Challenge and Opportunities in Urban Meteorology Research and Forecast*

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Abstract. An international workshop on urban meteorology: observation and modeling, was jointly held by the Institute of Urban Meteorology (China) and the National Center for Atmospheric Research (US) in Beijing, October, 2004. The workshop was intended to share recent progress in urban meteorological research, discuss issues related to research and development priorities faced by diverse Chinese institutions, and explore collaboration opportunities between Chinese and US research institutions. This article summarizes the major issues discussed at the workshop, including observation on urban boundary layer, urban landuse modeling, socio-economic impacts of weather and climates, and air quality in urban environment. It includes recommendations for future urban meteorology observational and modeling research, and potential collaborative opportunities between China and US.

Keywords: urban meteorology, urban boundary layer, observation, landuse, urban modeling, socio-economic impacts, air quality.

Today there are over 400 cities in the world with populations over 1 million and in the foreseeable future, virtually all population growth is projected to occur in urban areas. From the United Nations' report, World Urbanization Prospects (the 2003 revision)**[1]**: the world's urban population continues to grow faster than the total population of the world. In 2003, about 3 billion people, that is nearly half the world's population, live in urban areas. By 2030, the urban population is expected to rise to about 5 billion, while the rural population is anticipated to decline slightly from 3.3 billion in 2003 to 3.2 billion in 2030. By 2007, the urban population is projected to exceed 50% of the total population. This will mark the first time in history that the world has more urban than rural residents. Along with the increasing urban population, the number of "mega cities" (cities with 10 million or more inhabitants) will also increase from 20 in 2003 to 22 in 2015. The number of cities with 5 million or more inhabitants is projected to rise from 46 in 2003 to 61 in 2015.

Such rapid expansion of cities and increasing population are posing formidable challenges to the world community. For instance, urban environmental issues are becoming increasingly important within the cities of the developing country and, especially for mega cities. This has serious impacts not only on the health and welfare of urban residents, but also on weather and climate patterns due to increased fossil fuel burning, land use/cover changes and the accompanying effects on physical processes governing the energy, momentum and mass exchange between the land surface and the atmosphere (Dabberdt *et al.* 2000[2], Pielke *et al.* 2002[3], Claussen 2002[4], Dickinson 2003[5]).

To understand the environmental impacts of increasing urbanization, the science community has devoted increased efforts to urban weather and climate studies (Grimmond and Oke, 1995[6]), that includes recent field experiments such as the Joint Urban 2003 (Rotach,2002[7]; Brown et al., 2003[8]) in Oklahoma City, and BECAPEX in Beijing, China (Xu Xiangde, 2002[9]).

The Institute of Urban Meteorology (IUM) and the National Center for Atmospheric Research (NCAR) jointly organized the International Workshop on Urban Meteorology: Observation and Modeling, in Beijing, China, 12-13 October, 2004. This workshop was intended to share recent progress in urban research conducted at different institutions in China and US, discuss issues related to research and development priorities faced by diverse Chinese institutions, and explore collaboration opportunities between Chinese and US research institutions.

About 40 participants attended the workshop, representing research, operational and educational communities from the Institute of Urban Meteorology (IUM, Beijing), Chinese Academy of Meteorological Studies (CAMS, Beijing, China), Peking University (Beijing, China), the State Oceanic Administration (Beijing, China), Purdue University (West Lafayette, USA) Nanjing University (Nanjing, China), the Institute of Tropical and Marine Meteorology (ITMM, GuangZhou, China), Hong Kong University of Science and Technology (HKUST, HongKong, China), North Carolina State University (NCSU, Raleigh, USA), and the National Center for Atmospheric Research (NCAR, Boulder, USA).

This article summarizes the major issues that were discussed at the workshop including recommendations and collaborative opportunities between China and US for future urban meteorology observational studies and modeling research.

