## J19.6 The development of a prototype of a Canadian urban flow and dispersion modeling system

Richard Hogue[a], N. Benbouta[a], J. Mailhot[a], S. Bélair[a], A. Lemonsu[b], Y. Yee[c], F. Lien[d], and J.D. Wilson[e]
[a]Environment Canada, [b]Météo-France, [c]Defence R&D Canada, [d]University of Waterloo, [e]University Of Alberta

### 1. Introduction

The release of CBRN agents in an urban center and the subsequent exposure, deposition, and contamination are emerging threats in an uncertain world. Defence R&D Canada's CRTI (**C**hemical, Biological, Radiological and Nuclear **R**esearch and **T**echnology **I**nitiative) initiative represents the response of the Canadian government and scientific community to find solutions to address these challenges.

In order to meet the challenges of future threats, there is a need to develop operational systems that predict the consequences of atmospheric releases of hazardous materials in built-up areas, for real-time emergency response, pre-event planning, and post-incident assessment.

The urban environment poses unique challenges for emergency response modeling. Detailed examination of flow in urban areas reveals the development of separation and stagnation zones around buildings, turbulent wakes and vortices, interacting wake regions from neighboring structures, and street canyon channeling. Moreover, the urban canopy significantly affects mixing in the atmospheric boundary layer, and thereby has an impact on dispersion and transport over great distances. Hence, the understanding of the wind flow in an urban area and the concomitant dispersion of material released into that flow is crucially important.

A four-year research project entitled "*An Advanced Emergency Response System for CBRN Hazard Prediction and Assessment for the Urban Environment*" (CRTI 02-0093RD) funded under CRTI was undertaken to develop models for simulating the complex behavior of flow and dispersion in the urban environment. As a result, an advanced high-fidelity operational modeling system for the prediction of urban flows and the dispersion of agents released in urban environments has been developed. This system allows CBRN materials to be tracked at near field (up to about 2 km from street or building scale to micro-scale) and into larger scales where dispersion is governed by the local (meso-gamma), and then by the synoptic scales, at the appropriate resolution for each length scale and associated time.

[*]*Corresponding author address*: Richard Hogue, Environment Canada, Meteorological Service of Canada, Dorval, Canada, 514-421-4622; e-mail: Richard.hogue@ec.gc.ca

The Environmental Emergency Response Section (EERS) of Meteorological Service of Canada's the Canadian Meteorological Centre (CMC) has a mandated role to provide atmospheric transport modeling of radioactive material in the atmosphere in support to the Federal Nuclear Emergency Plan (FNEP) in Canada. The group also has operational response capabilities for chemical, biological releases in the atmosphere.

The multi-scale modeling system being developed is called the *Canadian Urban Flow and Dispersion Modeling System* (CUDM). It will increase capabilities to model and simulate the mean flow, turbulence and concentration fields in major Canadian cities and will provide EERS with additional key-enabling technology in the area of transport and dispersion of hazardous material in urban environments. It will also demonstrate the capability for EERS to be a primary National 24/7 reach-back and support centre for CBRN pre-event scenario planning, real-time emergency response and post-incident assessment in Canada. Such systems provide emergency planners and responders, public heath officials, military personnel and other users with critical information on which they base life-and-health decisions. The system will also be able to provide more accurate information to Health Canada's Radiation Protection Bureau (RPB) who leads the FNEP.

The main components described in this document have been implemented in a prototype context in a Government Operations Centre (Meteorological Service of Canada's, Canadian Meteorological Centre).

### 2. SYSTEM DESCRIPTION

This unique modeling system consists of four major components (Figure 1): the development of models for the prediction of building-aware flows in urban areas at high resolution, the inclusion of sub-grid scale urban parameterization in a meso-scale numerical weather model, the coupling of the urban building-aware flow prediction model with the "urbanized" meso-scale model and the development of Eulerian and Lagrangian stochastic models for the prediction of urban dispersion which are fed by the flow wind and turbulence from multi-scale models. A general description of this system is found in [Benbouta et al, 2007].

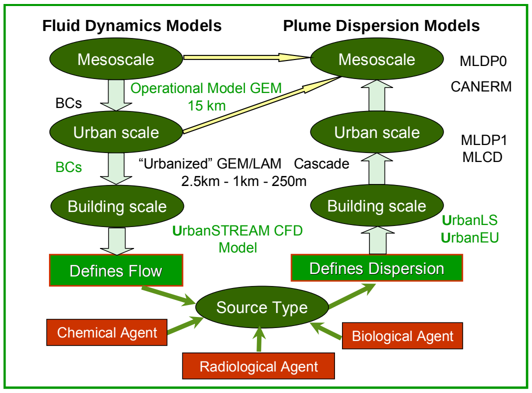


**Figure 1:** Canadian Multi-scale Modeling System of dispersion

The Canadian Meteorological Centre operates its main Numerical Weather Prediction (NWP) model, called GEM (Global Environmental Multi-scale), at a resolution of 15 km [Mailhot et al., 2006]. The outputs of this model feed in cascade mode the urbanized version (urbanGEM) of the model which is executed respectively at 2.5 km, 1 km and 250 m resolutions (Figure 2). In the urbanized version of the model the impact of the radiative, energetic and dynamical urban processes are taken into account in the computation exchanges between the urban surface and the atmosphere.

The outputs of this high resolution urbanized model serve as boundary inflow conditions to feed a "building aware" Computational Fluid Dynamic (CFD) model (urbanSTREAM) to provide realistic wind circulations around buildings; this in turn provides the mean flow and turbulence fields that can be used by a dispersion model (Lagrangian stochastic called urbanLS or Eulerian called urbanEU), to predict the urban transport, diffusion and deposition of hazardous contaminant in urban environment.

This integrated multi-scale CBRN modeling system has been validated by comparing modeled predictions with comprehensive data sets obtained from a full-scale urban field experiment campaign held in July 2003 and conducted in Oklahoma City.

## 3. URBANIZED MESO-SCALE NUMERICAL WEATHER PREDICTION MODEL, urbanGEM

In order to provide an efficient numerical weather prediction in major Canadian cities, an urban-ized version of a Limited-Area Modeling version of the GEM model (GEM-LAM) has been developed. The modeling system is based on a cascade consisting of three nested domains with resolutions of 2.5 km, 1 km and 250 m.

