Unknown</td>
<td>—</td>
</tr>
<tr>
<td>Winter storms and cold</td>
<td>130–200</td>
<td>500</td>
<td>Dec 1983</td>
</tr>
<tr>
<td></td>
<td></td>
<td>270</td>
<td>Mar 1992</td>
</tr>
<tr>
<td>Heat waves</td>
<td>1000</td>
<td>&gt; 10 000</td>
<td>1980</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 9500</td>
<td>1901</td>
</tr>
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*ranges reflect data from various sources
Temperature–mortality relationship was also observed to have a strong latitudinal dependence: mortality rates in northern cities are more sensitive to high temperatures and southern cities are more sensitive to colder temperatures. Landsberg (1981) reported on a 1966 case study from New York City that clearly shows the high-temperature mortality threshold (see Fig. 1) and the time lag between high temperature and excess deaths. Studies like these clearly demonstrate the importance of accurately forecasting both maximum urban temperatures and their duration. As mesoscale model resolution increases, it will be increasingly important to properly represent urban influences on the radiation budget, surface moisture, sensible heat exchange processes, and anthropogenic heat and moisture fluxes. The latter have been estimated to range between 20 and 100 W m\(^{-2}\) on an annual average basis for typical U.S. cities to a maximum of 200 W m\(^{-2}\) in winter for Manhattan (Klysik 1996).

Urban zones—and particularly their transportation systems—are especially sensitive to conditions involving poor visibility and icing. A variety of visibility issues need consideration, ranging from coastal and ground fog, smog, and dust to local restrictions due to precipitation-induced road spray. Dense patches of fog may form overnight in low-lying areas on highways resulting in sudden losses of control and increased risks of collisions between motor vehicles and roadside structures. Similar localized conditions may arise during the winter months when warm, moist air moves over existing snow cover. Many urban zones are also located in coastal areas, where onshore winds may occasionally produce very dense fog patches over coastal roadways, lowering visibility to near zero in many cases.

Icing conditions are another navigational challenge to residents of urban zones. Local transportation infrastructures contain numerous bridges and ramps that connect and provide access to principal arterials. Surface temperatures on these structures cool more rapidly than the surrounding roadbeds, often producing hazardous local icing conditions and resultant property damage. All modes of transportation are affected. Overhead catenary cables may freeze on transit systems, ferryboats may have to suspend operations as conditions deteriorate, and airports may curtail or shut down operations altogether. In the case of airports, a ripple effect may occur throughout the United States if the affected facility is an important transportation hub.

Other wintertime, ground-based icing phenomena of concern include freezing rain, so-called black ice, and light precipitation present in a rapidly moving cold front that quickly freezes and glazes roads as temperatures fall sharply over a short period of time. In northernmost coastal cities, other short-lived phenomena such as arctic sea smoke and freezing sea spray from high winds may also impair parts of the transportation system.

c. Approach

PDT-10 approached the urban forecast problem and the identification of research needs from three perspectives: 1) the needs of the user communities; 2) science-based forecast issues; and 3) the tools—models and observations—needed to facilitate the scientific research and meet the more practical needs of urban users. The approach followed in this paper more or less parallels that of the workshop. First, user needs are introduced in section 2 according to various aspects of the urban management problem. These components include forecast products and information dissemination systems that are needed, the role of environmental measurement systems and computation and telecommunications systems, and the range of impacted public utilities and services. Next, sections 3 and 4 discuss phenomenological and crosscutting issues that are important to understanding and forecasting weather in the urban zone. The phenomenological issues include winter storms, convection, air quality, and other weather features specific to cities. Two crosscutting issues were identified: the treatment of uncertainty, and issues pertaining to urban hydrology.

![Fig. 1. Weekly death rates and weekly mean temperatures in New York City during the summer of 1966. The hatched band represents the 95th percentile confidence limits of expected death rates. (source: Landsberg 1981).](image-url)
Finally, section 5 summarizes the recommendations of the team according to three categories: user-driven recommendations, science-driven recommendations, and recommendations for research that are derived from both user and science considerations.

2. User needs

Forecast needs within urban zones relate strongly to the problem of urban management and can be examined from this perspective in terms of three broad and overlapping categories:

1) public works and utilities, for example, impacts on airports, shipping ports, water-treatment facilities, streets, electric utilities;
2) public health and impacts from conditions of high thermal stress, wind chill, and poor air quality; and
3) public safety, related to heavy precipitation, poor visibility, lightning, high winds, and temperature extremes.

Although weather obviously impacts each of these categories directly, its effect on item 1 also has a potentially strong, indirect influence on the remaining two. Several general user needs become immediately apparent when viewed in this context; these needs include the following:

1) accurate nowcasting of local weather phenomena (urban flow patterns, heavy precipitation distributions, tornadoes, etc.) for use in immediate response strategies against threats of extreme pollution episodes, flooding, tornadoes, terrorism;
2) accurate forecasting of local extreme weather events, for use in risk-based decision analyses regarding electric power distribution, warnings of aviation hazards, impacts on surface transportation, flooding, public health alerts;
3) accurate forecasting of urban air quality, for use in flexible pollution management strategies and for establishing public health alerts;
4) rapid, reliable, and effective information dissemination systems, including systems for retrieving measurement, forecast and nowcast information by urban command and decision centers, as well as systems for disseminating information to the public and other members of the end-user community;
5) accurate climatological information, especially on flooding and runoff, for use in designing flood and water treatment facilities, and for associated operational strategies; and
6) modern and effective decision and implementation strategies in urban command centers, which maximize the use of new and developing tools in items 1 through 5 above.