1 Observing the urban boundary layer

There are an increasing number of urban boundary layer field experiments as reviewed by Roth (2000) and Arnfield (2003)[10]. Examples include, the Joint Urban 2003 Study in Oklahoma city, USA, the Canopy and Aerosol Particles Interaction in Toulouse Urban Layer (CAPITOUL), Pentagon Shield 2004, Beijing City Air pollution Observation Field Experiment (BECAPEX), Beijing Urban Boundary Layer Experiment (BUBLEX) 2004, Madison Garden 2004 trace gas experiment. One of the difficulties of conducting urban boundary layer observations is that all human activities are within the roughness sublayer (from the ground to several times of the average building heights), while all the numerical models parameterize surface turbulence using Monin-Obukhov similarity theory, which is strictly applicable in the layer above the roughness sublayer. The inertial sublayer is the layer where the boundary layer flow follows Monin-Obukhov scaling relationships (Oke, 1987)[11]. This layer begins at roughly two to three times the average building height.

Within the roughness sublayer the flow is three-dimensional and site-dependent since it is dynamically influenced by the length scales and morphological features such as density and porosity of individual buildings. Therefore, any observations within the roughness sublayer need to be interpreted in the context of local environment (Harman et al. 2004[12]). Observations above the roughness sublayer may be difficult, partly due to urban regulations which may not permit location of observational platforms that may be considered disruptive to terrestrial or aerial transportation.

Numerical models that characterize flow and dispersion in the urban environment need accurate estimates of a number of urban properties that include: 1) roughness lengths for momentum and scalar variables (Grimmond and Oke, 1999[13][14]), displacement height, and boundary layer depth; 2) albedo and radiative properties of urban surfaces and aerosols; and 3) subsurface and urban canopy heat storage and water transport properties. These properties need to be measured over seasonal timescales, which requires measurement throughout the year.

In order to estimate roughness lengths and displacement heights, we need to measure mean profiles of wind, temperature, and humidity, and turbulent fluctuations of these quantities at two or more levels in the inertial sublayer at a number of locations (to characterize the inherently heterogeneous urban boundary layer). This may require between 10 and 30 observation sites at different sites representing the various structural regimes throughout the city. In order to estimate albedo, a combination of satellite measurements (to obtain an overall integrated view), and tower measurements at several representative (perhaps 3 to 6) locations to calibrate and refine the satellite measurements are needed. Several sampling sites ranging from tall buildings within the urban core to towers in more rural environments are desired. Sufficient sampling of spectral radiometers, aerosol properties and trace gas can be obtained from a few select (three to four stations) stations within the city.

Observing subsurface and urban canopy properties is difficult. One approach is to measure the latent and sensible turbulent heat fluxes, the incoming and outgoing radiation, and estimate the anthropogenic heat input, and thus obtain the heat storage term (which depends on subsurface and canopy properties) as a residual. Again this needs to be done at several (possibly three to six) representative locations. In an urban environment this presents a special challenge because spatial heterogeneity can generate significant contributions from horizontal advection terms. The footprint requirements for flux measurements imply that flux measurements need to be at a level well above the mean building height.

It is anticipated that the developments in sensor technologies would help making more spatially representative measurements over the urban regions. Some new sensors that might be valuable in this effort would be aerosol backscatter lidar (e.g. Mayor and Spuler, 2004[15]) to measure the boundary layer depth. If deployed in a vertical scanning mode, the lidar can obtain a horizontal cross-section of the boundary – layer depth. If deployed in a horizontal scanning mode, the lidar can delineate structures in the boundary layer on a horizontal plane. Another possibility is a scanning Doppler lidar, which can be used for wind profile measurements, as well as radial velocity in horizontal and vertical planes (e. g. Chai et al., 2004[16]). Microwave wind profilers (e.g. Martner et al., 1993[17]) can provide mean wind profiles and boundary-layer depth; adding a RASS capability also allows temperature profile measurement. Developments in the satellite remote sensing algorithms are also expected to provide information on urban canopy morphology.

