MODELING WIND FLOW AND TURBULENCE IN OKLAHOMA CITY

Fue-Sang Lien[1], Eugene Yee[2], Hua Ji[3] and K.J. Hsieh[1]

[1]University of Waterloo, Canada
[2]Defence R&D Canada – Suffield, Canada
[3]Waterloo CFD Engineering Consulting, Canada
fslien@uwaterloo.ca

July 16 – July 19, 2006
The 4th International Symposium on Computational Wind Engineering, Yokohama, Japan

Acknowledgement

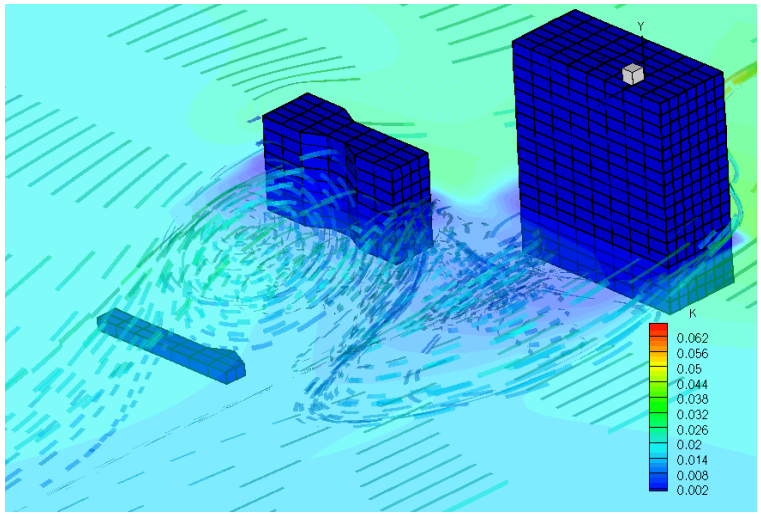
CRTI Project #02-0093RD

supported by

Defence R&D Canada – Suffield

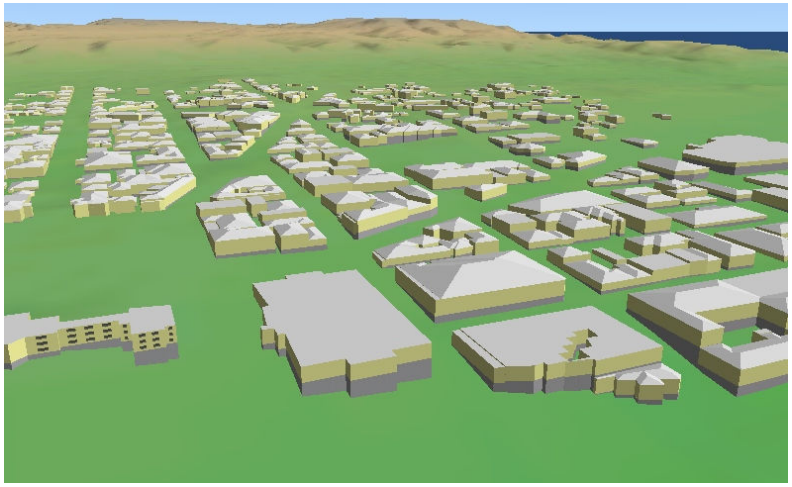
Environment Canada

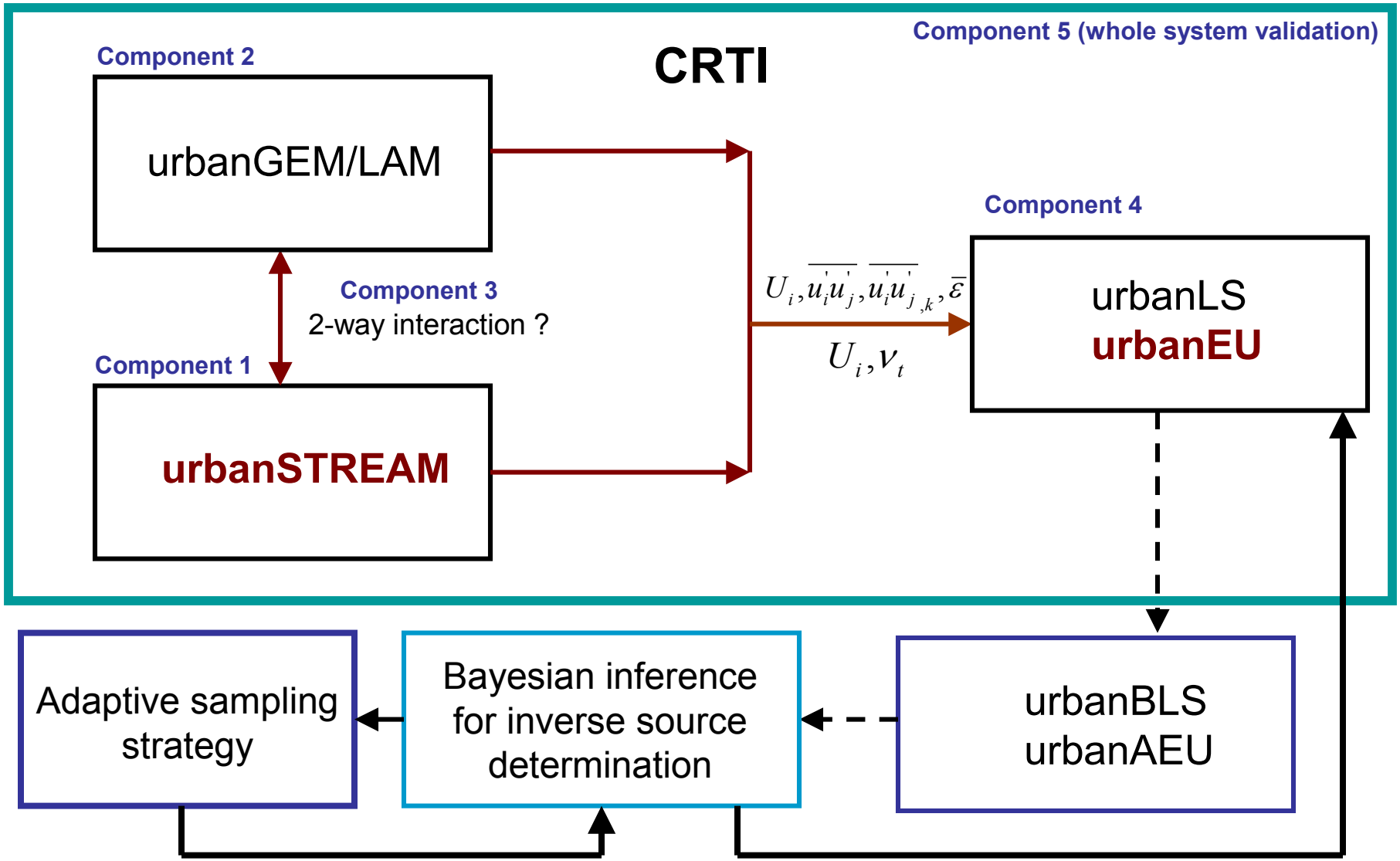
CRTI: **C**hemical, Biological, Radiological, and Nuclear **R**esearch and **T**echnology **I**nitiative