To better represent the near-surface atmospheric flow and the thermal structure influenced by the underlying obstacles, the urbanized model includes the Town Energy Balance (TEB) land surface parameterization scheme [Masson et al, 2000, 2002]. To feed the input of this urban canopy scheme with urban characteristics and anthropogenic heat emissions, methodologies to generate urban land cover and anthropogenic heat fluxes databases were developed.

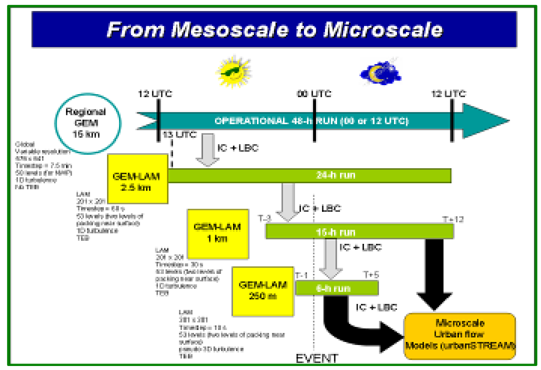


**Figure 2:** Configuration of the prototype urbanGEM cascades from15 km grid size to 250 m grid size.

### 3.1 Urban land use/land cover

Detailed data describing the complex urban geometry are needed to initialize the input parameters required by the urban-canopy scheme. Because of the lack of land-use and land-cover (LULC) databases for Canadian cities, a research and development effort was initiated to develop a general methodology for producing urban LULC in major Canadian cities (or any other city in any country). Two semi-automatic methods have been developed to derive land use and land cover urban classifications for the most important North American cities.

The first method [Lemonsu et al., 2006, 2009a] is based on the joint analysis of satellite imagery and digital elevation models (DEM). The application of a decision tree model allows the identification of 12 urban classes, at a spatial resolution of 60 meter, representative of urban cover variability for North-American cities.

The second method [Leroux et al., 2009] uses vector data from the Canadian National Topographic Data Base (NTDB) together with SRTM-DEM and Canadian Digital Elevation Data (CDED1) and census data, allowing 44 urban classes at a spatial resolution of 5 meter representative for major Canadian Cities.
An example of the urban cover classification obtained for the city of Vancouver in Canada using the semi-automatic processing methodology is shown in Figure 3.

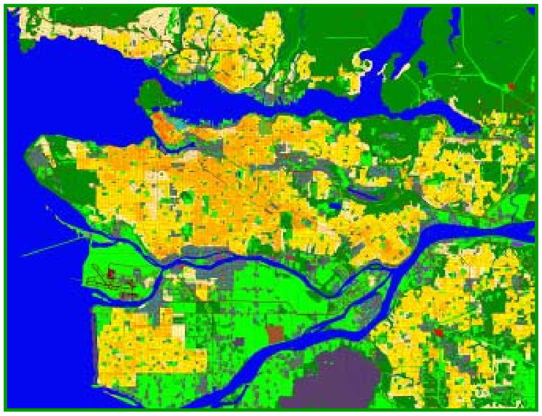

**Figure 3:** 44 urban classes of the city of Vancouver in Canada.

### 3.2 Montreal Observation Field Campaigns, MUSE 1 & 2

To evaluate the urban surface scheme TEB in winter conditions, an aspect that has not been extensively examined so far, two field observation campaigns (MUSE for **M**ontreal **U**rban **S**now **E**xperiment) were conducted in Montreal during March-April 2005 and February-March 2006.

**Figure 4:** MUSE 2005, dense urban area during the winter-spring transition (17 March - 14 April 2005)

The objective was to document the energy exchanges between the urban surfaces and the atmosphere in weather conditions typical of Canadian winters and winter-spring transition, i.e., cool, snowy and with snow melting. An overview of MUSE05 and analysis of results are presented in [Lemonsu et al., 2008] and more details about MUSE05 and MUSE06 are found in [Chagnon et al., 2007].

An "off-line" test (i.e.: surface modules integrated independently from the atmospheric model) was done to assess TEB ability to capture the snow cover evolution and its impact on the surface energy budget [Lemonsu et al., 2009b]. It showed good agreement with observations (Figures 5 and 6).

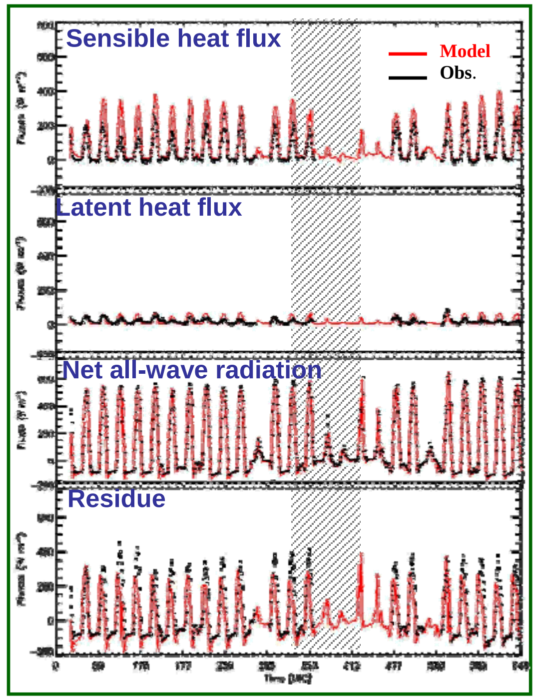


Figure 5**: Comparison of fluxes from off-line TEB with Obs**

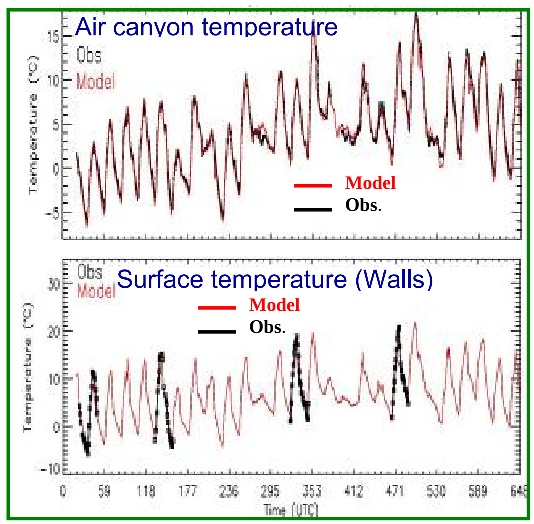


**Figure 6:** Comparison of temperature from TEB in off-line mode, with observation data.

### 3.3 Validation of the Urban Weather model, urbanGEM

The urbanized weather prediction modeling is validated with data from a real cityscape experimental campaign Joint Urban 2003 (JU03) conducted in Oklahoma City during the period from June 28 to July 31 [Allwine et al., 2003].

