Chapter 5. Summaries of Discussions, Recommendations, and Requirements

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Introduction

The urban canopy (UC), the layer of the atmosphere between the ground and the top of the highest buildings, is the region where people live and human activities take place. Because of this importance (e.g., human health, preservation of buildings) significant efforts have been dedicated to its investigation. Such studies shed light on the high complexity of atmospheric circulations in the UC, primarily because of the presence of obstacles (buildings) large enough to strongly modify air flow and the thermal exchanges between these surfaces and the atmosphere. This heterogeneity has been a challenge for atmospheric modeling in urban areas, particularly for mesoscale models with a typical resolution of the order of 1 km, which is greater than the scale of the perturbations induced by the obstacles. In the last decade, with the increase of computational processing unit (CPU) power, several mesoscale modeling systems, each with different urban canopy parameterization (UCP) schemes, have been developed and applied with the primary aim of representing the subgrid effects of urban surfaces on their mean variables.

5.1 "Fitness-for-purpose" guidance

UCP schemes used in models may range from simple ones with a limited number of parameters, ranging from basic roughness and scale length for thermal or density stability to multi-parameter sets that include vertical profile descriptions of building and vegetation size and shapes. As their level of detail increases, the computational demands for running such models also increase. We note that there are no existing rules governing the appropriate levels of detail and specificity of UCPs that a model must have. However, it is of practical importance to achieve a balance between the level of detail and precision desired to describe the urban boundary layer with the computational costs and availability of commensurate descriptive data to run such models. This leads to a practical guideline that the choice of level of descriptive complexity of these UCPs be based both on "fitness- for-purpose" and the appropriate grid resolution of the requisite application. Here we list and highlight the requirements of five common applications.

(1) *Air quality exposure studies* to assess the impact of atmospheric pollutants on human health. Model concentration outputs are needed that accurately characterize pollution "hot spots" or gradients at a sufficiently fine grid resolution commensurate to the extent in which significant exposure impacts occur.

(2) *Urban climatology studies and development of strategies for mitigating the intensity of heat islands.* Information is needed to estimate human comfort and stress based on air temperature, relative humidity, and radiation. Model parameterization schemes need information about physical attributes of surfaces; building and vegetation, such as albedo, soil moisture, building material's thermal conductivity, and capacity; and anthropogenic sources of heating.

(3) *Emergency response and predicting site locations* where toxic gases were purposefully released. Improved methods and modeling of both urban-scale transport and building and street canyon resolved dispersion.
(4) *Advanced air quality and weather forecasting* to improve on the predicted future state of the atmosphere (clouds, rain, air temperature, winds, etc.) and to inform and provide guidance to the public on adverse air quality conditions.
(5) *Urban planning* to evaluate local climate and air quality impacts caused by urban developments and three-dimensional (3D) urban morphological structures.

Air quality, urban climatology, emergency response, and urban planning models need detailed resolution of UC features, whereas weather and air quality forecasts are more focused on estimating the gross vertical exchange of heat, momentum, and pollution between the top of the canopy and the atmosphere. Case studies supporting air quality assessments, urban climatology, and urban planning studies are not relatively constrained with large CPU demands to achieve their target accuracy and precision estimates; whereas weather forecasting and emergency response model applications must, for practical reasons, scale down the details of their UC descriptions to achieve the required rapid output response times.

At some point, it will be necessary to perform evaluation of models based on their fitness for purpose. Depending on the type of application, the ranking (as proposed by Martilli) of atmospheric variables by their roles or importance may be useful for operational model evaluation purposes (see Table 5.1). This exercise is somewhat subjective as the atmospheric variables are interconnected in some way. For example, wind speed and direction is considered more important for air quality and dispersion applications than for urban climatology studies as those variables control pollutant transport. However, the role of wind is of indirect importance because it affects the magnitude of heat exchange between surfaces (walls, roofs, and streets) and the atmosphere, thus impacting urban microclimates.