Chinese scientists have also conducted various field observations in the last few years. Preliminary analysis of those measurements are encouraging and reveal important urban boundary layer characteristics in localized urban environments. Data from those field programs and from future urban experiments are considered essential for improving the models and the resulting data sets need to be made available to modeling groups within a few months of obtaining the measurements in order to be expeditiously included in modeling efforts.

2 Urban landuse modeling

Incorporating urban landuse models can improve the overall performance of numerical models for both urban areas and their surroundings (Holt and Shi, 2004[18]; Chen et al., 2004[19]). High-resolution coupled mesoscale models, which consider urban thermal and dynamic effects with a proper representation of urban areas, are powerful tools that can aid decision-making. Urban models, ranging from simple bulk parameterization to more complex urban canopy models (UCM), are currently being adopted in mesoscale weather and climate modeling systems. One limiting factor, though, is the lack of input data (i.e., parameters required by urban model). An example is temperature profiles above and within roofs, walls, and roads, which are not routinely measured. For urban-scale weather analysis and prediction, improving the representation of the surrounding rural areas is equally important and will lead to improvements in predicting mesoscale model dynamics. Current practice is to represent the effects of the surface in mesoscale models using the constant-flux layer approximation in the surface layer (Monin-Obukhov similarity theory). However, field measurements (e.g., Rotach, 1993[20]) have shown that this approach is not able to reproduce the vertical structure of the turbulent fields in the urban roughness sublayer (from street level up to heights of 50–100 m) of the urban environment. New approaches need to be developed to correctly reflect the urban effects on air flow and will likely advance as more detailed observations become available in future.

Estimating latent heat flux from urban regions still remains an unresolved issue because of the highly heterogeneous urban landscape. The scaling problem (e.g., effects of individual building versus that of a cluster) also remains unresolved and will likely be an important factor in designing and selecting an urban model in weather and climate models. Existing landuse maps that are derived from climatologcial datasets and available now as a default setting in many coupled modeling systems are generally acceptable only for largescale model applications. With finer grid spacing and more complex urban models, there are large inconsistencies between the default landuse datasets and the actual urban landuse. Moreover, evaluating the performance of high-resolution urban models remains a challenge and additional datasets specifically designed to assess the urban model output have to be collected. Detailed aerosol, radiation, and air quality measurements (aerosol observations and optical depths for multiple wavelengths, visibility, absorption, scattering, extinction coefficients, ozone, and aerosol concentration and speciation) are desired. In China, such data sets, however, are typically obtained at experimental sites and the data may not be publicly available. There are also boundary layer profile measurements available from a few select sites in Beijing, Nanjing, and Guanzhou. These surface and boundary layer measurements could assist the model applications in the urban area.

Changes in landuse in the periphery of the city have implications on the weather systems affecting the urban environment. The urban landscape may provide sufficient convective forcing (i.e., lifting and convergence zones). With the availability of moisture sources from the non-urban regions, thunderstorms and heavy precipitation may be generated over urban areas and their vicinity (Niyogi et al. 2002).

One problem, often encountered around the urban regions in China, is related to the haze occurrence. Haze formation is a multifaceted issue, but meteorological conditions appear to be one controlling factor. Synoptic systems such as frontal passages and shoreline processes (e.g., mesoscale sea-breeze circulations) can contribute to the severity of air pollution. Furthermore, local surface forcing may cause its diurnal variability of pollutants. Currently, the radiative feedback between haze and urban landscapes is not being considered in coupled land surface models. Observations from field experiments in and around mega cities in China can help with developing and testing such models.

It is necessary to model landuse change outside the city, which have implications on the weather systems affecting the urban environment. The urban feedbacks may provide sufficient convective forcing (i.e., lifting and convergence zones). With the availability of moisture sources, thunderstorms and heavy precipitation may be generated over urban areas and their environs. Interactions between haze and air pollutants could lead to changes in the radiative environment and hence the land–atmosphere interactions, but these interactions are currently largely unresolved and need to be considered in urban scale models.