The model cascade of three domains around Oklahoma City, at resolutions of 2.5km, 1km and

250m was run. The Figure 7 shows the topography for this cascade configuration.

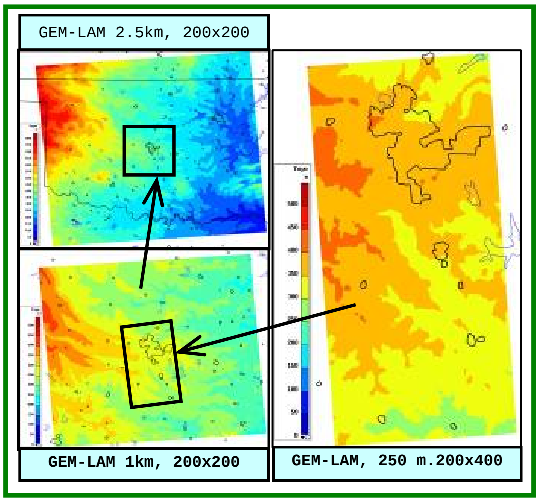


**Figure 7:** Configuration of the domains cascade used in urbanGEM, JU03-Oklahoma City case study.

To quantify the impact of urban processes on the surface energy budget and on the structure of the urban atmospheric boundary layer, the modeling results were compared with observations from two Intensive Observation Periods (IOPs) of the Joint Urban 2003 campaign [Lemonsu et al., 2009c].

The urban microclimate simulated with 250-m run for IOP9 (night) is showed in Figure 8. Modeled and observed averaged air temperatures from 11 MESONET rural sites and in the Center Business District (CBD) of Oklahoma City with the 13 PWIDS stations.

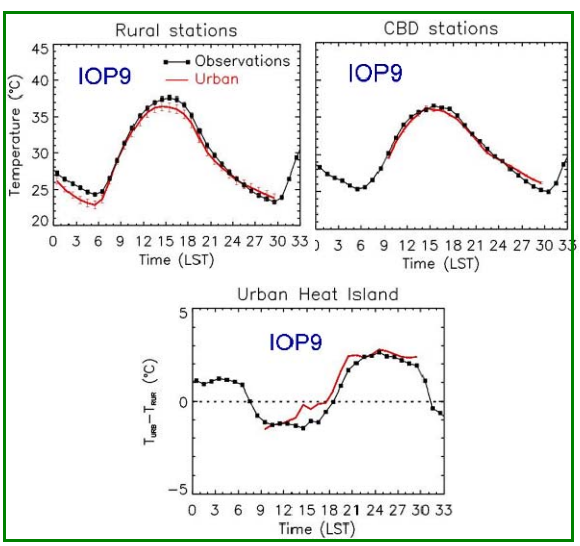


**Figure 8:** Averaged air temperature. Model .vs. Observations.

Comparisons of modeled and observed vertical profiles of potential temperature, wind speed and wind direction at ANL and PNNL sites using radiosonde and radars during IOP9, are showed in Figure 9. A near neutral layer is observed at night in the first 300 m and the atmospheric boundary layer is warmer downwind than upwind of the Center Business District of Oklahoma City.


**Figure 9:** Oklahoma City Site of JU03 campaign.

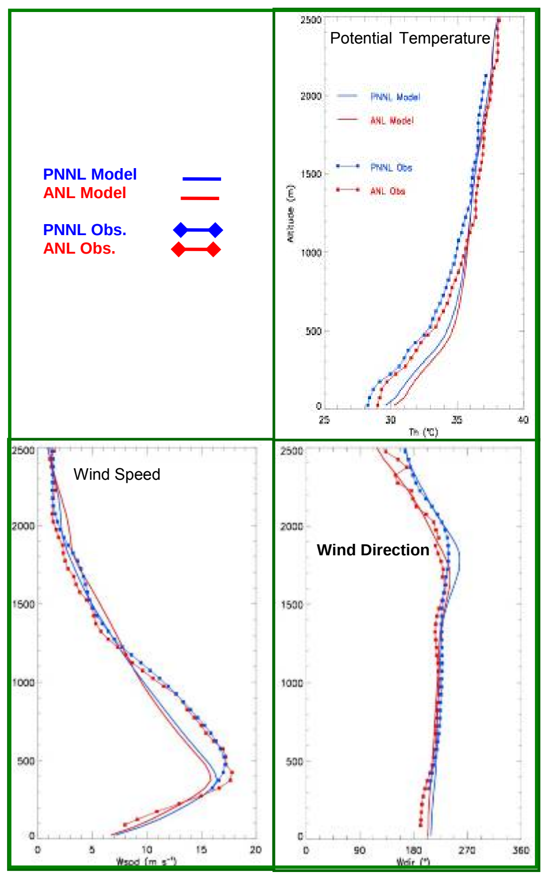


**Figure 10:** Urban effect at night. Vertical profiles upwind and downwind of the CBD of Oklahoma City Time average from 0100 to 0400 LST on 27 July 2003

## 4. URBAN CFD FLOW AND DISPERSION MODELING, urbanSTREAM, urbanLS AND urbanEU

The component for the provision of a building-aware urban flow and dispersion modeling includes six main modules urbanGrid, urbanBoundary, urbanSTREAM, urbanPost and urbanEU/AEU and urbanLS. Figure 11 shows these modules and how they interface with each other. For a detailed technical description, the reader is referred to [Yee et al., 2007] and [Wilson J. D., 2007].