Several points associated with this list deserve specific recognition. First, effective and practical urban decision strategies must consider all salient elements of risk, and consequently they must be based on realistic, quantitative measures of forecast and nowcast uncertainty. Estimates of these uncertainties by model developers and practitioners are thus essential elements of this process.

As a second point, needs expressed in items 1–4 must be recognized to involve both measurement and computational systems and modeling systems, and basically reflect a threefold need.

- Urban decision centers and their industrial counterparts need to take full advantage of the meteorological measurement systems and model products that have emerged during the past several years, from activities such as the NWS modernization effort. In many instances this will involve substantial investment in local staff training, strategy development, and information facilities.
- Leaders within urban communities need to assess and respond to unmet community needs pertaining to observational and modeling resources that exist within current technology.
- Scientists and community leaders need to jointly establish those key needs not met by existing technology and develop a science-based strategy to bring these technologies into practice.

Finally, it is important to recognize that each of the “city management” needs and issues intersects a wide variety of end products and services, including energy production, load-shifting, and distribution; aviation, marine, and surface (land) transportation systems, and their associated commercial distribution of products and services; telecommunications and information dissemination, including broadcast meteorology; air quality management; water management, including water quality, waste treatment, and runoff/flooding control; emergency response to off-normal events, such as fires, explosions, and terrorism; and human health.

These functions involve activities that range from crisis management (e.g., toxic releases from an indus-
trial explosion) to routine efficiency optimization. As a routine example, it is widely recognized that efficiency and reliability of electrical power generation—and associated savings to urban consumers—can be greatly enhanced by dependable and accurate weather forecasts, simply on a load-shifting and network-distribution basis. Subsequent sections of this paper investigate specific aspects of these items in further detail.

3. Phenomenological issues

a. Introduction

The several examples of urban weather phenomena given in this section were discussed by PDT-10, and are intended to illustrate the importance of weather and forecasting to urban planning and management, to indicate present capabilities, and to identify imperatives for additional progress as well as for current implementation. Considerable overlap exists between these issues, both on a scientific basis and because each impacts several common features of urban planning. This material is organized to describe the nature of each issue, including its urban impact, along with benefits of forecasting and/or nowcasting from an urban management standpoint. These individual discussions examine prospects for future improvements in associated forecasting systems, including numerical models and their bases of measurement support.

b. Winter storms

The impact on urban areas of winter storms ranges from merely inconvenient to disastrous. Heavy snow and/or ice accumulation can completely disrupt an urban region for days (see Kocin and Uccellini 1990). The urban region’s surface and air transportation sectors are particularly sensitive to the effects of high winds and snow- and ice-covered road and rail networks and airport runways. As urban regions grow, an ever-increasing number of commuters travel to and within urban regions (Fig. 2). Urban transportation disruptions are becoming more commonplace even with relatively light accumulations of snow or ice. Snowfall amounts of as little as a few centimeters, if left untreated on bridges and roadways, can result in numerous traffic accidents, which effectively disrupt overcrowded urban commuter routes. Even more insidious are the effects of freezing rain and drizzle, whose slick and icy glaze on roadways and sidewalks causes perils for motorists and pedestrians alike. Winter ice storms due to heavy freezing rain can also severely disrupt an urban region’s utility infrastructure. Similarly, snow and freezing precipitation can slow or suspend airline operations locally and can also have a major impact on air travel. Finally, a winter storm’s impact on urban economies can be staggering. For instance, the U.S. Office of Personnel Management estimated that closing all federal government offices in the greater Washington, D.C., metropolitan area in response to the winter snowstorm of 25 January 2000 cost $60 million per day in lost productivity and wages.

Prediction of wintertime weather involves meteorological phenomena that occur over a wide variety of spatial and temporal scales. Extratropical cyclones, common in winter, occur on the synoptic scale (horizontal scale of 2000+ km and timescales of 12–72 h) and can traverse the nation from the Pacific coast to the Atlantic seaboard, affecting numerous states with accumulations of snow and ice. Within these cyclones, smaller-scale (or mesoscale: 2–200 km, 0–12 h) atmospheric features determine the location, timing, and intensity of snow and ice as well as extreme temperatures and wind chill. There is variability in both spa-
tial and temporal patterns of wintertime precipitation due to mesoscale-storm features, particularly the presence of banded precipitation structures.

Synoptic-scale forecasts of winter weather have generally improved over the last 10–15 yr, with the most impressive factor being the lead time that has increased from about 6.2 h in the 1984/85 winter to 10.6 h for the 1998/99 winter season. However, forecasts of critically important mesoscale details (mainly banded precipitation structures) are still inadequate. Near the Great Lakes and in areas located close to large water bodies (e.g., the Great Salt Lake), urban regions are susceptible to the vagaries associated with lake-effect or lake-influenced snowbands (Niziol et al. 1995). These bands can be quite narrow (< 10 km) but long in horizontal extent (50–200 km). Lake-effect snowbands can produce prodigious snowfall amounts over both short (hours) and long (days) timescales. Amounts of as much as 200 cm concentrated over narrow areas have occurred in several multiday snow events in urban areas located near the Great Lakes. While forecasters provide excellent lead time and notice of most significant lake-effect snow events affecting urban regions, forecasters still cannot provide precise forecasts of the location and timing of individual snowbands more than 2–3 h from onset of the snowband.