Motivation

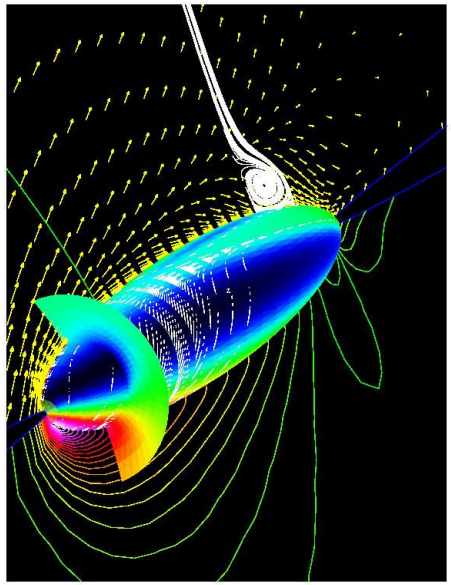
- Release of **C**hemical, **B**iological, **R**adiological, or **N**uclear **(CBRN)** agents in populated urban centers is an emerging threat
- Dispersion of CBRN agents in an urban environment encompasses multiple time and space scales and hence, is a very complex phenomenon
- **Need to develop a real-time, multi-scale modeling system to determine**
  - **Where is the agent now**
  - **Where has it been**
  - **Where is it going**




Component 5 (whole system validation)
CRTI
Component 2
urbanGEM/LAM
Component 3
2-way interaction ?
Component 1
urbanSTREAM
$U_i, \overline{u_i' u_j'}, \overline{u_i' u_j'}_{,k}, \overline{\varepsilon}$
U_i, ν_t
Component 4
urbanLS
urbanEU
Adaptive sampling strategy
Bayesian inference for inverse source determination
urbanBLS
urbanAEU

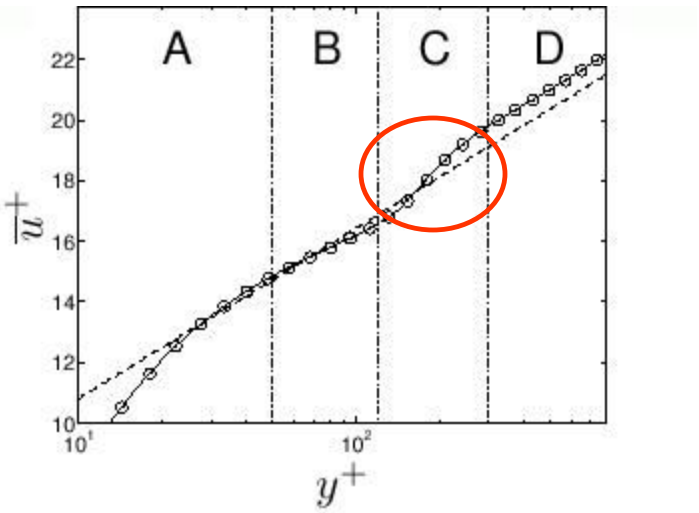
urbanSTREAM

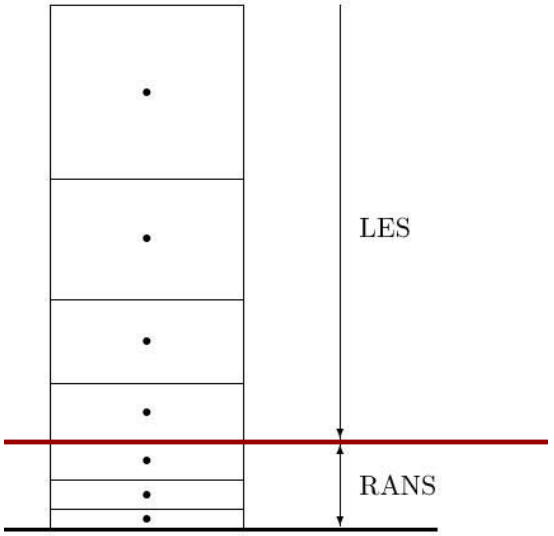
- general non-orthogonal, cell-collocated formulation
- monotonic version of QUICK satisfying TVD constraints (**UMIST** limiter)
- pressure-correction methodology (SIMPLEC)
- **parallelization using MPI**
- a range of turbulence closure models and simulation methodologies for
  - RANS
  - URANS
  - **LES** (**explicit** and **implicit**)
  - Hybrid URANS/LES
  - **PRNS**



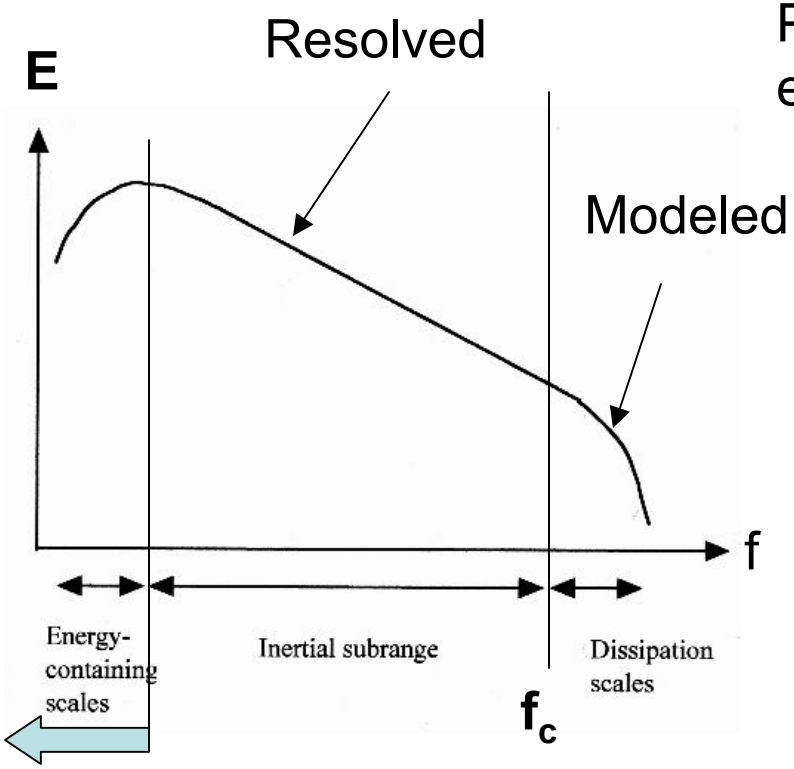
LES or Hybrid RANS/LES?

1. Typical grid resolution required for LES in wall-bounded flows is still quite high because there exits no longer a separation in length scales near walls.
2. Hybrid RANS/LES is promising. However, ***an artificial buffer-like layer*** often occurs at the interface.