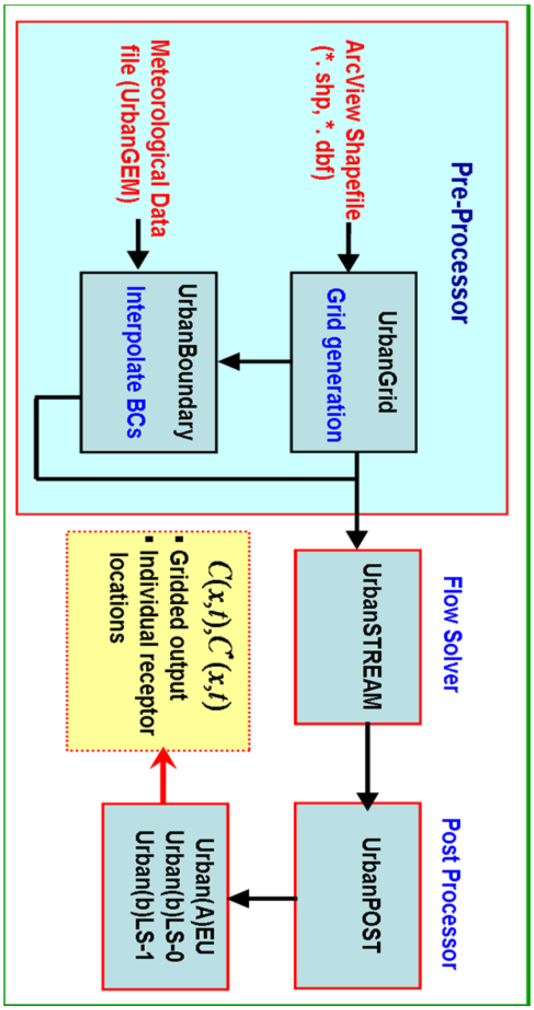


**Figure 11:** Various modules of the building-aware flow and dispersion modeling.

### 4.1 Grid generator

urbanGrid is a grid generator module that interfaces with common Geographic Information Systems (GIS) file formats (Shapefiles) from urban databases and uses these data to generate a structured grid over a user selected computational domain in a given cityscape.

### 4.2 Boundary interpolator

urbanBOUNDARY imports three dimensional meteorological fields (e.g., mean wind, turbulence kinetic energy, etc.) provided by urban GEM LAM and uses this information to supply inflow boundary conditions for urbanSTREAM (see Figures 12 and 13).

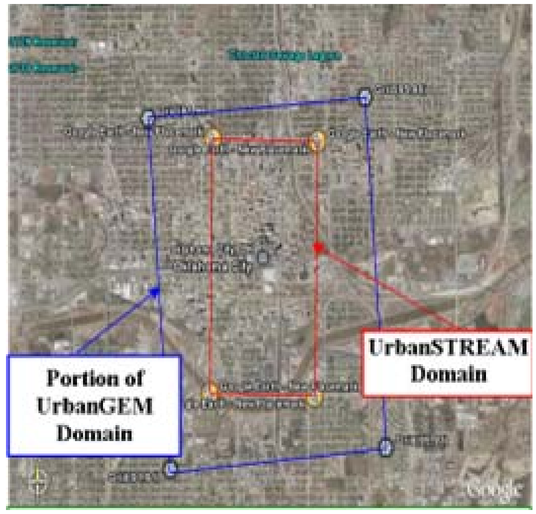


**Figure 12:** Coupling NWP model, urbanGEM and CFD model, urbanSTREAM

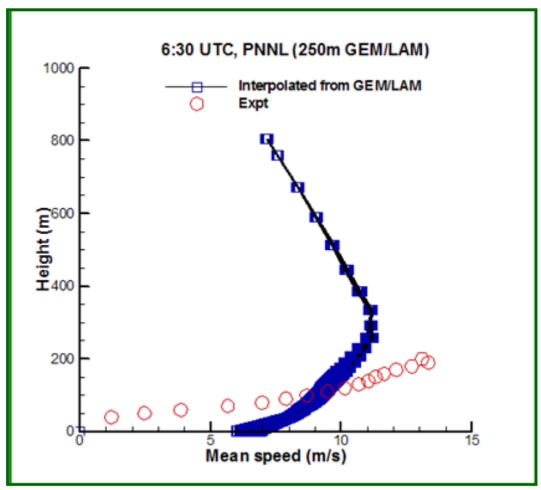


**Figure 13:** Horizontal wind speed interpolated from NWP model, urbanGEM.

### 4.3 Flow solver

The flow solver urbanSTREAM [Lien et al., 1994], is a CFD model simulating the mean flow and turbulence fields in urban areas. It is based on unsteady Reynolds Averaged Navier-Stokes equations with a pressure-based approach implemented through the SIMPLEC algorithm [Van Doormal et al., 1984], and a standard two equations turbulence-closure model, k-ε is implemented.

To reduce the computational demands for resolving all the building in large domains the grid is split in two areas, an internal domain and an external domain, see the Figure 14. In the targeted (internal) area, all buildings are explicitly resolved in the sense that appropriate boundary conditions are imposed at all the building surfaces (e.g., walls, roofs). In the external grid, a virtual building concept is used whereby groups of buildings are unresolved and the aggregate of these individual buildings is treated simply as a porous medium [Lien and al., 2005].

The equation is formulated in general curvilinear coordinate system allowing the terrain to be described accurately but in the current prototype, a collocated finite volume structured Cartesian mesh elements is used.

The flow solver urbanSTREAM provides the high-resolution wind and turbulence fields used to drive dispersion models.

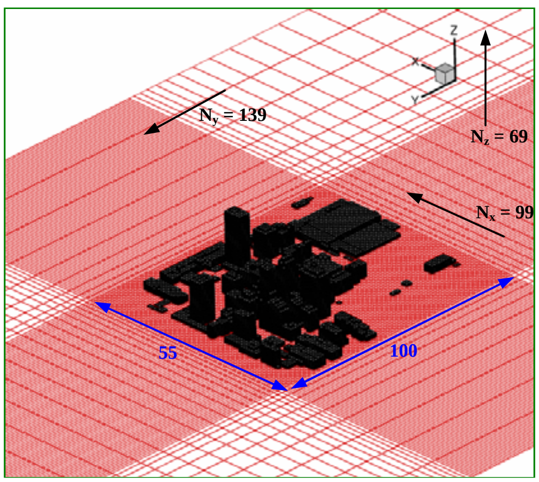


**Figure 14:** Computational grid generated by urbanGRID for Oklahoma City.

### 4.4 Transport and Dispersion models

The Eulerian grid dispersion models urbanEU (source-oriented) and urban**A**EU (receptor-oriented) is developed to simulate the dispersion of contaminants in the urban area. These two urban dispersion models are based on the numerical solution of a K-theory advection-diffusion equation or its adjoint.