Air quality (including haze) and water resources (through precipitation and water cycle assessments) are two important areas that can be benefited through the integration of detailed mesoscale modeling and observational approaches to understand: (a) the physical processes involved, (b) possible ways to mitigate the severity of air pollution and shortages of urban water resources, and (c) the effects of urban development on local weather and quality of life (socioeconomic aspects). Improvements in land surface process representation in coupled models are an important driver of this problem. Hence, accurate description of landuse and land cover at high resolution is necessary. This information needs to be updated to the default dataset available through NCAR's MM5 and WRF models. Different components of the urban models need to be verified (and improved) with field observations. There are point observations available over a number of regions, which can be used for such assessment (observations of surface meteorological variables, wind profiles, air quality/radiation, and surface-layer heat fluxes). Different urban models need to be tested with dedicated field observations. Typically 72-hours of data are needed to develop a case study to evaluate high-resolution mesoscale model and these data should include: urban and surrounding landuse characteristics, surface-layer and PBL wind and thermodynamic variables (temperature, humidity, winds), albedo and emissivity, urban fractions, radiation forcing at the surface (short and long wave, as well as diffuse and direct component), precipitation and pan evaporation rates for both urban and surrounding areas. Data sources can be augmented with radar and satellite estimates of precipitation, surface temperatures, soil moisture and temperature, albedo etc. These measurements can be used to identify the scaling coefficients for estimating urban latent heat flux.

It will be necessary in the future efforts, to couple air quality (tracer type as well as detailed) models with urban canopy models so that the trajectories and distribution can also be evaluated. Also important is to consider the role of assimilation of conventional (in-situ) observations into land surface models to develop high-resolution assimilation products. This approach will require adopting the latest developments in urban and non-urban land surface models and assimilation schemes to provide surface state maps for the urban and surrounding rural region. Ingesting high-resolution satellite (e.g., MODIS and IKONOS) datasets over urban regions is expected to improve the model performance. Additional tests using MODIS and GOES surface temperature for updating the surface temperature fields (with a detailed surface energy balance equation for urban surface) are recommended.

Finally, due to unique weather patterns in different urban regions, there is a need for developing a coordinated research community focusing on urbanization issues dedicated to specific regions (e.g. Beijing, the Yangtze river valley, and the Pearl River Delta). These region-specific groups should exchange information in a community framework to coordinate analysis of data, intercomparisons of model results, model development and evaluation, measurements, and monitoring as well as research initiatives.

3 Socio-economic impacts of weather and climates in the urban environment

Socioeconomic impacts of weather and climate meteorology are an important component of the urban decision-making problem. While this issue was not a major focus of the workshop presentation, it was raised at several discussion sessions. The processes affecting land surface processes at the urban scales and the inter-relation between land-atmospheric interactions and the regional social well-being is intuitively known but not well quantified.

For instance, the meteorological information is typically designed for meteorological models and scientists; there is a need to develop indices, which combine the information that can be used as a means of dissemination to the public and decision/ policy makers. The development of such indices is an iterative process, which will evolve following dialogue between decision makers, the public, and scientists. Meteorological information is available to the public in large part from default datasets. Localized corrections and updates of local and regional landuse maps are necessary and critical. It is anticipated that improved understanding of local land surface processes and the processes affecting land atmospheric interactions can directly improve the predictability of haze, air quality, and water resources in the region (e.g. Trier et al. 2004, Holt et al. 2005) There is a need to develop studies which investigate 'if then' scenarios and an analysis approach which can have socioeconomic feedback integrated in the complete system. Such an end-to-end system needs to have two-way feedback among scientists, the policy makers, and the public, and vice versa.

Although the workshop participants did not discuss ensemble techniques and issues associated with the evaluation of model forecast from socioeconomic (value of forecast) approach, these techniques are routinely available and can be applied over urban regions (Palmer 1999). These techniques have until now been applied to regional climate models to evaluate the value of seasonal predictions and would find ready application to urban problems.

Efforts such as GLOBE, and other community partnerships can provide means for acquiring large global datasets, which are not available through routine monitoring or academic institutions. A local effort involving the public for data collection may be initiated and might provide localized information. Initial community effort could concentrate on simple measurements (e.g. air temperature) that can be communicated to the forecasters. Initially such measurements are best suited for evaluating the models, and after quality control, can be assimilated for urban scale studies.