Other wintertime atmospheric regimes modulate the amounts and kinds of winter precipitation. For example, along the eastern U.S. seaboard, the presence of a mesoscale coastal front (see Bosart 1981) not only influences the rapid intensification of cyclones, but determines the location, timing, and type of precipitation that affects many large urban centers along the east coast. Other geographic factors also modulate the pattern, intensity, and type of wintertime precipitation. Promixity to a large body of water can make the difference between liquid and frozen precipitation. Urban areas located close to high relief terrain (e.g., Denver, Colorado, situated in the lee of the Rocky Mountains) can experience enhanced snowfall effects owing to the nearby mountains. These storms are characterized by intense leeward snowbands oriented parallel to the

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1Quantitative precipitation forecasting was the subject of PDT-8, which was summarized by Fritsch et al. (1998).
2Data for the 1984/85 winter are for the United States for a nationwide subset of small areas (zones), whereas data for the 1998/99 winter season include the entire contiguous U.S. area and Alaska. Probability of detection for both 1984/85 and 1998/99 winter storms remained about the same at 0.85 (P. Polger, NWS, Silver Spring, MD, 1999, personal communication).

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Most major winter storms are usually well forecast and well publicized. However, even a seemingly benign wintertime cold front can pose substantial risks to an urban region. As an example, on the evening of 25 December 1993, a fast-moving arctic cold front raced east from the Ohio Valley and crossed the mid-Atlantic region. Prior to passage of the arctic front, surface temperatures ranged between 2° and 4°C, but quickly fell below freezing to between −5° and −9°C in less than 1 h after frontal passage. Forecasters had predicted a brief period of snow showers or flurries to accompany frontal passage, with little or no snow accumulation for the urban region anticipated. As it turned out, a narrow line (10–20 km wide) of snow showers did accompany the arctic front. Snow fell for 15–30 min over the Washington, D.C., metropolitan area with < 5 mm liquid equivalent. As snow began falling, air and road surface temperatures were above freezing, and the snow melted on contact with roads. As temperatures quickly fell below freezing behind the front (which was accompanied by gusty northwest winds of 10–15 m s⁻¹), water from the melted snow froze on roadways and created a dangerous black-ice condition. Only a minimal number of road treatment crews were on duty that night owing both to the holiday and a forecast of little snow accumulation. Travel on these ice-covered roads quickly became hazardous with many holiday travelers involved in accidents or abandoning their vehicles. The forecast of snow showers was essentially correct, but the negative impact on road travel was not anticipated. While liquid precipitation amounts for this event were low, the rapid drop to subfreezing temperatures with no appreciable drying of roadways created very hazardous road conditions, which were not well anticipated by forecasters or road crews.

While there has been a noticeable trend toward improved lead times in wintertime precipitation forecasts, there are still cases where forecasts miss their mark. In one such case, a narrow but heavy snowband occurred on 9 March 1999 that significantly impacted portions of the Washington, D.C., metropolitan region. Snowfall amounts of up to 25 cm in less than 6 h fell in a very narrow band (< 20 km wide; see Fig. 3). Forecasters had predicted 12-h total snow amounts of only 5–10 cm. The narrow scale of this band is not resolvable by currently available operational NWP guidance, making forecasting details on its occurrence (in both timing and location) extremely difficult.
A common feature exhibited during many wintertime precipitation events is for the precipitation to fall from banded structures (i.e., structures having a length axis many times greater than the width axis). Figure 4 shows an NWS-1988 Doppler (WSR-88D) Weather Surveillance Radar reflectivity image of a snow event impacting two major urban areas (Washington, D.C., and Baltimore, Maryland). Evident in Fig. 4 is the placement and orientation of several roughly east-west (E–W) bands of precipitation. For this event, as discussed in Weismuller and Zubrick (1998), local forecasters anticipated the possibility of heavy snowbands on 26 February 1993 due to conditional symmetric instability and frontogenesis, and had included this thinking in local forecast products. However, it was impractical to accurately and with certainty predict the exact timing and location of each band that formed more than 1–2 h from the onset of band formation. Such a precise forecast would have strained the credible use of observational data as well as current model guidance whose coarse model grid resolution and physics are incapable of delineating such finescale bands. For this event, one band formed well to the north of the Washington, D.C., urban region; another formed to the south. Snowfall totals in the Washington, D.C., urban region were relatively small (less than 8 cm) compared to amounts (20–30 cm) falling within the northern band located over central Maryland. Consequently, urban transportation disruptions were minor in Washington, D.C., owing to the rather fortuitous location of the heaviest snowbands.

The basic prediction of such bands has been particularly vexing, owing to the interplay of processes occurring on multiple scales (from synoptic to mesoscale to cloud scale). Many of the known smaller-scale processes (mesoscale and cloud scale) have not been adequately characterized even with present-day observing systems. Given that there is now an adequate sample of archived WSR-88D radar data, along with other data sources (surface, satellite, upper air) for many wintertime banded precipitation events, it may be possible to conduct retrospective high-resolution numerical model experiments to better understand and characterize prediction of banded mesoscale precipitation structures. Microphysical processes (which are not routinely measured) can also factor into organizing precipitation bands (Houze and Hobbs 1982).

In view of the above considerations, there is a strong need for application of high-resolution mesoscale numerical weather prediction models (resolution of 1–5 km). To accomplish this, research is required both to better understand the underlying physics and to characterize predictability issues related to forecasting mesoscale wintertime banded precipitation structures within a 1–6-h timescale, and a 5–200-km space scale. For example, on the microphysical scale within a cloud, what are the amount, type, and distribution of ice crystals and liquid and supercooled water droplets, ice particle concentrations, and so forth in the precipitating clouds? On the mesoscale, what type of mass field adjustments are required to create zones favorable for bands to maintain and develop precipitation over the course of several hours? Also, implementation of parameterization schemes for slantwise convection or "moist symmetric instability" (MSI), often associated with banded precipitating structures, might provide better model simulations of precipitation. Research by Lindstrom and Nordeng (1992) showed improvements in model simulation of the
quantity and areal extent of precipitation associated with a midwest U.S. cyclone; see Shultz and Schumacher (1999) for a recent review of MSI applied to forecasting.