Partially **R**esolved **N**umerical **S**imulation [**PRNS**, Shih & Liu (2004)]



URANS

$C_\mu = 0.09$

PRNS is based on **time-filtered** NS equation

$$\nu_t = F_{\mathrm{RCP}}(f_c) C_\mu \frac{k^2}{\varepsilon}$$

$$\text{RANS: } F_{\mathrm{RCP}}(f_c) \to 1^- \text{ as } f_c \to 0^+$$

$$\text{DNS: } F_{\mathrm{RCP}}(f_c) \to 0^+ \text{ as } f_c \to 1/t_K$$

where t_K is Kolmogorov time scale

Question here is how to determine the precise functional form for the **R**esolution **C**ontrol **P**arameter $F_{RCP}(f_c)$

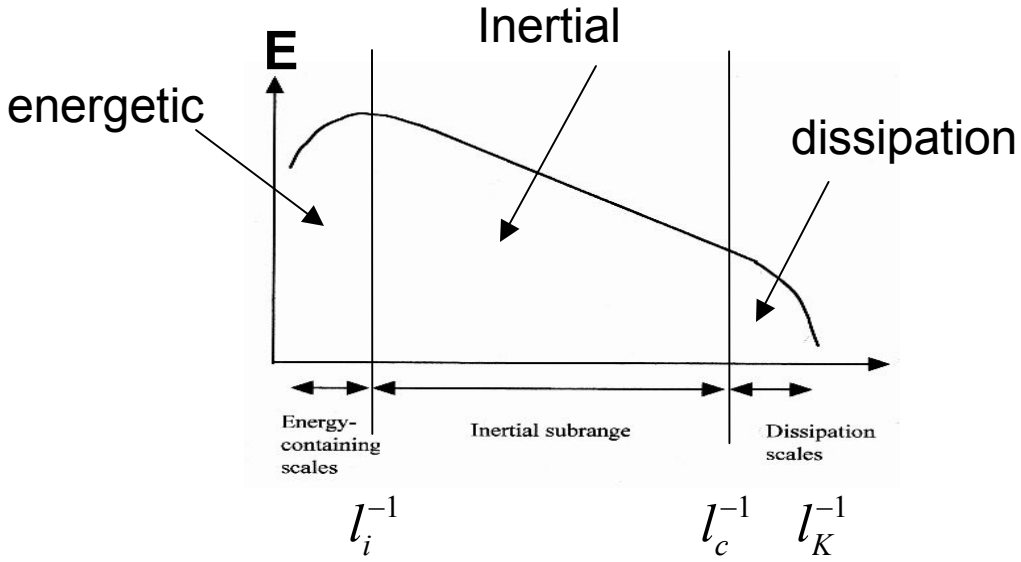
Proposal for Resolution Control Parameter

Since temporal and spatial filtering operations are initimately link,

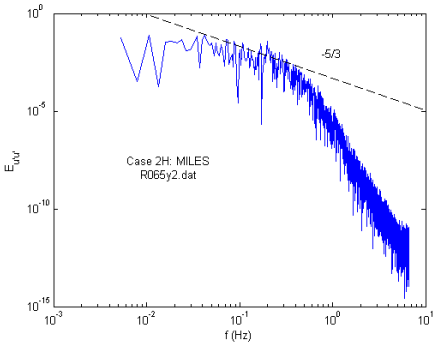
$$F_{\mathrm{RCP}} = F_{\mathrm{RCP}}(l_i, l_c, l_K)$$

where l_i, l_c, l_K are integral, cutoff and Kolmogorov length scales:

$$l_i = k^{3/2} / \varepsilon, \quad l_c = 2\max\left[(\Delta_x \Delta_y \Delta_z)^{1/3}, |\vec{u}|\Delta t\right], \quad l_K = (\nu^3 / \varepsilon)^{1/4}$$



Let us assume the energy specturm $E(\kappa) \propto \kappa^{-5/3}$ and $\kappa \propto l$

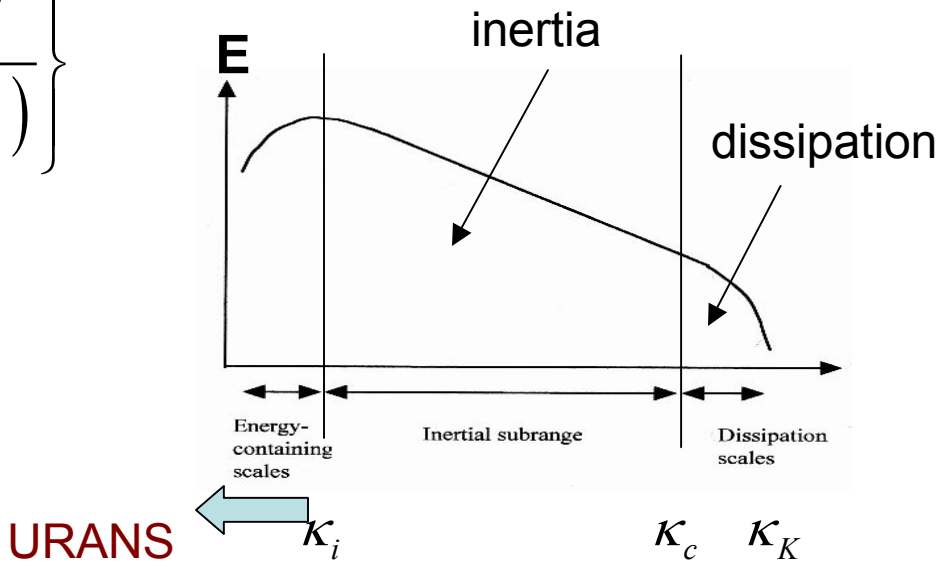


$$\Rightarrow F_{RCP} = \left\{ \frac{\int_{\kappa_c}^{\kappa_K} E(\kappa) d\kappa}{\int_{\kappa_i}^{\kappa_K} E(\kappa) d\kappa} \right\}^n = \left\{ \frac{\text{inertial}}{\text{inertial+dissipation}} \right\}^n$$

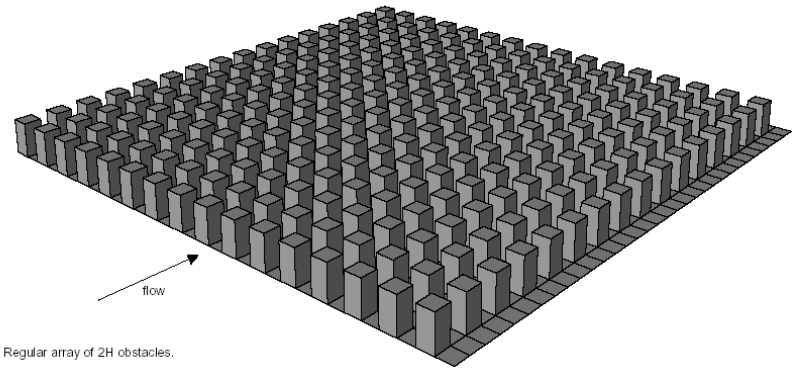
$$= \left\{ -\frac{\left[\kappa_K^{2/3} - \left(r\kappa_K - r\kappa_i + \kappa_i \right)^{2/3} \right] \kappa_i^{2/3}}{\left(r\kappa_K - r\kappa_i + \kappa_i \right)^{2/3} \left(\kappa_i^{2/3} - \kappa_K^{2/3} \right)} \right\}^n$$