4 Urban air quality and pollution

4.1 Understanding local and regional atmospheric flow features

Another focus area of the workshop was to find ways to understand interactions between meteorology and urban air pollution. The air quality problem can often be broken up into two parts – emission and formation of pollutants, and their transport and dispersion. Although the emission of pollutants can change substantially over time, day-to-day variations in air quality are typically more closely related to changes in the atmospheric flow. Changes in emissions tend to occur on a much slower time-scale than changes in meteorological conditions. Hence, it makes sense to approach the problem from both topics.

A common theme seen from the presentations is that there exists special circulation features under which trapping or transport of air pollutants become important. These features are geographically dependent but may also include large-scale advection of pollutants by the background flow, compression of the boundary layer through large-scale subsidence, thermally induced local circulation in the urban environment, or dynamically forced circulation by local topography or a coastal environment. Identifying and analyzing such flow features, through observation as well as modeling studies, are critical for improving our understanding of urban air quality issues, and are recommended as one of first steps in urban air quality studies.

The second step is to use models to accurately reproduce those observed circulation features – including all temporal and spatial scales needed for the specific problem in question. This will involve using particular cases to calibrate or fit the model for a specific urban environment. Some details of this process have already been discussed in previous sections; for example, improved land-use dataset and refined Noah-LSM have been shown to be very important for accurate simulation of the local circulation features important for development of severe air pollution events in the PRD region.

Also discussed is the role of meteorologists in air quality studies. Focusing more on the physical processes of the air quality problem, meteorologists tend to have a better understanding and appreciation of the detailed flow structure, stability and dispersion characteristics of the air pollutants at different scales than those involved more intimately with the constituents of the pollution. A failure of understanding those physical processes can lead to confusing, if not erroneous, conclusions. For example, some earlier studies involving the use of mesoscale models and/or trajectory analyses for the study of urban air quality problems erred in their identification of pollutant sources because the fine scale urban trapping circulations were not properly resolved in their simulations or flow analyses. Such studies often put the emission source in upstream locations, while in reality the pollutants may be emitted locally and trapped by the urban circulation. Nevertheless, due to the multi-scale nature of the air quality problem, it is an iterative process to: 1) better identify the key circulation regimes/features important for development of air pollution episodes; and 2) improve models to be able to simulate/forecast these features.

Given the rapid development and urbanization in China for the last twenty years, it is of interest to examine simulations performed with land-use data derived for past decades, and evaluate model atmospheric circulation features against corresponding observations taken for those periods. This provides a good way to verify the models, as well as for setting the stage for evaluation of different land-use scenarios in the future.

4.2 Urban air quality: observations, analyses, and advanced modeling

Discussions for this part focused more on the design of an observational network for both air quality and meteorological studies. The instrumentation for this type of network should include, but not be limited to, wind profilers, tethersondes, sonic anemometers, gradient observation systems, lidars, sodars, tower and roof mounted meteorology and atmospheric chemistry sensors (e.g., SO_2, NO_2, O_3, CO and PM).

The design of this integrated network should address the following questions:

- What variables to measure and how often?
- Where to locate the sensors?
- When to observe? Continuous monitoring versus spot observations?
- How to perform quality control over the measurements – particularly for chemical measurements where constant up-keep and calibrations are important.

The last point is very important for air quality measurements. A protocol must be set up to record the precision and accuracy of the measurements, and with quality control procedures. This is particularly true if the data are to be used for other users (including others within one's own organization or users in the future).