Table 5.1: Ranking of importance of variables by (example) application

Application Versus Importance	Air Quality	Urban Climatology	Emergency Response	Weather Forecasting	Urban Planning
Wind Speed	Very important	Important	Very important	Important above the canopy	Very important
Wind Direction	Very important	Important	Very important	Important above the canopy	Very important
Temperature (and Humidity)	Important	Very, very important	Important	Very important (2-m temperature)	Very important
Pollutant Concentration	Very, very important		Very important		Very important
Turbulent Fluxes	Very important	Very important		Very important (at the top of the canopy)	Very important

Additional aspects are needed for a robust evaluation based on fitness of purpose concepts. For example, whereas pollutant concentration is a crucial variable for air quality studies, it will be important, in some applications, to focus on different statistical measures. For example, when considering averaging time, one should be clear whether the focus is on the averaging period, on the peak or the number of hours above a certain threshold, or on some other discriminator. Similarly, it would be useful to set objectives based on the degree of precision needed (e.g., Is it sufficient to have a modeled wind speed within 1 m s^{-1} of measurements for air quality simulations?). Thus, practical targets to be reached in terms of level of precision of outputs for the UCP implemented into models would be established for the models' intended use at the outset of the evaluation.

5.2 Strategy to urbanize different types of models

Current types of UC schemes available for model implementation in the context of their application requirements are reviewed in this section. Given different modeling objectives, there are several types of UC schemes and associated atmospheric models available. They can be separated into three primary categories:

(1) single-layer and slab/bulk-type UC schemes,
(2) multilayer UC schemes, and
(3) obstacle-resolved microscale models.

The first two categories are sufficiently simple (in their grid-averaged representation of urban morphological features as parameters) to be coupled into classical numerical atmospheric models. The third corresponds to computational fluid dynamic (CFD)-type explicit building-scale resolved models.

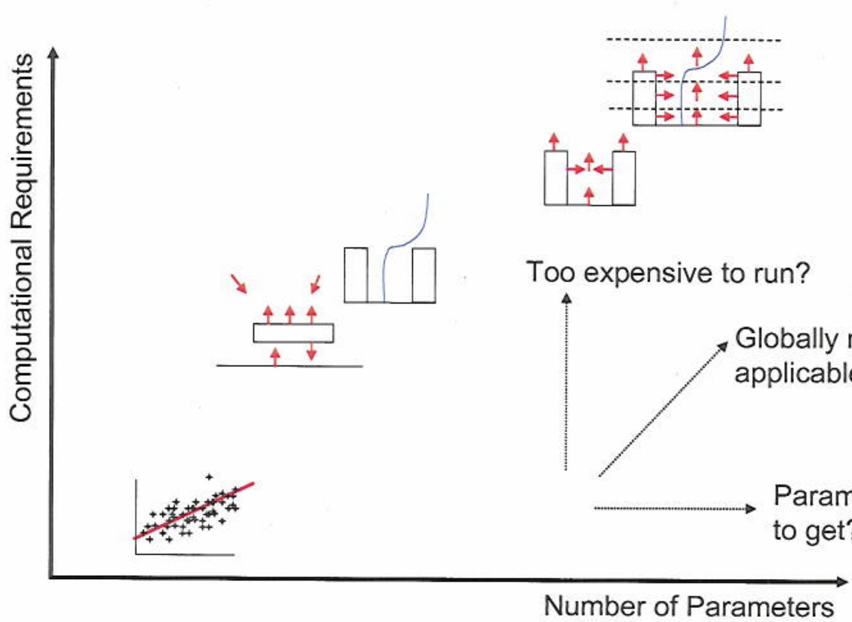

Figure 5.1: Schematic depicting computational requirement increases with the inclusion of increased levels of UCP sophistication in UC models (from workshop presentation by *Grimmond et al., 2008*).

The simplest approaches, which include the traditional Reynold's averaging scheme (using roughness [Z_0]) and displacement length), are single-layer schemes that link the UC effects to the atmospheric boundary layer through the model's lowest layer. In these methods, the urban scheme is implemented through parameterization of each grid's radiative and turbulent flux values. However, details regarding drag aspects typically are addressed with various ad hoc approaches. For example, simple analytical wind profile formulations for applications inside the canopy typically are introduced. Removing this limitation requires implementation of urban schemes with multi-layers in which the flux quantities interact with the atmospheric variable (*Martilli et al., 2002; Dupont et al., 2004*). This approach requires additional terms in the prognostic equations of the atmospheric models (e.g., drag term in momentum equations, heating term in temperature equations, production term in turbulent kinetic energy equations). Such models require the addition of layers from the surface to the top of the highest urban feature, thus representing the morphological features as functions of height for each grid. This allows the schemes to explicitly model the interactions between air and the urban structures (walls and roofs) at several heights. Thus, the in-canopy flows are simulated with greater precision than single-layer models. However, additional prognostic equations and vertical layers are required for this type of implementation. Consequently, whereas the effects of surface features are better represented, the computation burden is increased because of the increased integration time step and treatment of additional modeling details. This is a burden incompatible with current numerical weather prediction (NWP) models, thus currently limiting the use of multilayer canopy models in the forecasting mode. Clearly, as seen in Figure 5.1, care must be taken at the outset to understand and balance the need for greater precision obtainable with full canopy details and model turnaround time.