The urban Lagrangian stochastic particle trajectory model urbanLS (forward dispersion model) or urban**b**LS (backward dispersion model) is also developed. Both zeroth-order forward and backward Lagrangian stochastic models involving the evolution of the position of a “marked” fluid particle (urban(b)LS-0) and first-order forward and backward Lagrangian stochastic models involving the joint evolution of the position and velocity of a “marked” fluid particle (urban(b)LS-1) have been formulated.

### 4.5 Post-processing

Finally, urbanPOST is used to post-process the primary output files from urbanSTREAM to provide an appropriate specification of wind statistics required as input by either the two Eulerian urban dispersion models urbanEU and urbanAEU or, alternatively, by the urban Lagrangian stochastic dispersion model (urban(B)LS-0/1).

### 4.6 Validation of Urban Flow and Dispersion Modeling

Here, a computational study is performed in which the capabilities of urbanSTREAM, urban(A)EU and urban(B)LS for urban dispersion predictions are examined by reference to the full-scale experimental study of flow and dispersion in a real cityscape, Oklahoma City in Oklahoma.

The modeling domain have the extent of 1, 934.25 m × 3, 610.6 m × 800.0 m in the W-E, S-N and vertical directions, respectively, covers the CBD of Oklahoma City and surrounding environs. At ground level where z = 0, the southwest corner of the modeling domain is at 35.449959$^{O}$ N and −97.52694$^{O}$ E. The grid domain is shown in the Figure 14.

All distances shown here have been normalized by a reference length scale which is chosen in this case to be 644.75 m. A proper subset within this modeling region (644.75 m × 709.23 m) is chosen as the region in which buildings will be explicitly resolved in the flow simulation. In the portion of the modeling region lying outside the building-aware region, all buildings are treated as virtual and their effects on the flow are modeled using a distributed drag force representation in the mean momentum equations.

The flow field in the computational domain is computed using urbanSTREAM in a stand-alone mode, not coupled with urbanGEM. Therefore, at the inflow boundary of the domain, the measured profiles of the undisturbed mean velocity and turbulence kinetic energy are used to define the inflow conditions.

The flow simulation conducted here was for IOP9 for the time period from 06:00-06:30 UTC (01:00-01:30 CDT) on July 28th 2003 when the prevailing winds were from the south at about 6.8 m/s at 50-m above ground level at the southern edge of the computational domain. The inflow mean velocity and turbulent kinetic energy are from the Pacific Northwest National Laboratory

(PNNL) sodar located 2 km south of the central business district (CBD) of Oklahoma City. See Figure 15.

The predicted wind statistics were averaged over 50 time steps after the flow had achieved a steady state. The predicted vertical profiles of the mean horizontal wind speed are compared with associated measured values obtained at three different locations in the computational domain: two minisodars from the Argonne National Laboratory (ANL) and one sodar from the Atmospheric Research Laboratory Field Research Division (ARLFRD).

The figures 16, 17 and 18 compares the predicted vertical profiles of the mean horizontal wind speed with associated measured values obtained at three different locations in the computational domain.

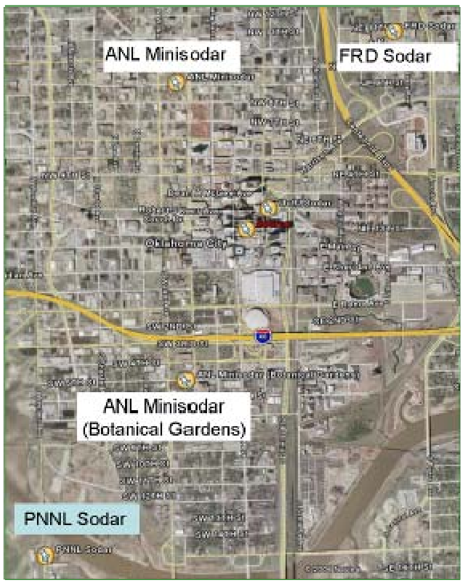


**Figure 15:** Site of JU03 experiment campaign. OKC.

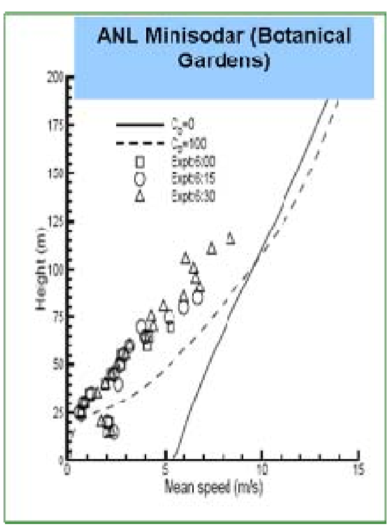


**Figure 16:** Mean speed. Model .vs. Obs

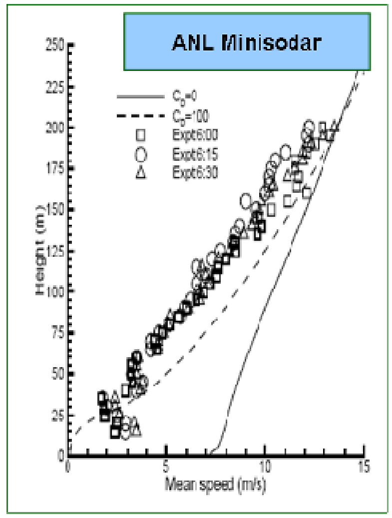


**Figure 17:** Mean speed. Model .vs. Obs

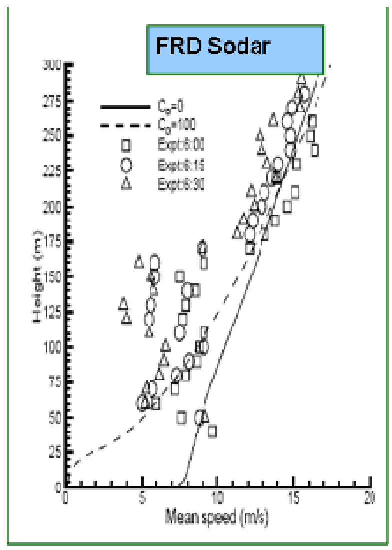


**Figure 18:** Mean speed. Model .vs. Obs

The flow field statistics predicted by urbanSTREAM were used to drive the urban dispersion models. Within the Eulerian framework, both the source-oriented (urbanEU) and receptor-oriented (urbanAEU) modes were tested, as well as the stochastic Lagrangian model (urbanLS) also in both forward and backward versions.