Some associated issues and needs include the following:

1) refinement of radar precipitation estimates in wintertime precipitation regimes;
2) improvement of prediction of the location of mixed water–ice-phase precipitation on timescales of 1–6 h and space scales of less than 10 km;
3) improvement of quantitative and area forecasts of frozen/freezing precipitation amounts on scales of 1–12 h and less than 10 km;
4) differentiation and characterization of precipitation structures conducive to supporting convective snowfall events (which typically result in heavy snowfall rates);
5) exploration of the value—relative to characterizing banded precipitation prediction—of using ground-based Global Positioning Satellite (GPS) derived estimates of integrated precipitable water vapor and refractive index profiles at scales of 0–3 h and 0–100 km; and
6) full exploration and exploitation of the use of aircraft-based in situ measurements of temperatures, winds, and (future) moisture afforded through the Aerodynamic Communication Recording System (ACARS) program of commercial aircraft measurements.

One thrust of this activity is to characterize potential limits in the predictability of wintertime precipitation structures. Given the current state of observing systems and numerical models, there is the need to isolate the practical limit to predictability of temporal and spatial scales of banded precipitation structures. Further, some models may currently be constrained by immense computing requirements that make getting the model output into the hands of forecasters impractical. Whatever the case, an adequate characterization of the prediction of wintertime precipitation can lead the way to future research opportunities in producing better forecasts of all wintertime precipitation regimes affecting the urban region. Improved NWP guidance employing higher-resolution models along with improved data assimilation techniques may one day provide accurate forecasts of individual banded precipitation structures as observed in Figs. 3 and 4.

c. Convective storms

Severe convective storms can produce tornadoes, strong winds, hail, flooding, and lighting, all of which have profound effects on the environment, and especially the urban environment. The urban zone is especially susceptible to landfalling hurricanes because of the large numbers of people at risk, the high density of manmade structures, and the increased risk of flooding and contamination of potable water supplies. PDT-10 did not focus on the special issues pertaining to hurricane impacts, as these were the focus of PDT-3 (Rotunno et al. 1996) and PDT-5 (Marks et al. 1996). Similarly, the team did not address tornado impacts in urban areas. However, recent tornadoes have caused significant harm and destruction in urban areas. A category F2 tornado touched down during the middle of the day on 12 August 1999, in downtown Salt Lake City (see Fig. 5). The tornado killed one person, sent 49 to the hospital, and caused

![Fig. 4](image-url). Composite reflectivity from the Sterling NWS WSR-88D radar (KLWX), valid 1406 UTC 26 Feb 1993.
results, routine numerical forecasts of thunderstorms cannot be expected for a number of years. As a consequence, typical “definitive” forecast lead times are quite short and depend on the specific phenomena of interest. Strong tornadoes are usually predictable with lead times of about 30 min or less (currently, many F0–F1 tornadoes are predicted with only 0–15-min lead times or are missed completely). Severe convective wind events not associated with tornadoes (usually occurring on scales of 50–500 km²) are typically predictable with lead times of 15–30 min—with extremes of 45 min for bow-echo events—to less than 5 min for microburst events. Most severe hail events on scales of 10–100 km² are predictable with 10–30-min lead times, and essentially no advance prediction is currently possible for lightning.

Convection can have a large influence on air traffic management, and there is a cascade of impacts at airports in the urban zone, especially for hub operations. Forecasts of severe convection out to 6 h in advance are now being made in a pilot study, the Collaborative Convective Forecast Product (see Fahey et al. 1999). The forecast is input into a daily decision process that is shared by participants in the federal government and the air transport industry. Forecasts of convection at these timescales rely heavily on accurate observations and on increasing skill of mesoscale numerical model simulations.

Accurate flash flood warnings require forecasts of spatial extent, intensity, duration, and location of convective events relative to river basins, a particularly difficult task given the fact that local terrain forcing and complex low-level boundary interactions often force the storm dynamics in complex ways. In addition, flooding conditions—and their forecast—depend on basin-accumulated rainfall prior to the convective event. A program called the Areal Mean Basin Estimated Rainfall (Davis 1993; Johnson et al. 1999) is being tested as part of the System for Convection Analysis and Nowcasting (SCAN; Smith et al. 1998) program at the Sterling, Virginia, NWS Forecast Office (WSFO). The prototype system provides graphic information on the rainfall accumulation in various basins. Forecast feedback indicates that the system has proven quite useful in helping to determine the location and timing of weather events that require the issuance of flash flood warnings. In another program involving the University of Virginia, the Pittsburgh WSFO, and the Wilmington, Ohio, River Forecast Center, probabilistic forecasts of river stages are being produced for lead times up to 3 days from routine op-

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3 Property Claim Services, Insurance Services Office, 7 World Trade Center, New York, NY 10048-1199.
eral NWS models and data. This probabilistic forecast system (Krzysztofowicz 1998) embodies both probabilistic quantitative precipitation forecasts and probabilistic river stage forecasts. Clearly, anthropogenic features can have a significant impact on river stages and flooding potential in urban areas.

As noted above, more extended forecasts of convective phenomena are more probabilistic in nature. For the 12–24-h forecast period, quantitative precipitation forecasting has shown a steady increase in skill over the past 30 years. Current numerical model threat scores for 24-h forecasts of 1 in. of rainfall are about 0.20–0.25 (Fritsch et al. 1998). Threat scores should continue to increase with improved observations, models, and analysis methods, but only up to the limit of predictability.