5.3 Overview of major applications

5.3.1 Numerical weather prediction and meso-meteorological models

The simplest approach for NWP or meso-meteorological models is to modify the existing non-urban approaches (e.g., the Monin-Obukhov similarity theory, MOST) for urban areas by introducing different values to represent each grid's effective roughness lengths; displacement height; and components and parameters of heating, including the anthropogenic heat flux, heat storage capacity, albedo, and emissivity for each urban land use class. With computer advancements, the forecasting for urban areas may be enabled to introduce more sophisticated urban schemes. Beginning with *Brown and Williams (1998)*, who included urban effects in their turbulence closure scheme, methods have been introduced with increasing levels of sophistication incorporated into mesoscale models. *Masson (2000)* included a detailed canyon energy balance scheme into the surface energy balance and *Martilli et al. (2002)* and *Dupont et al. (2004)* included the effects from canyon walls, roofs, and streets in each prognostic planetary boundary layer (PBL) equation. A similar, but less complex urbanization scheme was a single-layer scheme developed by *Kusaka and Kimura et al. (2004a, b)* that shows promise toward capturing fine-scale urban weather phenomena. With these advances came the requirement for detailed urban morphological data (i.e., on the scale of a few meters), including land use and land cover, surface roughness, building geometric and thermal characteristics, and anthropogenic heat fluxes (*Ching et al., 2008*). Thus, depending on fit-for-purpose analyses for specific urban applications, the next level of sophistication in NWP models may be consideration of implementing advanced single-layer UCP schemes. This approach is a relatively inexpensive and practical means to improve on the modified MOST approach.

5.3.2 Urban air pollution and emergency response models

For applications of urban- and regional-scale atmospheric pollution models, there are two general fitness-for-purpose modes. One is the prognostic mode, and the other is the retrospective mode; each mode has separate and distinct requirements. The prognostic mode is the forecasting of air quality based on meteorological forecasts. The retrospective mode is used in air quality simulations necessary to conducting regulatory impact and cost-benefit analyses, developing source control strategies, and performing human exposure assessments. Requirements for such simulations are the highest precision and accuracy possible based on the most complete and highly detailed meteorological simulations for specific meteorological scenarios of interest, typically those for which air quality is poorest. For retrospective assessments, the precision and accuracy of the meteorological simulation is more important than timeliness in producing forecast products. For air quality forecasts, because timeliness is a critical requirement, NWP models that drive such forecasts need to be urbanized to a degree that is consistent with operational requirements. Using outputs from the forecast mode, special products to provide guidance in reducing poor air quality in street canyons will require special, ad hoc urban meteorological post processing to be devised. However, for applications such as those needed to be devised for emission control strategies, where vertical profiles of the meteorological and turbulent characteristics are needed in great detail, may not be satisfied using forecast products alone. In such cases, the level of research and development to satisfy this level of fitness-for-purpose undoubtedly will require utilizing the retrospective approach. Studies to assess air pollution health effects are an important objective that may be satisfied best with retrospective approaches. Population exposure modeling will require highly detailed multi-pollutant and multi-scale air quality models, as well as high-resolution urban morphology, population distribution, and human activities databases (*Baklanov et al., 2007*). For these and similar applications, the emphases will be on implementing urban schemes at a grid resolution that can provide the appropriate transport and turbulence details within the UC.

The fitness-for-purpose analysis also governs the choice of local-scale emergency preparedness modeling for accidental biological, chemical, or nuclear releases, and moreover, is clearly one of scale. For direct response and for operational purposes where timeliness is needed for guidance, urban meteorological observations of forecast products coupled with dispersion models are appropriate. For planning and assessment purposes and for the near-sources region, obstacle-resolved modeling approaches (e.g., CFD modeling) may be required. Such approaches will require careful linkage to outputs of urban-scale models, and both will require basic building and vegetation descriptions. Ideally, specific urban feature effects that should be incorporated into this type of application will include the following.