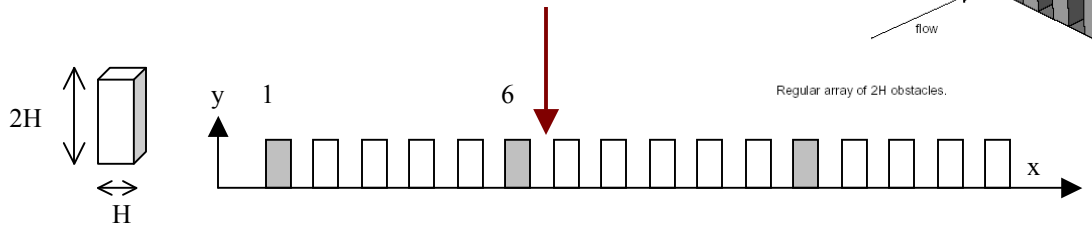
where

$$r = (\kappa_c - \kappa_i)/(\kappa_K - \kappa_i)$$

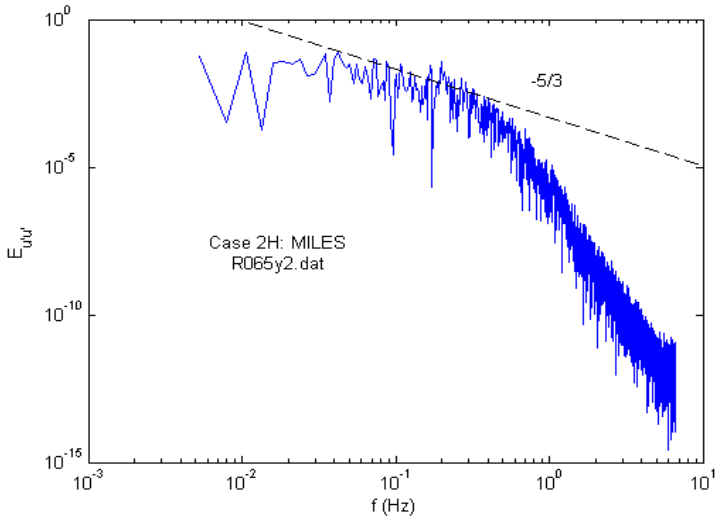


Energy Spectra

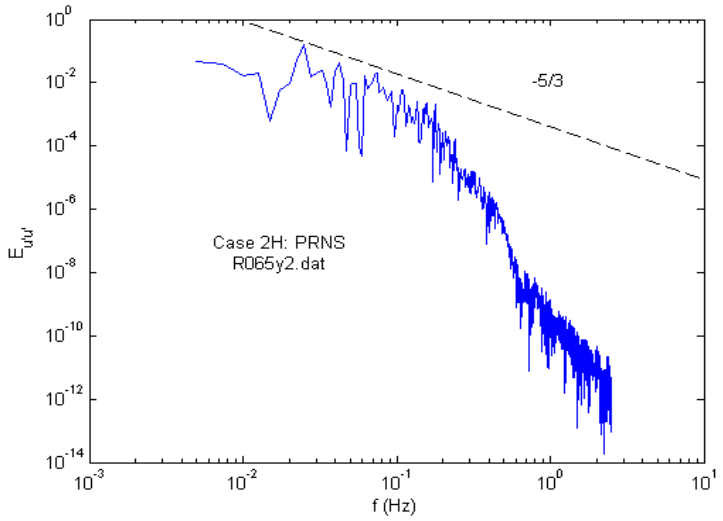




MILES: dt=0.075



PRNS: dt=0.2

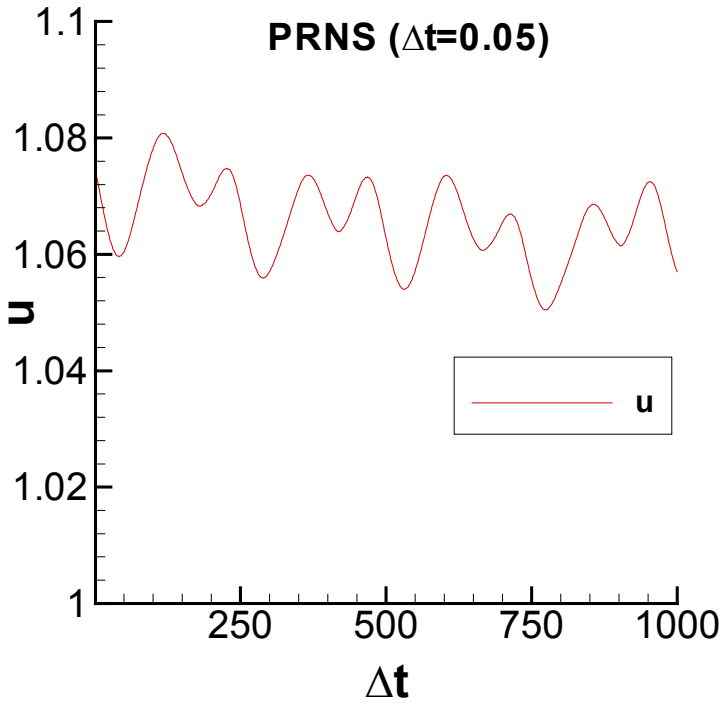


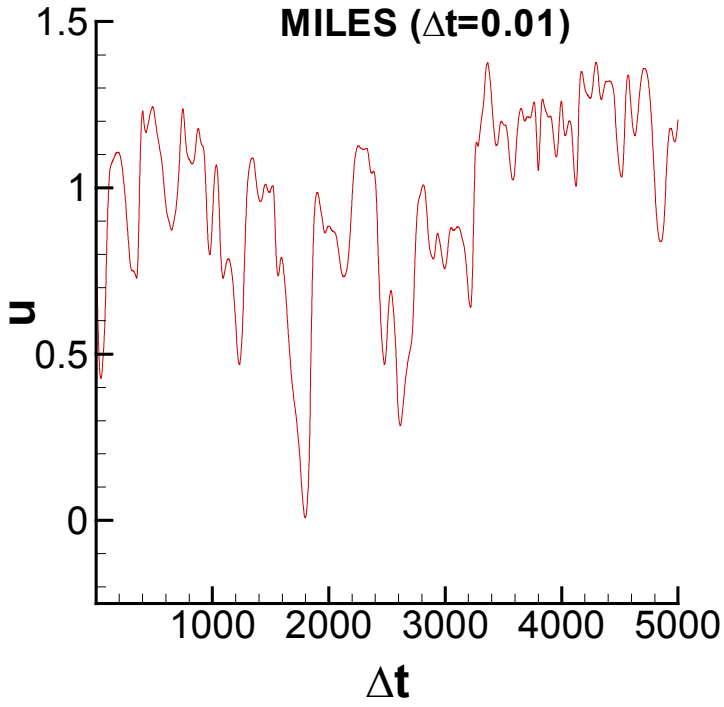
Time step used in PRNS is larger than in LES