In addition to the observational and conventional modeling techniques noted above, rule-based “expert” forecast systems are becoming increasingly prevalent. Such systems use either automated or manual techniques to integrate current observations from a variety of sensors to produce detailed maps showing the location and characteristics of thunderstorms, clouds, winds, and thermodynamic fields that are then combined into a conceptual model-based forecast. One expert system, the National Center for Atmospheric Research (NCAR) Thunderstorm Nowcast System (also referred to as Auto-nowcaster), was deployed at the Sterling WFO as part of the SCAN program and at the White Sands Missile Range (Mueller et al. 1997; Roberts et al. 1999). It will also be used as part of the Sydney 2000 Olympics forecast demonstration project. The Auto-nowcaster uses data from WSR-88D radar, satellite, mesonet, and soundings. The system is composed of several feature-detection algorithms including Thunderstorm Identification Tracking, Analysis and Nowcasting, Surface Convergence Line Detection and Extrapolation, Tracking Clear-Air Radar Echoes by Correlation, and an objective analysis scheme. The system now also routinely uses an adjoint mesoscale model to assimilate disparate wind data in order to produce boundary layer wind and divergence fields for use in rule-based nowcasting. The different feature detectors are coordinated and combined using a fuzzy logic approach.

As a consequence of the above considerations, research, development, and operational implementation (particularly in NWS WFOs that support urban areas) of short-term (0–2 h) time- and space-specific thunderstorm forecast systems should be encouraged. The areas of work include (a) high-resolution depiction and forecasts of boundary layer winds, stability, and lines of convergence; (b) integration of satellite, mesonet, radar, and other datasets, together with algorithms and numerical model outputs into forecast systems that operate either interactively or automatically to forecast thunderstorm evolution; and (c) explicit modeling of convection. Partnerships between the research, operational forecast, and user communities must be established to quickly implement and make best use of short-term thunderstorm forecast tools. Additional emphasis should be given to operational implementation of new techniques.

d. Air quality and toxic releases

The close relationship between meteorological conditions and air quality has long been recognized but in many instances interest has focused more on the analysis and understanding of severe pollution events rather than on forecasts of impending ones. Alternatively, climatological characteristics of an area have been used to help specify the input drivers for air quality models used by local or state agencies in formulating mitigation strategies for air quality problems or in planning for future development in urban areas. With the advent of improved forecasting tools and continued advances in computational resources, opportunities now exist to address two important air pollution forecasting needs in urban areas.

1) Mesoscale forecasting/nowcasting for emergency response applications

The juxtaposition of industrial, manufacturing, and transportation facilities in areas of high population density creates a situation with potentially severe consequences in the event of a major accident. In the event that a toxic spill or other release of hazardous materials to the atmosphere occurs, emergency response teams often must rapidly predict the likely path of the released material in the hours immediately following the release. For such purposes the first priority is to obtain accurate wind field, mixed layer, and stability characterizations, and to apply these for plume rise and pollution transport estimates. These actions are most useful when they can be implemented and updated quickly, with response times of 15 min or less.
Estimates of the extent of the vertical and horizontal dispersion are useful for refined pollution transport estimates, but are of somewhat lesser importance in short-term emergencies.

Such needs are being addressed to widely varying degrees in various cities, but it is now possible to make substantial improvements in this critical area through the use of real-time monitoring and reporting systems that are coupled with nested, high-resolution meteorological and chemical transport models. Such models, with resolutions of 1 km or even less in the innermost grid, are capable of continuous operation for urban areas.

Constrained by data from the fast response measurement networks, modern mesoscale meteorological models are rapidly becoming a practical means for reliable forecasting/nowcasting of local transport phenomena. It should be noted, however, that urban features such as street canyons and energy-balance partitioning continue to pose significant challenges to model-based characterization, and development continues to progress. The French communal urban model SUBMESO (Mestayer 1996), for example, has been developed to bridge the gap between conventional planetary boundary layer models and urban street canyon environments, and possible linkage mechanisms between these model subclasses are discussed in Mestayer and Bornstein (1998, unpublished manuscript). The simplest linkages include parameterizations of urban canopy layers using observations, physical models, and/or numerical models applied over various urban–rural land-use mixes. Parameterizations could be based on building length-to-height ratios, building-length-to-street-width ratios, building roof angles, effective urban roughness lengths, and effective urban displacement heights. An example of this approach is the Bottema (1997) model of urban roughness length and displacement height as functions of building heights and arrangement. Another approach is the use of the objective hysteresis model of Grimmond et al. (1991) by Taha (1999) to estimate urban storage terms in an urbanized version of the Colorado State University Mesoscale Model. In this context it is important to recognize that improved observational systems, including well-sited and dense wind measurement networks, can provide an important source of improvement in this area. Design of coupled modeling–monitoring systems of this type should be included as an important component of modern urban planning and urban design.

2) IMPROVED FORECASTING FOR AIR QUALITY USERS

In the past, some efforts have been made to forecast extreme pollution episodes in urban and regional areas so that preventive measures (e.g., traffic or industrial restrictions) can be taken to minimize potentially hazardous conditions. As better forecasting tools become available and as the ability to model both atmospheric chemistry and dynamics improves, episodic forecasting will become more practical and desirable for both economic and health reasons. A likely attendant benefit of developing better forecasting tools for air quality predictions is the improved ability to carry out longer-term planning for air quality management and control. The PDT-10 recognizes the potential for significant advances and benefits in these areas but unfortunately had no direct input from the most likely users of improved forecasting capabilities.