The simulations were conducted for the second continuous 30-min release of SF6 in IOP-9, which occurred in the period from 6:00-6:30 UTC (01:00-01:30 CDT) on 28 July 2003. The release height was 1.9 m. The constant release gas for this experiment was 2.0 g/s. The samplers used for comparisons include 19 samplers located on the CBD sampling grid and six samplers located along the 1-km sampling arc.

Figures 19, 20 and 21 compare predictions of the mean concentration [in parts-per-trillion by volume (pptv)] obtained using urbanEU, urbanAEU and urbanLS-1 with the experimental concentration data measured respectively, at 10 different sampling locations along Kerr Avenue and McGee Avenue; at eight sampling stations located along 4th Street and 5th Street and finally at two sampling locations along 6th Street and six sampling stations along the 1-km sampling arc.

The experimental concentration data shown here is for a 30-min averaging time.

Generally speaking, the predictions for mean concentration at or near the mean plume centerline were quite good, with predictions within a factor of two of the observed concentration. However, the predicted concentrations at sampling locations 56, 66, and 76 were more than a factor of five lower than the experimentally measured values, suggesting that either the predicted plume was too narrow or the eastern edge of the predicted plume was too far west at these locations. Furthermore, it is interesting to note that the 30-min average concentration at the receptor calculated using the influence function (receptor-oriented approach) generally agrees well with the concentration predicted using the source-oriented approach. The discrepancy in the predictions using these two approaches is due to the non-uniform grid utilized in the simulations (the mesh was finer in the region surrounding the source and coarser generally in the region downwind of the source where the receptors were located).

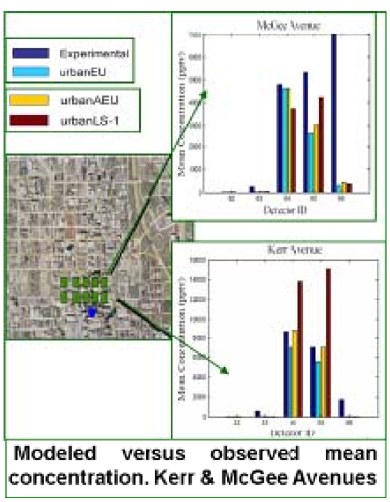


**Figure 19:** Mean concentration .vs. detectors measurements at Kerr & McGee Avenues.

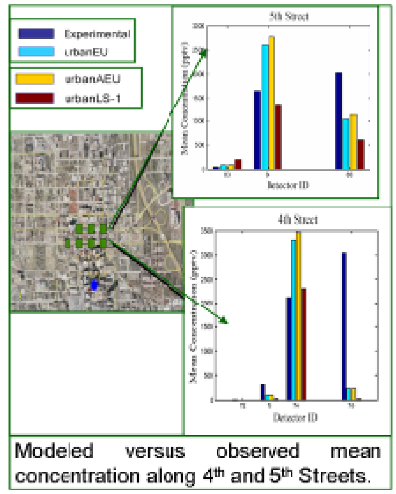


**Figure 20**: Mean concentration .vs. detectors measurements at 4th and 5th Streets.

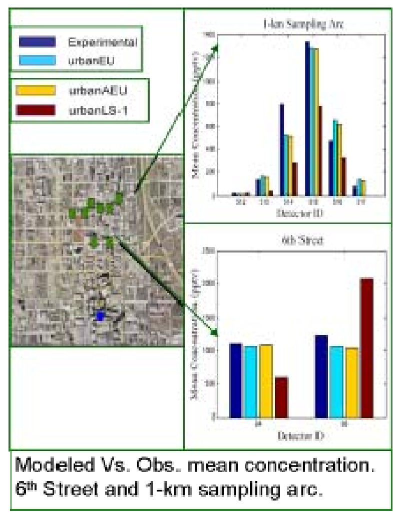


**Figure 21:** Mean concentration .vs. detectors measurements at 6th Street and 1-km sampling arc.

## 5. CANADIAN URBAN DISPERSION MODELING PROTOTYPE CAPABILITIES

A prototype of the urban flow and dispersion modeling system has been implemented in the computing environment of a government operations centre at the Canadian Meteorological Centre's Environment Emergency Response Division (EERS).

The prototype has been tested over Montreal and Vancouver. The following example illustrates its application to Vancouver where a hypothetical gas release is considered in the downtown area. The context of many of the scenarios in Vancouver is related to the planning of the 2010 Olympic Games.

The duration of the simulation is 30 minutes. For this particular test, wind was blowing from North-East (45$^{o}$) with speed of 11 m/s at 10 m AGL, and the amount of the SF6 tracer gas was 8.0 kg/s with a puff release. The release location is at Fairmont Waterfront Hotel (49.28809 N, 123.11526 W).

A graphical software tool developed by EERS and called "SPI" [Gauthier, J. P., 2005] is used for the 3D urban flow and dispersion visualization.

Figures 22 and 23 show respectively the portion of the city of Vancouver and the grid used in CFD suite calculation. In the internal grid the buildings are resolved explicitly and in the external grid the buildings are resolved virtually by calculating their impact through a drag force.