Sample Time History

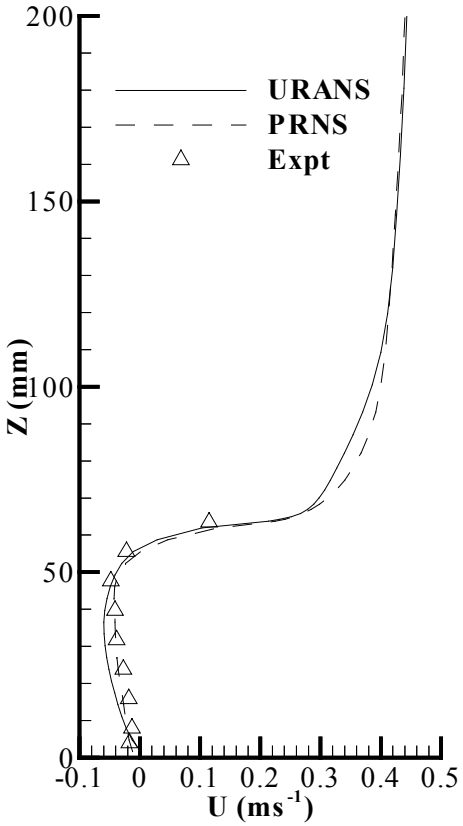
PRNS { smaller Δt
shorter averaging time