Within this context, efforts should be made to begin a broad discussion with individuals and groups responsible for air quality management in urban areas to describe what new forecasting products relevant to air quality may be desirable and useful in the coming years, determine which of these products are likely to be most critical, determine what scientific issues will need to be addressed to provide the necessary information, and discuss methods by which that information can be made available to the users. It is further recommended that the USWRP sponsor a workshop to be held in the next 12–18 months to facilitate this process.

4. Crosscutting issues

a. Hydrometeorology, and surface- and groundwater hydrology

As noted in section 3, high runoffs resulting from rapid snowmelts and heavy precipitation events periodically impact a variety of U.S. urban areas. Under such circumstances runoff often exceeds capacity of urban storm water systems, resulting in flooding and—for those municipalities with combined storm water and sewage treatment systems—overburdening of treatment facilities, leading to degraded surface, ground, and domestic water quality. Because substantial portions of urban surfaces are paved, the “dampening” effect of the catchment system is limited, and the surface hydrology responds very quickly (on the order of minutes to a few hours) to rainfall intensity and snowmelt rate. Moreover, the spatially and temporally variable nature of typical convective storms
results in locally transient forcing of the impacted hydrological systems, necessitating real-time hydrometeorological information on a spatially resolved basis.

Meteorological information can be applied directly for both storm system design and for preventative action in a variety of ways and, thus, is of particular interest from an urban runoff standpoint. First, local storm climatology, if characterized in a statistically meaningful fashion, can be applied to high advantage for design of urban storm sewers and other runoff control facilities. Second, short-term storm forecasting provides operators of such facilities beneficial lead time to make general adjustments in runoff-control systems to minimize potential impacts. Finally, fast response and spatially resolved observational data (e.g., weather radar, reporting rain-gauge networks), possibly combined with short-turnaround storm and hydrology model systems, can provide a “nowcasting” capability that is potentially of high utility. Given such fast response and spatially resolved information, public works operators can alleviate, or at least reduce such problems by controlling system flow structures such as gates, pumps, and intakes. Moreover, urban planners can use predictions from such systems, in addition to climatological information, to large advantage in designing runoff-control systems; indeed, several modern systems include various nowcasting elements as integral components of their basic design.

Incorporating predictive uncertainty into response strategies is also an important feature of modern urban response planning. City managers and emergency response operators often make decisions under conditions of substantial uncertainty in their efforts to maximize public safety subject to resource-availability constraints. Attempts to quantify uncertainties associated with hydrometeorology and runoff forecasting have been shown to improve decisions in this area. Accordingly, research is needed to develop error estimation and propagation techniques and to validate them. Errors associated with precipitation forecasts propagate through the models used to forecast flows. Due to the nonlinear nature of these models, there may be error cancellation or error amplification effects, and these need to be recognized.

Quantification of errors associated with both observations and models facilitates improved assimilation of the data. Thus, although the rainfall forecasting requirements are rather demanding for urban applications (in terms of accuracy and resolution), the fact that the flows are easily and accurately observable presents an opportunity to provide feedback to the rainfall prediction models. This, in turn, results in better forecasts for the next time horizon.

As a consequence of the above discussion, it is important that improved precipitation observing and estimation systems be developed to satisfy urban hydrology needs for high temporal and spatial resolution data, meeting sufficient accuracy requirements. In addition, uncertainty quantification models and methods for rainfall and urban runoff and flow should be developed, especially in the coupled hydrometeorological framework.

b. Urban weather modification

Modification of weather and local climate by urban environments is an important crosscutting issue, especially because such phenomena may serve to accentuate temperature extremes, precipitation, and other weather features discussed above. Such perturbations include the following:

- alteration of the atmospheric energy balance, by changes in surface albedo and energy storage capacity, changes in surface moisture fluxes and moisture storage capacity, changes in atmospheric optical properties by addition of pollutants, and anthropogenic heat flux from internal and external combustion sources;
- alteration of the atmospheric momentum balance by changes in the surface roughness, channeling effects of street canyons and other structures, and barrier effects of tall building complexes;
- alteration of visibility and actinic flux through modification of pollution and moisture fields; and
- alteration of precipitation and other storm processes through combinations of the above phenomena, combined with microphysical interactions with urban pollutants.

Alteration of the atmospheric momentum and energy balances are well known to cause significant perturbations to local temperatures and to the structure of the planetary boundary layer, and can be complicated and accentuated appreciably when they occur in conjunction with other mesoscale phenomena, such as land-breeze and sea-breeze circulations. These factors sometimes result in appreciable collateral effects involving changes in visibility and precipitation. The latter is particularly important from a transportation standpoint, inasmuch as urban-induced fogging and aerosol-induced visibility changes have obvious deleterious impacts on airport closures and other visibil-
ity-related issues. Moreover, actinic flux alterations associated with aerosols and clouds have been demonstrated to affect urban photochemistry in an appreciable manner.

There have also been indications from several observational studies that major urban areas may have an appreciable effect on meso-γ-scale weather features and patterns under certain synoptic regimes. Surface wind velocity observations appear to indicate that New York City (NYC) retards the speed of movement of both synoptic cold fronts (Loose and Bornstein 1977) and sea-breeze fronts (Bornstein and Thompson 1981). The authors hypothesize the cause of this retardation is the increased urban surface friction. In another study (Gaffen and Bornstein 1988) of PBL winds, temperatures, moisture, and sulfur dioxide concentrations during cold frontal passages, a pocket of prefrontal air (to a depth of 250 m) remained over NYC after frontal passage. The authors suggest that the urban buildings cause a barrier effect, resulting in bifurcation of the synoptic flow around the city.