- Impact of urban surfaces on pollutant deposition (e.g., vertical walls, building materials and structure, vegetation)
- Information regarding chemical transformation such as lifetime of chemical species (e.g., inside street canyons), heterogeneity of solar radiation (street shadows, albedo,

and emissivity), and specific aerosol dynamics in street canyons (e.g., resuspension processes)

- Very detailed, high-resolution data on the mobile emission of pollutants
- Indoor-outdoor pollutant exchange information

5.3.3 Multiscale atmospheric environment modeling

Air quality in urban areas is impacted both from its local pollutant emission sources as well as from inflow of species transport on regional and global scales. In turn, transport of air pollutants from urban areas will impact regional- and global-scale air quality. Current atmospheric-chemical-transport (ACT) models now apply model nesting approaches as a means for treating the up- and down-scaling to account for this multi-scale dimension (*Moussiopoulos, 1995*; *Fernando et al., 2001*; *Baklanov, 2007*).

For down-scaling, a chain of urban models of different scales with sub-domain nests using finer grid sizes is applied. A common approach is to use outputs of large-scale models as boundary condition inputs to domains employing smaller grids successively from global to urban and street scales. It is well recognize that transport and transformation are nonlinear in scale (especially for reactive and rapidly deposited species), and parameters controlling atmospheric processes are typically grid-size dependent. Usually, the microscale (street canyon) models are obstacle-resolved and consider a detailed geometry of the buildings and UC, whereas the up-scaled city-scale (sub-meso) or mesoscale models consider parameterizations of urban effects or statistical descriptions of the urban building geometry. FUMAPEX (Baklanov, 2006) is an example of model down-scaling with integration of urban meteorology, air pollution, and population exposure modeling. Downscaling from regional (or global) meteorological models to the urban-scale meteorological models, with statistically parameterized building effects, and further downscaling to microscale obstacle-resolved, CFD-type models was including in the methodology.

Likewise, methods are needed by regional- and global-scale models to properly account for downwind transport of pollutant species from urban sources in regional- and global-scale contexts. This is because the modeled composition by species is grid-size dependent. Thus, for global and climate change models, the mesoscale model can provide a proper pollutant species accounting from biogenic and urban sources ranging from small urban areas to megacities to regional and global scales. It serves investigations of the evolution of pollutants from large urban plumes (e.g., *Sarrat et al., 2006*) or from major industrial and power-generation point sources. Such plumes are subgrid phenomena for the regional-global models that have the highest resolution (between 10- and 100-km grid sizes) in the zoomed areas. Therefore, urban-scale models can provide appropriate composition mix for the regional-global model. Currently, to understand the impact of aerosols and gas-phase compounds emitted from local/urban sources on regional and global scales, at least three scales of the integrated atmosphere-chemistry-aerosol and general circulation models are being considered: (1) local, (2) regional, and (3) global. Note that two-way nesting approaches are ideal for situations in which the scale effects in both directions (from the mesoscale on the microscale and from the microscale on the mesoscale) are important. However, such approaches are difficult to implement.

5.3.4 Urban pollution and climate integrated modeling

Integrated air quality modeling systems are tools that help in understanding impacts from aerosols and gas-phase compounds emitted from urban sources on the urban, regional, and global climate. The integration of urbanized NWP and ACT models is a strategic approach to providing the science-based tools for assessments of urban air quality and population exposure in the context of global to regional to urban transport and climate change. This is reasonable because meteorology governs the transport and transformations of anthropogenic and biogenic pollutants, drives urban air quality and emergency preparedness models; meteorological and pollution components have complex and combined effects on human health (e.g., hot spots, heat stresses); and pollutants, especially urban aerosols, influence climate forcing and meteorological events (precipitation, thunderstorms, etc.). The online integration of mesoscale meteorological models and atmospheric aerosol and chemical transport models enables the utilization of all meteorological 3D fields in ACT models at each time step and the consideration of feedback among air pollution (e.g., urban aerosols), meteorological processes, and climate forcing (e.g., DMI-ENVIRO-HIRLAM [*Baklanov and Korsholm, 2007,* Community Multi-scale Air Quality [CMAQ] system [*Byun and Ching, 1999).*

Chemical species in the atmosphere, such as CO_2 and ozone act as greenhouse gases to influence weather and atmospheric processes. Aerosols such as sea salt, dust, primary and secondary particles of anthropogenic and natural origin are also airborne and contribute to atmospheric processes in a complex manner. Some aerosol components (black carbon, iron, aluminum, and polycyclic and nitrated aromatic compounds) warm the air by absorbing solar and thermal-infrared radiation, whereas others (water, sulphate, nitrate, and most organic compounds) cool the air by backscattering incidental short-wave radiation into space. The effects of urban aerosols and other chemical species on meteorological parameters have many different pathways (direct, indirect, semi-direct effects, etc.) that these online, coupled modeling systems are capable of addressing.