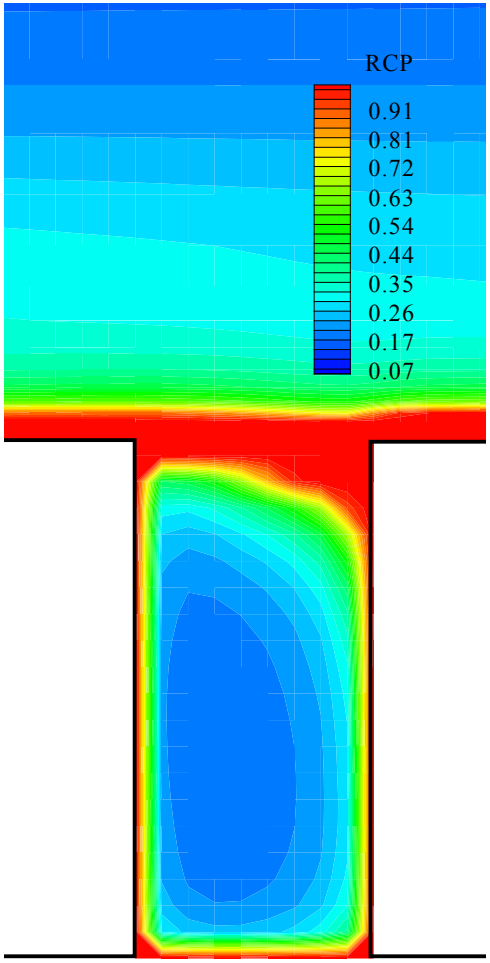
LES

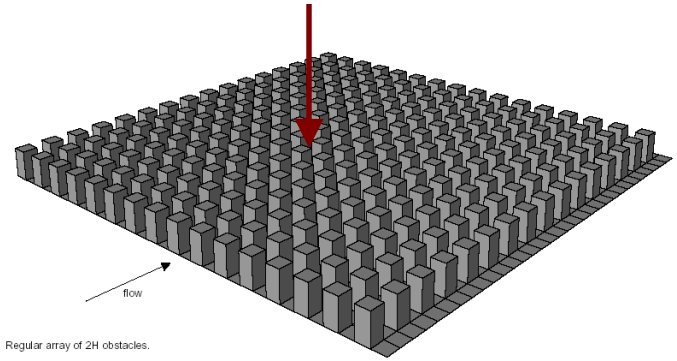




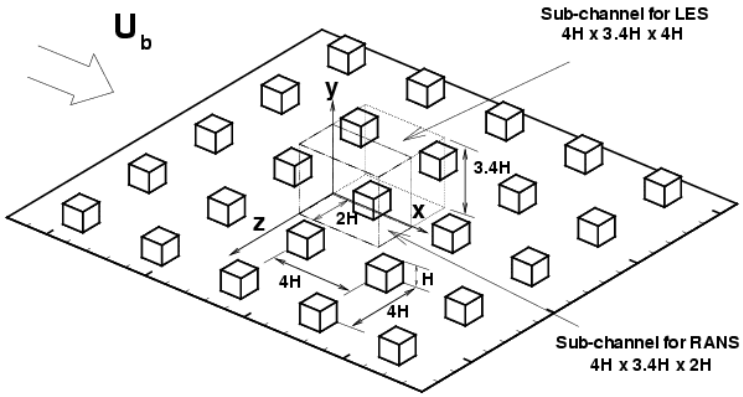
Mean Velocity Profiles and F_{RCP}

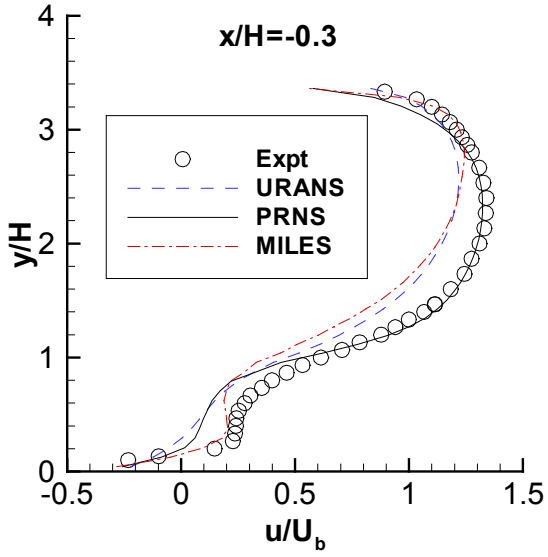


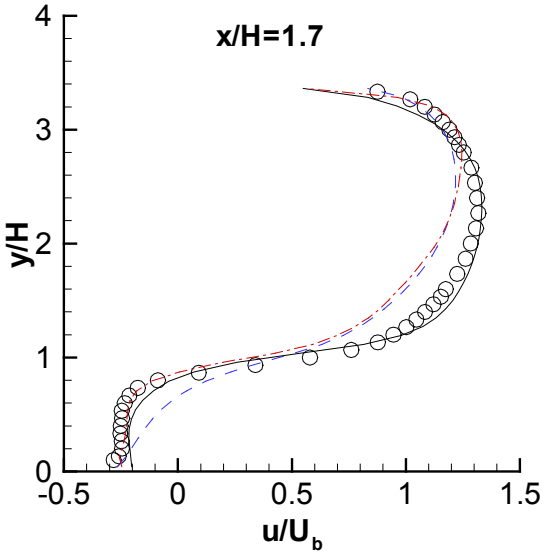


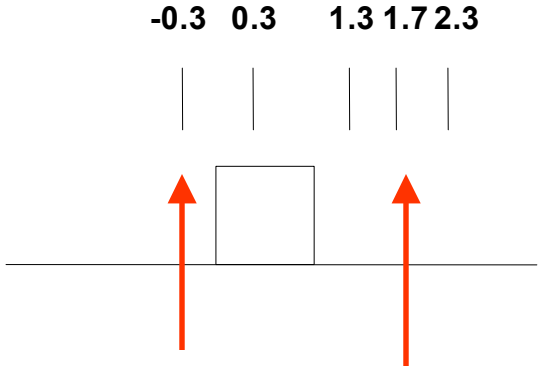


Fully-Developed Flow Over a Matrix of Cubes





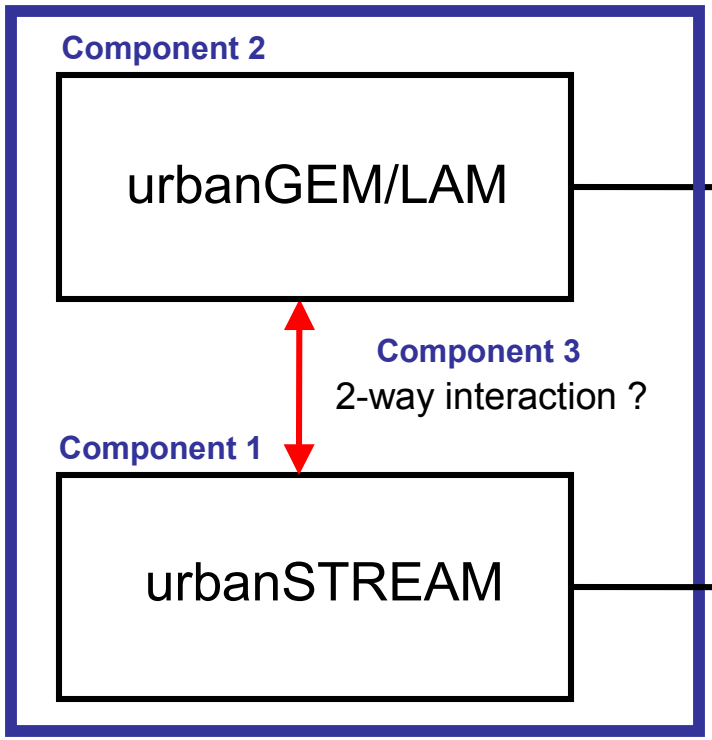


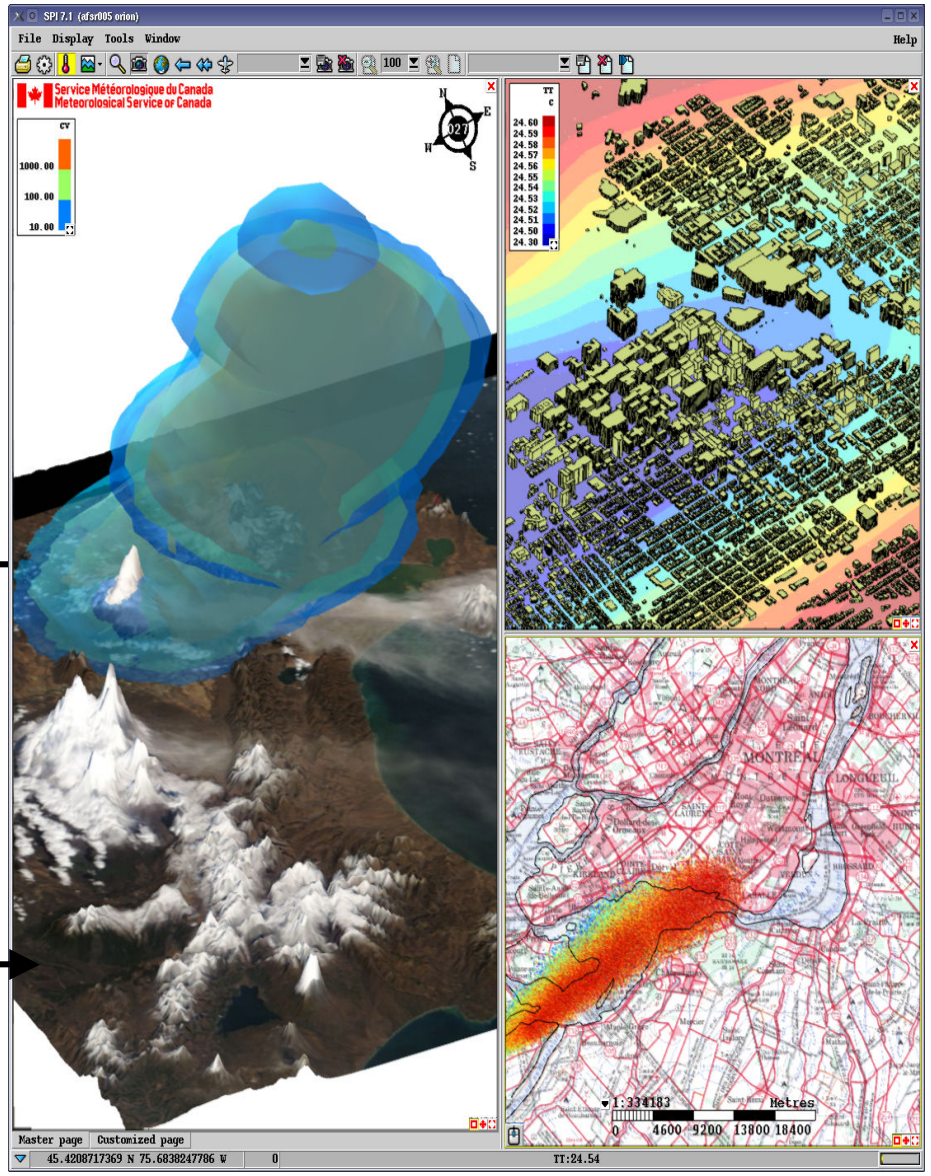


8th ERCOFTAC Workshop on Turbulence Modeling

Coupling GEM/LAM with urbanSTREAM

1. urbanGEM/LAM is a mesoscale code from Environment Canada
2. urbanSTREAM is a microscale CFD model





Flow models

Present Drag-Force Approach

(Lien, Yee and Wilson, 2005)

Momentum Equation

$$\frac{\partial \langle \overline{u}_j \rangle \langle \overline{u}_i \rangle}{\partial x_j} = -\frac{\partial \langle \overline{p} \rangle}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu + \nu_t)\left(\frac{\partial \langle \overline{u}_i \rangle}{\partial x_j} + \frac{\partial \langle \overline{u}_j \rangle}{\partial x_i} \right) - \frac{2}{3}\delta_{ij}\overline{k} \right]$$