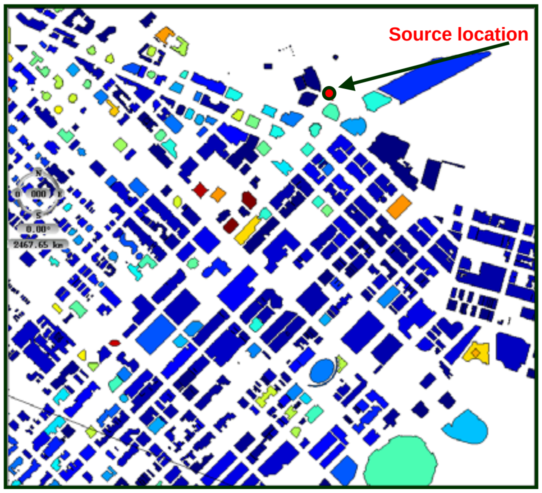


**Figure 22:** Hypothetical release in Vancouver Downtown

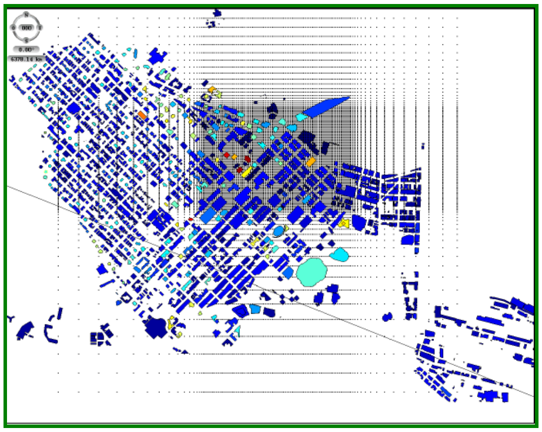

**Figure 23:** Grid showing the inner (building-aware) region with the fine grid and the outer (virtual buildings) region

The whole domain covers 3399 m x 3184 m x 936 m and the inner region covers 1215 m x 844 m x 936 m, in W-S, S-N and vertical directions.

The grid size for the large domain is 100 x 120 x 80 and the inner region grid size is 80 x 100 x 50.

In Figures 24 and 25, the horizontal wind and the mean concentration at 1.3 m above ground level are presented. We can see clearly the effect of the building on the flow pattern and hence on the dispersion pattern.

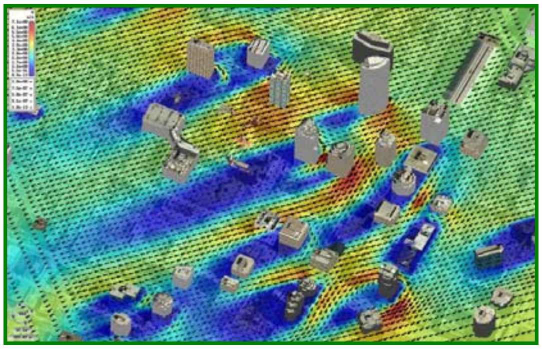

**Figure 24:** Horizontal wind at 1.3m AGL**.**

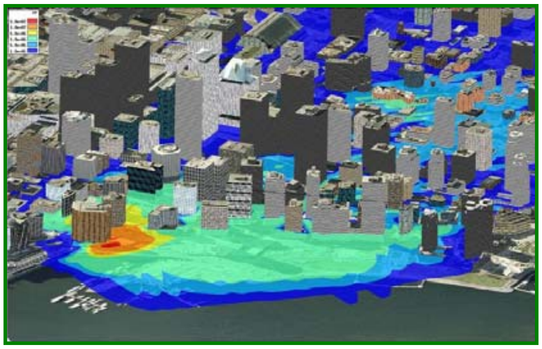

**Figure 25:** Mean concentration at 1.3m AGl. (Time average is 30 min.)

### 6. CANADIAN SYSTEM APPLICATION

Being built, for operational use, this system aims to, identify the hazardous zones more accurately and improve emergency preparedness and management of CBRN incidents in Canadian cities by providing quantitative and qualitative guidance that can lead to useful estimates of the resulting health risks to exposed population.

Future efforts will be made to ensure higher level of usability, efficiency, and robustness of the prototype system. It will incorporate practical dissemination methods to standardized set of customer products, and connection with other tools such as Health Canada's (RPB) ARGOS and offer options to provide users outputs in GIS formats.

Plans are to use this prototype system for, planning events of national Importance (such as

2010 Winter Olympic Games), operational response and post-event assessment.
The work from this project also links well with other projects that are studying the urban environment, such as The Environmental Prediction in Canadian Cities (EPiCC, http://www.epicc.uwo.ca/) project which is a project funded through the Canadian Foundation of Climate and Atmospheric Sciences (CFCAS) that seeks to better understand the urban atmosphere in Canada through a program of observation, modeling and remote sensing.

## 7. CONCLUSIONS

The principal objective of this project was the development of an advanced, fully validated, state-of-the-science modeling system for the prediction of turbulent urban flow through cities and the concomitant problem of modeling the dispersion and transport of CBRN agents released in a populated urban complex.

This system comprises an urban version of the Canadian meteorological model, downscaling from the regional scale at 15 km to a grid-size of 250 m including geometrical and thermal characteristics of cities, which provides boundary condition to the high resolution computational fluid dynamics model. The urban micro-scale building aware flow model provides turbulent statistics used by an Eulerian and Stochastic Lagrangian dispersion models.

The features of CUDM for modeling the transport and dispersion of Chemical, Biological, Radiological and Nuclear substances in urban areas include a rapid and easy generation of cityscape models directly from geospatial data, an explicit and implicit (force drag representation) modeling of buildings, an efficient numerical processing via distributed parallel computing, and a realistic representation of prevailing atmospheric conditions and turbulence. The system allows clear expansion capability to include in the future other important physical effects, such as thermal stratification effect, natural convection and buoyancy effect, advanced turbulence modeling, non-linear k-ε model, local grid refinement and space-filling curve (SFC) to achieve load-balancing on parallel system.

This work is part of a system to simulate agent transport and provide quantitative guidance leading to the estimation of the resulting health risks to the exposed population. A broad range of validated atmospheric flow and dispersion models is needed to cover a broad range of spatial and temporal scales and source types and to provide the appropriate level of detail, fidelity, and performance required for pre-event scenario planning, emergency response, and post-event assessment.

A follow-up 3-year project (CRTI 07-0196TD) has started in fall 2008, to i) further improve the science behind the urban modeling prototype, ii) develop additional infrastructure to move towards an operational system environment and iii) to further demonstrate the prototype system. Work is on-going towards demonstrating the capability for EERS to serve as a 24/7 National reach back and resource centre for provision of CBRN hazard model predictions and decision support products for emergency managers/decision makers at all levels of government.

## 8. ACKNOWLEDEGEMENTS

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## 9. REFERENCES

Allwine, K. J., Leach, M. J., Stockham, L. W., Shinn, J. S., Hosker, R. P., Bowers, J. F. and Pace, J. C. (2004). Overview of Joint Urban 2003 – An Atmospheric Dispersion Study in Oklahoma City. Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone. Seattle, Washington: American Meteorological Society.