Various observational case and climatological studies have shown that urban areas may influence the formation and movement of convective storms. Recent analyses of observed summer convective thunderstorms over NYC (Bornstein and LeRoy 1990), Phoenix (N. Selover 1997, personal communication), and Atlanta (Bornstein and Lin 1999) have led to a possible “dual effect” physical hypothesis that 1) building-induced flow bifurcation around a city lowers the frequency of moving storms that pass directly over an urban area, and 2) urban heat island-induced convergence initiates new storms over urban areas in otherwise clear, calm conditions. While these studies appear to support the dual-effect hypothesis, the results cannot be considered definitive at this time and more research is needed. In addition to more complete observational studies, mesoscale model sensitivity studies are also needed to aid in isolating the relative effects of urban and topographic forcing.

c. Forecast uncertainty

Because of inherent limits of the predictability of the atmosphere, it is important that weather forecasts also be accompanied with an estimate of forecast uncertainty. At the present time, this is rarely done and hence this PDT recommends supporting research into methods to quantify uncertainty in weather and air quality forecasts.

The weather phenomena that can impact urban areas have a broad range of predictability limits. For example, extreme heat waves can sometimes be predicted out to around a week, winter storms on the east coast of the United States around 3–6 days and 1–3 days on the west coast, and extreme pollution events around 1 day. On the other hand, the predictive skill associated with most convective storms essentially goes to zero in a few hours. Hence it is important to further quantify the predictability limits of the various phenomena that impact urban areas, and to convey that knowledge to urban managers and decision makers.

One promising technique for quantifying forecast uncertainty is ensemble forecasting. A number of operational centers are already producing ensemble forecasts on the global scale. Techniques to produce short-range ensemble forecasts are also under development (see Brooks et al. 1995). Ensemble forecasting could be particularly beneficial for the urban area since many of the atmospheric phenomena that directly affect these areas (such as banded structures in winter snow storms and summertime thunderstorms) may be higher nonlinear.

Methods also need to be developed to convey probabilistic and uncertainty information to the urban end user for the most effective utilization. At present, forecast uncertainty is only used by a small proportion of urban end users and hence there is a large scope for advancement in this area. Probabilistic forecasting (e.g., by ensemble methods) can provide a wealth of information; however, it can easily be overwhelming to the end user. Research is required to determine the degree of customizing that is required for individual users. It is also suggested that steps should be made to communicate with urban end users on how to most effectively create and use information about forecast uncertainty. The average skill of single numerical forecasts has increased steadily over the last two decades. The quantification and effective use of forecast uncertainty may accelerate this significant progress.

In view of the above discussion, PDT-10 considers it essential that research be supported into 1) methods to quantify the uncertainty in forecasts of weather that impact urban zones and 2) methods to convey information about forecast uncertainty to urban managers and decision makers for its most effective utilization.

5. Recommendations

Forecast issues in the urban zone are dictated by the specialized and pressing needs of a plethora of intermediate and end users. These issues in turn present...
special challenges to the research community in general and the USWRP in particular. It is the consensus of PDT-10 that urban zone issues should be a principal focus of the USWRP. In particular, the team believes that human life and well-being in urban areas could be protected and enjoyed to a significantly greater degree than at present if there were 1) improved access to real-time weather information, 2) improved tailoring of weather data to the specific needs of individual users groups, and 3) more user-specific forecasts of weather and air quality.

The individual recommendations can be summarized according to nine themes: 1) development of a user-oriented weather database; 2) focused research on the impacts of visibility and icing on transportation; 3) improved understanding and forecasting of winter storms; 4) improved understanding and forecasting of convective storms; 5) improved forecasting of intense/severe lightning; 6) further research into the impacts of large urban areas on the location and intensity of urban convection; 7) focused research on the application of mesoscale forecasting in support of emergency response and air quality; 8) quantification and reduction of uncertainty in hydrological, meteorological, and air quality modeling; and 9) the need for improved observing systems.

These recommendations evolved from the needs of various sectors of the user community and also the scientific research and operations communities. The following discussion parallels the origins of the recommendations and is organized according to recommendations of the user community, the scientific community, and those that are common to both the user and scientific communities.

a. User recommendations

1) End users have a pressing need for what may best be called a dynamic users’ weather database that provides current and forecast weather and air quality information that is comprehensive, accurate, timely, and highly resolved in space and time. The data products should be synthesized to meet users’ specific needs; simply stated, the data need to be transformed into information that is understandable to the nonspecialist and is user friendly. The dynamic users’ weather database can be thought of as the atmospheric equivalent of “data warehouses” now becoming commonly used in conjunction with management information systems.

It is especially important to provide information on current and forecast weather to end users in a form and format that is tailored to their special needs. PDT-10 only scratched the surface in this regard. It is further recommended that a user workshop be convened to scope out the details of the weather products needed by the various sectors of the user community.

2) Detection, prediction, and warning of low-visibility and icing conditions are critical to the aviation and surface transportation communities, yet research results have not been widely implemented into operational practice. An extensive measurement program coupled with model simulations would aid further research in tropospheric icing. It is very important to tailor the forecast to the specific needs of the transportation user. Timely and user-friendly communication of weather data is critical. (Note that visibility impairment includes aerosols and hydrometeors, such as fog, heavy precipitation, smog, smoke, and dust.)