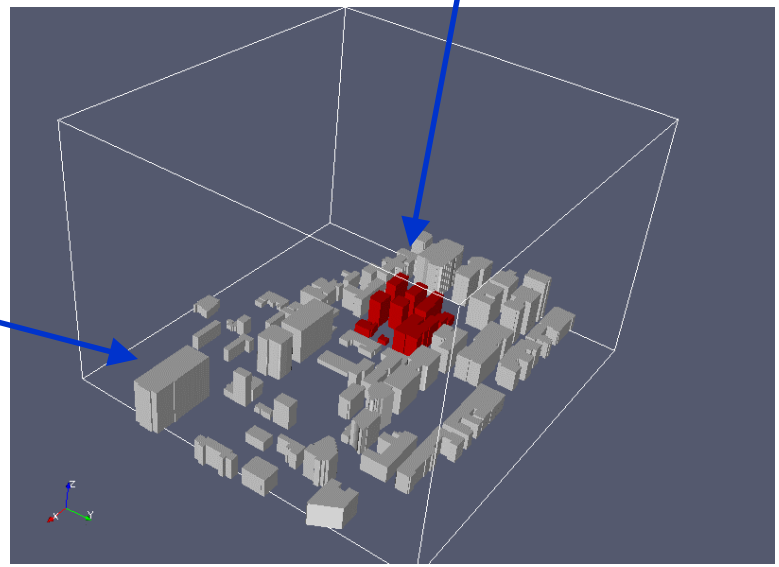
$$+ C_D \hat{A}\left[\left(Q + \frac{2}{3}\frac{\overline{k}}{Q} \right)\langle \overline{u}_i \rangle + \nu_t \left(\frac{\partial \langle \overline{u}_i \rangle}{\partial x_j} + \frac{\partial \langle \overline{u}_j \rangle}{\partial x_i} \right)\frac{\langle \overline{u}_i \rangle}{Q} \right]$$

Drag force

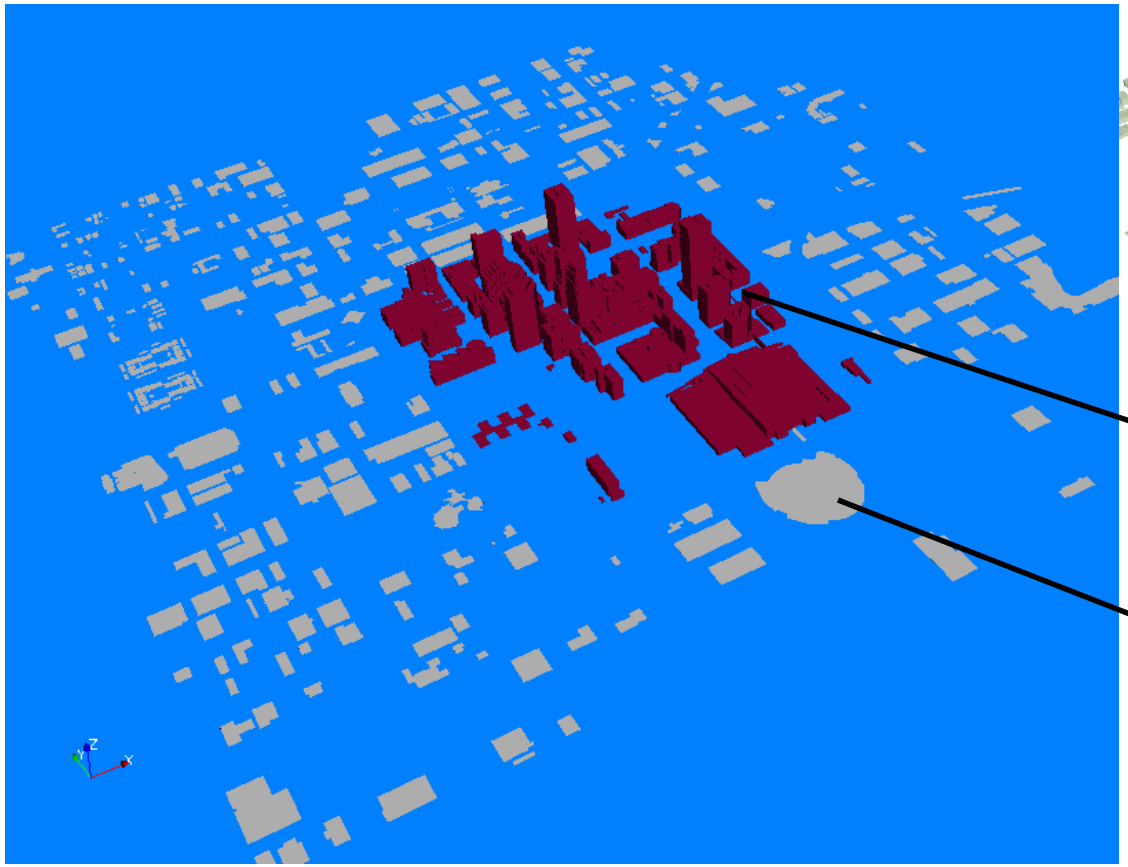
where $Q = \sqrt{\langle \overline{u}_i \rangle \langle \overline{u}_i \rangle}$