Benbouta, N. (2007). Canadian Urban Flow and Dispersion Model (CUDM): Developing Canadian Capabilities in Urban Areas. Technical Report, Environmental Emergency Response Section, Canadian Meteorological Centre, Meteorological Service of Canada, Dorval Quebec, 25 pp.

Chagnon, F., (2007). Montréal Urban Snow Experiment (MUSE) - Report on the measurement campaigns of 2005 and 2006. Component 2 of CRTI Project 02-0093RD. EER Environment Canada.

Gauthier, J. P., (2005). Responding to environmental emergencies in real time at the Canadian Meteorological Center using SPI. Presentation at 10th Workshop on Meteorological Operational Systems, 14-18 November 2005, Exeter, UK, ECMWF.

Lemonsu, A., Leroux, A., Bélair, S., Trudel, S. and Mailhot, J. (2006). Methodology of Urban Cover Classification for Atmospheric Modeling. Preprints, Sixth Symposium on the Urban Environment, 30 January–2 February 2006, Atlanta, GA, American Meteorological Society, Paper 5.5.

Lemonsu, A., Bélair, S., Mailhot, J., Benjamin, M., Chagnon, F., Morneau, G., Harvey, B., Voogt, J. and Jean, M., (2008). Overview and first results of the Montreal Urban Snow Experiment 2005. *J. Appl. Meteor. Clim.*, 47, 59-75

Lemonsu, A., Leroux, A., Bélair, S. Trudel S., and Mailhot, J., (2009a). A general methodology of urban land cover classification for atmospheric modeling. *J. Appl. Meteor. Clim.*, (submitted)

Lemonsu, A., S. Bélair, and J. Mailhot (2009b): Evaluation of the Town Energy Balance model under cold and snowy conditions for the Montréal Urban Snow Experiment (MUSE) 2005. J. Appl. Meteor. Clim. (submitted).

Lemonsu, A., S. Bélair, and J. Mailhot (2009c). The new Canadian urban modeling system: Evaluation for two cases from the Joint Urban 2003 Oklahoma City experiment. Bound.-Layer Meteor., (submitted).

Leroux, A., A. Lemonsu, J.-P. Gauthier, S. Bélair, and J. Mailhot (2009). Automated urban land use and land cover classification for mesoscale atmospheric modeling over Canadian cities. Geomatica, 63, (in press).

Lien, F-S. and Leschziner, M. A. (1994). A General Non-Orthogonal Collocated Finite-Volume Algorithm for Turbulent Flow at all Speeds Incorporating Second Moment Closure, Part 1: Computational Implementation. Comp. Meth. App. Mech. Eng. 114, 123–148.

Lien, F.-S., Yee, E. and Wilson, J. D. (2005). Numerical Modeling of the Turbulent Flow Developing Within and Over a 3-D Building Array, Part II: A Mathematical Foundation for a Distributed Drag Force Approach. Boundary-Layer Meteorol., 114, 245–285.

Lien, F.-S. and Yee, E. (2005). Numerical Modeling of the Turbulent Flow Developing within and Over a 3-D Building Array, Part III: A Distributed Drag Force Approach, Its Implementation and Application. Boundary-Layer Meteorol., 114, 287–313

Mailhot, J., S. Bélair, L. Lefaivre, B. Bilodeau, M. Desgagné, C. Girard, A. Glazer, A.-M. Leduc, A. Méthot, A. Patoine, A. Plante, A. Rahill, T. Robinson, D. Talbot, A. Tremblay, P. Vaillancourt, A. Zadra, and A. Qaddouri (2006). The 15-km version of the Canadian regional forecast system. Atmos.-Ocean, 44, 133-149.

Masson, V. (2000). A Physically-Based Scheme for the Urban Energy Budget in Atmospheric Models. Boundary-Layer Meteorol., 94, 357–397.

Masson, V., Grimmond, C. S. B. and Oke, T. R. (2002). Evaluation of the Town Energy Balance (TEB) Scheme with Direct Measurements from Two Districts in Two Cities. J. Appl. Meteorol., 41, 1011–1026.

Van Doormal, J. P., and Raithby, G.D., (1984). “Enhancement of the SIMPLE Method for Predicting Incompressible Fluid Flows”. *Numerical Heat Transfer*, **7**, 147-163.

Wilson, J. D. (2007). Technical Description of Urban Microscale Modeling System: Component 4 of CRTI Project 02-0093RD. J. D. Wilson and Associates, Edmonton, Alberta

Yee, E., Lien, F-S., and Ji, H. (2007). Technical Description of Urban Microscale Modeling System: Component 1 of CRTI Project 02-0093RD. DRDC Suffield TR 2007–067, Defence R&D Canada – Suffield, Ralston, Alberta.

**ACRONYMS:**

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| ANL: | Argone National Laboratory, USA. |
| ARLFRD: | Atmospheric Research Laboratory Field Research Division, USA. |
| CBRN: | Chemical, Biological, Radiological or Nuclear. |
| CFD: | Computational Fluid Dynamics. |
| CMC: | Canadian Meteorological Centre. |
| CRTI: | DRDC's Chemical, Biological, Radiological or Nuclear Research and Technology Initiative. |
| CUDM: | Canadian Urban Flow and Dispersion Model. |
| DEM: | Digital Elevation Model. |
| DRDC: | Defence Research and Development. |
| EER: | Environmental Emergency Response Division. |
| GEM: | Global Environmental Multi-scale Model. |
| IOP: | Intensive Observation Period. |
| ISBA: | Interaction Surface Biosphere Atmosphere, the surface land scheme. |
| JU03: | Joint Urban 2003 Experiment Campaign hold on June-July 2003 in Oklahoma City. |
| MSC: | Meteorological Service of Canada. |
| MUSE: | Montreal Urban Snow Experiment. |
| NTBD: | National Topographic Base Data. |
| OKC: | Oklahoma City. |
| RPN: | Recherche en Prévision Numérique, Environment Canada. |
| SPI: | Spherical Projection Interface, EER Viewer Tool. |
| TEB: | Town Energy Balance Scheme. |
| TKE: | Turbulent Kinetic Energy |