3) Users of lightning forecasts include both large “distributed” users (e.g., electric utilities) and individuals. The needs of each group are different but equally important. Users need forecasts on the 0–2-h timescale in urban areas of thunderstorms that have a high probability of “intense” electrical activity.

b. Science recommendations

1) WINTERTIME PHENOMENA AFFECTING URBAN NOWCASTING

There is a pressing need to characterize predictability issues related to forecasting mesoscale banded precipitation structures within a 1–6-h timescale and 5–150-km space scale using operational high-resolution mesoscale models (resolution 1–2 km). Such models need to assimilate state-of-the-art integrated data from disparate observing systems. Additional basic research is required to better understand basic atmospheric physical processes and cloud microphysics, and to adequately characterize banded precipitation structures. The following specific observational and forecast issues require improvement or further investigation and research:

(i) radar precipitation estimates in wintertime regimes;
(ii) location of mixed-phase precipitation (snow vs rain) on timescales of 1–6 h and space scales < 10 km;
(iii) quantitative forecasts of frozen/freezing precipitation amounts at scales < 10 km on the 1–12-h time frame;
(iv) the value of GPS-derived estimates of integrated precipitable water vapor and refractive index
profiles, particularly to short-range (0–3 h; 10–100 km) forecasts of wintertime phenomena; (v) characterization of precipitation structures conducive to supporting convective elements (that produce lightning and “thundersnow”); and (vi) the use of in situ measurements of temperatures, winds, and moisture available through the ACARS program of commercial aircraft measurements.

2) THUNDERSTORM FORECAST SYSTEMS

Additional emphasis is required for support of research, development, and operational implementation (particularly in NWS WFOs that support urban areas) of highly resolved (0–2 h and 1–2 km) thunderstorm-specific forecast systems.

Specific areas of research include (i) high-resolution depiction and forecast of boundary layer winds, stability, and lines of convergence; (ii) integration of datasets (e.g., satellite, mesonets, and radar), algorithms, and numerical model output into forecast systems that operate either interactively or automatically to forecast thunderstorm evolution; and (iii) explicit use of cloud-resolving models.

3) INADVERTENT URBAN CONVECTIVE-STORM MODIFICATION

Because of the significance of the implications on urban forecasting, PDT-10 recommends convening a workshop of research experts (modelers, forecasters, observationalists, and climatologists) to review previous studies, explore the merits of the hypothesis, and, if warranted, develop a research plan for further testing.

4) FORECAST UNCERTAINTY QUANTIFICATION

PDT-10 recommends additional research into methods to quantify the uncertainty in forecasts of weather that impacts urban zones, and convey information about forecast uncertainty to urban managers and decision makers for the most effective utilization. Ensemble forecasts may be particularly useful in the urban area since many of the atmospheric phenomena that directly affect these areas are highly nonlinear. Methods also need to be developed to convey probabilistic and uncertainty information to the urban end user for the most effective utilization. Steps should be taken to educate urban end users on how to most effectively use information about forecast uncertainty, and physical scientists need to be aware of the needs of the various user communities.

On a related theme, PDT-10 also recommends improving Model Output Statistics temperature forecasts for urban areas by increasing the spatial resolution and explicitly incorporating urban-specific attributes, such as land-use patterns, topography, building shadowing, and so forth. Beneficiaries would include the electric power industries and heat-sensitive individuals.

c. User and science recommendations

1) MESOSCALE FORECASTING FOR EMERGENCY RESPONSE APPLICATIONS

The team recognized the unmet needs of the emergency response community that is charged with providing timely high-resolution mesoscale analyses and forecasts in support of natural and anthropogenic emergencies. Accordingly, PDT-10 recommends development of a focused program to provide operational meso-β and -γ-scale forecasts of transport and mixing for emergency response operations in urban areas. The program should include demonstration projects for selected cities, with careful evaluation of the performance of the model, particularly under conditions of light synoptic forcing, stable stratification, and in areas affected by complex terrain. An essential element of such a program should be the joint participation of air quality and mesoscale research scientists together with public and private sector managers and decision makers.

2) FORECASTING IMPROVEMENTS FOR AIR QUALITY USERS

PDT-10 recommends that efforts be made to begin broadly based discussions and interactions with individuals and groups responsible for air quality management in urban areas in order to (i) describe what new forecasting products relevant to air quality may be desirable in the coming years, (ii) determine which of these products are likely to be most critical, (iii) determine what scientific issues will need to be addressed to provide the necessary information, and (iv) discuss methods by which that information can be made available to the users. It is further recommended that the US WRP sponsor a workshop to be held in the next 12–18 months to assist in initiating this process.

3) WEATHER AND URBAN HYDROLOGY

The impact of weather on urban hydrology presents important challenges to researchers and users alike through effects on runoff and sewage management. PDT-10 makes two broad recommendations relevant to urban hydrology: (i) develop improved rainfall observing and estimation systems to satisfy urban hydrol-
ology needs for highly accurate data with both high temporal and spatial resolution, and (ii) develop uncertainty quantification models and methods for rainfall and urban runoff and flow, especially in the coupled hydrometeorological framework.

In summary, the overarching recommendation of the members of Prospectus Development Team 10 is to make the various urban aspects of weather and forecasting, hydrology, and air quality a priority research theme of the United States Weather Research Program.

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References


With the development of meteorological science and the continual refinement of the technologies used in its practical application, the need to produce a new edition of the *International Meteorological Vocabulary* (IMV) became evident (the original edition was published in 1966). This volume is made up of a multilingual list of over 3500 terms arranged in English alphabetical order, accompanied by definitions in each of the languages (English, French, Russian, and Spanish) and an index for each language. This new edition has been augmented with numerous concepts relating to new meteorological knowledge, techniques, and concerns. It should help to standardize the terminology used in this field, facilitate communication between specialists speaking different languages, and aid translators in their work.

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