How exactly the air quality observational network should be designed depends primarily on the objective of the network. There can be many different objectives, e.g., background or baseline monitoring, exposure and health analyses, prediction of air pollution/haze/blue sky indices, understanding specific processes or pollution events, etc. With limited resources, the network design for different objectives will be very different. For example, a network designed for exposure and health monitoring will likely consists of mainly ground-based air quality measurements in populated areas, while a network designed for better air quality predictions may include measurements at the surface as well as in the vertical in upstream or surrounding areas. On the other hand, if the focus area has complex terrain or other features with strong differential heating, chemical forcing, a good understanding of the local airshed will be helpful for optimal use of limited observational resources for urban air quality monitoring. An initial identification of the airshed can be carried out through analyses of existing meteorological observations, or by running high-resolution urban models resolving these forcings. Alternatively, one can also try to address the problem by a preliminary chemical survey, also known as saturation monitoring (i.e. by deploying inexpensive samplers for short-term multi-site pollutant studies using non-reference methods). Results from these measurements can also help identify hot spots in the city, where longer-term observational efforts can be focused.

Ground-based remote-sensing equipment like lidars are able to provide continuous and real-time measurements of the boundary layer depth and coherent structures by sensing aerosol backscatter for selected meteorological/air quality parameters. They are particularly useful for improving our understanding of impacts of large-scale conditions on air pollution, for evaluating the incorporation of air quality models, and for predicting air pollution events. While their initial setup cost can be quite high, that can be justified for the better understanding they offered. Moreover, their operational costs are typically less than filter-base systems that often require substantial manpower and calibration materials for regular maintenance and calibration.

Within any given city, multiple research and government organizations should collaborate to study and measure various meteorological and air quality variables at different locations, and share data and results. One of the main topics to be included in such collaboration should be the maintaining of a record of quality control procedures. Another point that was raised but not discussed in detail was the application of air quality studies for disaster and hazard management (e.g., in the event of chemical accidents and or terrorist attacks).

Finally, there was also discussion on the use of advance air quality models like the Community Multiscale Air Quality (CMAQ) model. There was concern about whether the required emission inventory will ever be available. If not, how can one approach the problem? The use of satellite imaging to help identify the emission sources, and to help generate initial fields to be assimilated into the model were briefly discussed.

5 Recommendation for future urban research

In order to move forward on issues of urban meteorology research in China, the workshop participants strongly suggested that: 1) forming productive collaborations with other national and international research institutions and university groups, 2) coordinating large national and regional urban observation field experiments, and 3) setting up a test center for incorporating advanced modeling and data assimilation techniques for urban weather prediction.

There was a consensus that there is an urgent need for developing a comprehensive urban modeling and monitoring effort dedicated to different mega cities in China. Such an effort needs to be based on and integrated through community collaborations, which should establish ways for model intercomparison and evaluation, urban model developments, and archive urban/ mesoscale models products and observational data sets.

Recognizing that there are unique features with each urban region, within any city, collaborations should be encouraged among different research and government organizations to study and measure various meteorological and air quality parameters at different locations. Collaboration and data sharing amongst these institutions is the key for the success, and data archiving and sharing policy should be clearly defined. For instance, all observational data should, after quality controlled, be archived and made available to the community within 12 months after field work. It is critical that good records of quality control procedures and metadata information.

In using advanced urban models in mesoscale models for urban weather forecast, several issues related to urban-model parameter specification and initialization need to be addressed. It was also stressed that efforts are necessary to accurately represent the response of non-urban areas to improve the urban forecasts.

The final goal for precision urban weather forecast, which may well depend on specific urban regions, has to be clearly defined and the appropriate steps of model development and evaluation criteria need to be identified. Furthermore, scientific objectives have to be defined for urban field experiments and monitoring networks to address requirements and scientific issues specific to each mega city. Modelers should be involved in the early stage of urban field experiment design and provide insights into what measurements are the most beneficial for urban model development and assessment.

The relative role of landuse/landcover/urbanization changes, aerosols production, radiation, and their potential feedbacks to atmosphere, hydrological cycle, urban human welfare, and ecosystem need to be also addressed. Given the diverse scientific investigations related to urban meteorology currently conducted in Chinese institutions, there are many opportunities for forming closer collaborations among them. More importantly, such collaboration will make the best use of the limited resources at those institutions.

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