5.4 Database and evaluation aspects of urbanized models

It is evident that there are a large range of applications that involve an urban focus. Moreover, given the wide range of model complexities, operational and data input requirements, and diverse applications, we find that there is no "one-size-fits-all" modeling approach that addresses the wide range of modeling objectives. Thus, for urban applications, the fitness-for-purpose concept is a relevant and important consideration. In this survey, we have identified a number of considerations; some of the major ones are outlined below.

5.4.1 Database requirements

Models of urban areas will be required to provide predictions with increasing fidelity and at finer scale 3D resolution of turbulent exchanges, flows, and thermodynamic characteristics and variables. To meet these requirements, parameterizations are being developed and implemented with varying degrees of detail in terms of features and sophistication relative to the actual physiographic features of individual cities. One limitation to the degree of complexity in the model parameterizations is the availability of appropriate morphology information. For operational needs, the requirements are fulfilled using specifications associated with limited numbers of urban land use categories, each with specified surface properties such as roughness, displacement lengths, albedo, moisture availability, and thermal properties. For research and development and applications, models that can capture more detailed effects of urban morphological features and underlying surfaces and building materials, at increasingly higher spatial resolutions, employ more explicit and highly detailed sets of 3D canopy parameters and within-grid land use classes.

A common requirement for environmental models is the description of the underlying surface layer. Technological advancements allow increasingly sophisticated definitions of land cover characteristics (e.g., shape files with high resolution [~1 m] definition of buildings and vegetation). Data of this type are now becoming routinely available for many urban areas of the world with the information technology available to facilitate dissemination. In the United States, a pilot project is underway to serve as a community-based technology enabler of such data; this or comparable systems can be developed to handle the needs on an international basis (*Ching et al., 2008,* this volume). A community-based system should decrease administrative barriers and increase international collaborative efforts to advance modeling tools.

5.4.2 Evaluation

Once the target variables and degree of precision needed for the application purpose are identified (Table 5.1), it is necessary to determine whether the parameterizations are capable of reaching these targets. Several techniques are available.

- *Real scale measurements.* As measurements are taken in a real city, a model should be able to reproduce them; however, very often it is difficult to have enough measurements, and, where measurements are taken, its representativeness of the gridded fields must be ascertained. The model computes the equivalent of a spatial average over the grid cell (usually a few kilometers or, at best, several hundreds of meters). Outputs from models that introduce vertical resolution within the UC and capture the effects of urban building and vegetation features are virtual fields, and the task of evaluating such outputs is challenging. Model-predicted vertical profiles of variables in the canopy reflect the aggregated influence of all the canopy features as virtual elements within the grid. In reality, such features take up finite volumes, and building-induced flows are subgrid features. Thus, any single or set of measurements will not provide a representation of the gridded fields but will, more or less, be under the influence of the nearest buildings or obstacles. This is a design feature that has yet to be resolved in developing field measurement strategies to evaluate predictions of within-canopy fields.

  Future guidance may come from insights gained using coupled UC models and building-resolved flows, both of which are driven by the same set of building datasets. Currently, evaluations performed above the canopy layer (blending layer) should not be subject to this conceptual difficulty, but, in and of itself, it does not provide the requisite within-canopy evaluation.
- *Remote sensing data.* A variety of satellite platforms do now provide data on surface variables and for urban areas. In particular, skin temperature is considered a very important variable because it exerts a strong control on boundary layer processes and the intensity of the heat island. Such data would be very useful toward diagnostic evaluation of urban model predictions. Of course, care is required to address scale

issues of observation and models. There are some critical assumptions in the derivation of the remotely sensed variables (e.g., emissivities, mixed pixels). The comparison also is biased to conditions that the remotely sensed data are operational (e.g., clear sky conditions for surface temperature, time of overpass).

Also, because models have varying treatments for handling subgrid land use and coverage, some of the resulting differences between observed and modeled skin temperature may be result, in part, from these treatments.

- *Scale-model measurements.* Wind tunnels have the advantage that external conditions can be controlled easily but are limited by certain conditions (e.g., Reynolds number may be a factor of 100 less than in the real world; no concurrent radiative moisture forcing; typically treats only neutral stratification cases). Outside models allow for a wide range of conditions with real meteorological forcing to be compared (*Kanda, 2008,* this volume). To date these models remain simple in morphology and arrangement.
- *CFD (large eddy simulation [LES] or Reynolds-averaged Navier-Stokes [RANS]) models.* Such building resolving models can be run over a limited part of a city to investigate flow properties to be used in UCP. Using CFD models, it is possible to derive the spatial averages required for UCP (*Galmarini et al., 2008,* this volume; *Martilli and Santiago, 2008,* this volume). CFD-RANS lacks the accuracy for some complex configurations. CFD-LES is more accurate but much more expensive in CPU time, which, thereby, limits its use.
- *Operational testing.* Real-scale routine data from weather networks are used for evaluation, most typically for weather forecasts (e.g., *Bohnenstengel and Schlünzen, 2008,* this volume).

5.5 Potential community activities

There is a wide range of activities that are needed to support the recent improvements to the state of urbanization of models. These fall into a variety of classes. To date, a systematic evaluation of urban land surface schemes has not taken place as it has for vegetated environments. The model comparison outlined in *Grimmond et al. (2008*, this volume) takes some initial steps to address this. As they note, it is anticipated that there will be need for further observations. There is a clear need for both intensive and extensive observational data sets to allow the wide range of variables to be evaluated over a wide range of synoptic conditions. The development of urban testbeds and urban atmospheric observatories (e.g., Helsinki, Shanghai, London, Paris, Hanover, Phoenix, Oklahoma City, Houston, New York City, and Washington, D.C.) and long-term urban campaigns (e.g., CAPITOUL, BUBBLE) enable these issues to be addressed. For example, studies evaluating the Martilli scheme show that it is able to reproduce the generation of the urban heat island effect and to represent correctly most of the behavior of the fluxes over Basel and Marseilles city centers (Hamdi and Schayes, 2005). There is a continuing need for modelers and observers to communicate. As models are used for a variety of purposes, there is a need for increasing the range of variables observed to ensure as complete a range of evaluation as possible. This may mean having testbeds and observatories with different objectives and dataset richness.

There is a wide range of processes and variables that need to be evaluated over a broad spectrum of conditions (meteorological, morphological, geographical setting, etc.).

For example, a deeper understanding of urban PBL dynamics requires development of long-term urban testbeds in a variety of geographic regions (e.g., inland, coastal, complex terrain) and in many climate regimes, with a variety of urban core types (e.g., deep versus shallow, homogeneous versus heterogeneous).

The conceptual issue of evaluation of model prediction of the flow within the canopy is not satisfactorily resolved at this time, and a framework to address this is needed. Ideal urban testbeds would include quasi-permanent mesoscale networks, with surface, canyon, rooftop, and PBL meteorological and air quality observations. These real-time, quality-assured data would be used for real-time urban-scale weather and air quality forecasts, as well as for emergency response actions after releases of air toxins (with an indoor-outdoor linkage) and for climate change impact studies.

In addition, the testbeds should be able to accommodate intensive short-term field observational studies that could involve turbulent flux and pollutant tracer measurements. Problems also exist in the evaluation of microscale CFD meteorological model results by use of field study or canyon wind tunnel observations (e.g., wind tunnel wall effects, the isolated nature of wind tunnel urban domains, the periodic LES and CFD lateral boundary conditions). When comparisons are done with these limitations in mind (e.g., only compare model results with wind tunnel results over urban centers), however, they show good agreement among the methods.

Obviously, with increasing evaluation, there will be enhanced development of the models. It is also clear that, within the chain of needs between meteorological forcing and applications, there is a range of new developments needed (see section 5.3). Finally, user friendly and multifaceted urban databases and enabling technology are critical and core capabilities for advancing urban modeling and boundary layer research. With careful thought to its implementation, we foresee a National Urban Database and Access Portal Tool or similar system as a research and development resource toward future improved UCP descriptions and scientific bases for advanced urban modeling applications, to accelerate the pace of their operational implementation, even internationally. For such an enterprise, we suggest several guiding principles be adopted. First, that this type of database be open and community-wide and available both universally and in as an unrestricted form as possible. Second, that both protocols and mechanisms should be established for its maintenance, upgrading, updating, and archiving. Further, issues of availability and sources of high-resolution data sets will need to be addressed.

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