Resolved Building

Virtual Building



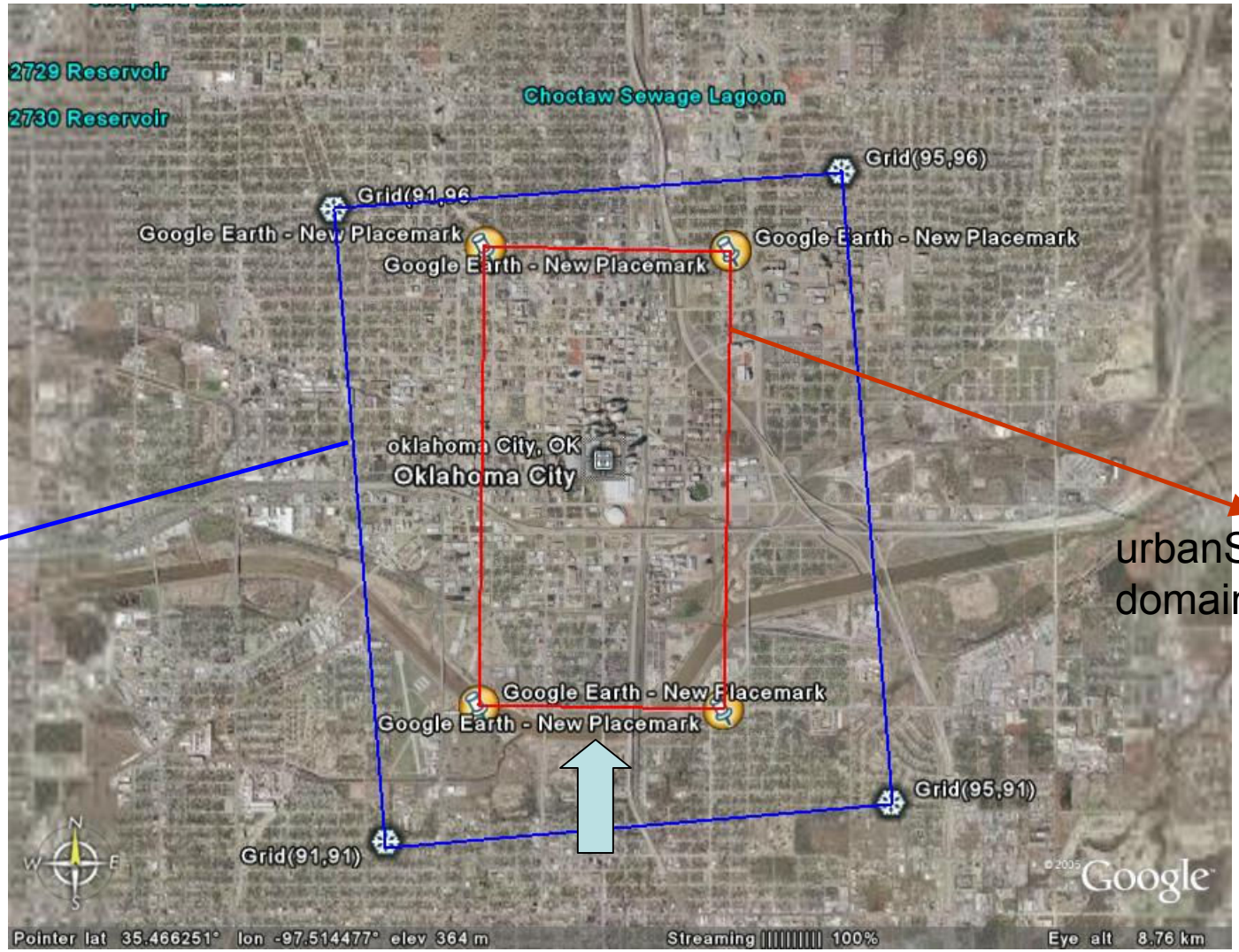
Present Focus: JU2003
Oklahoma City



Resolved Building

Virtual Building

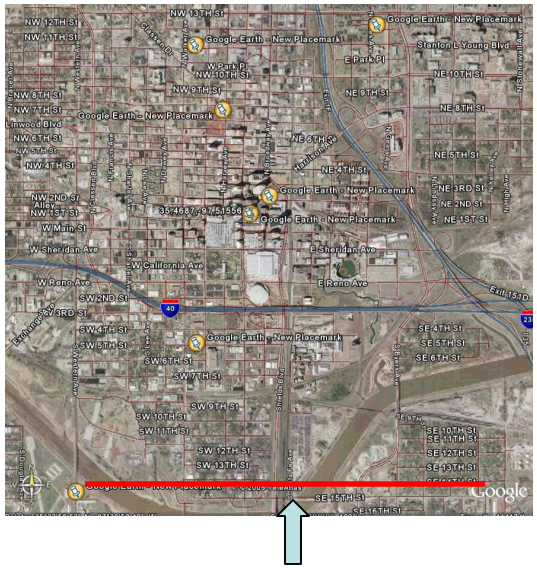
Coupling GEM/LAM with urbanSTREAM (One-Way Interaction)

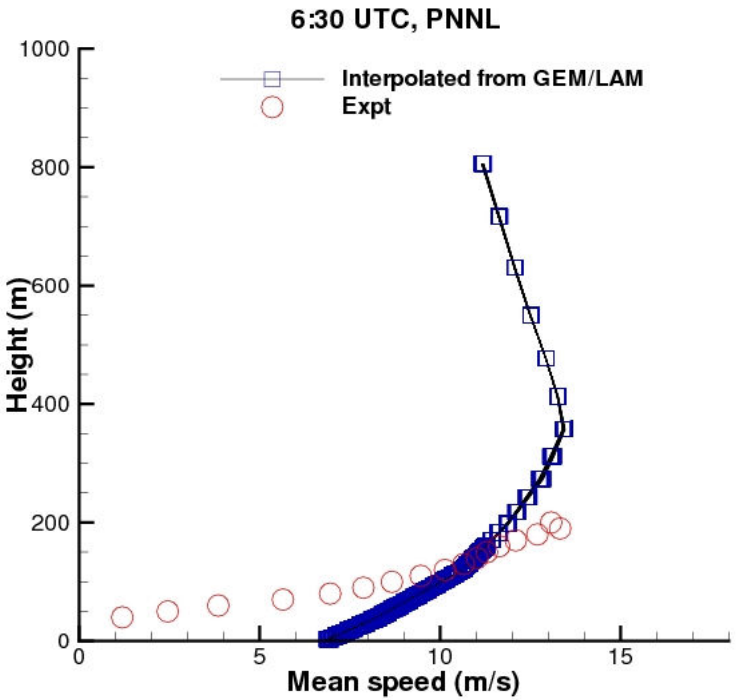


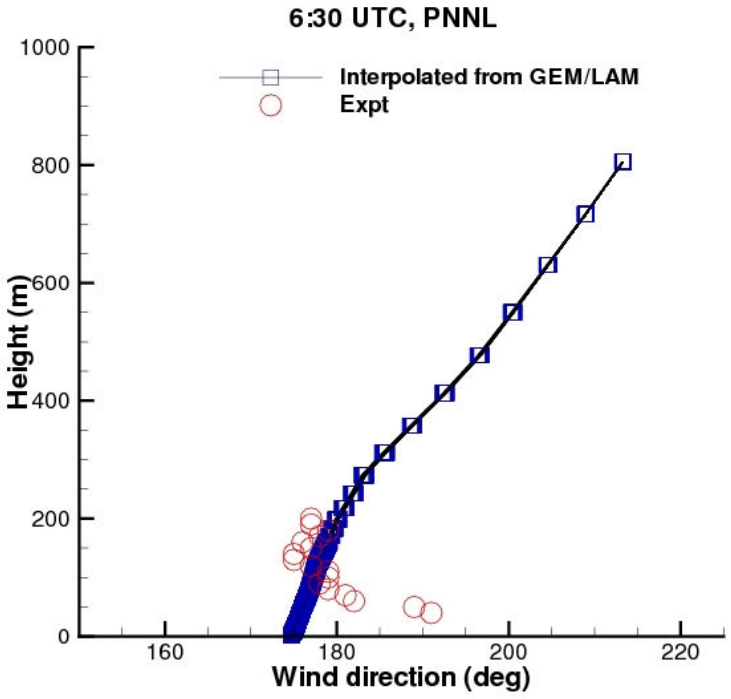
GEM/LAM domain

urbanSTREAM domain

Inflow Condition from GEM/LAM

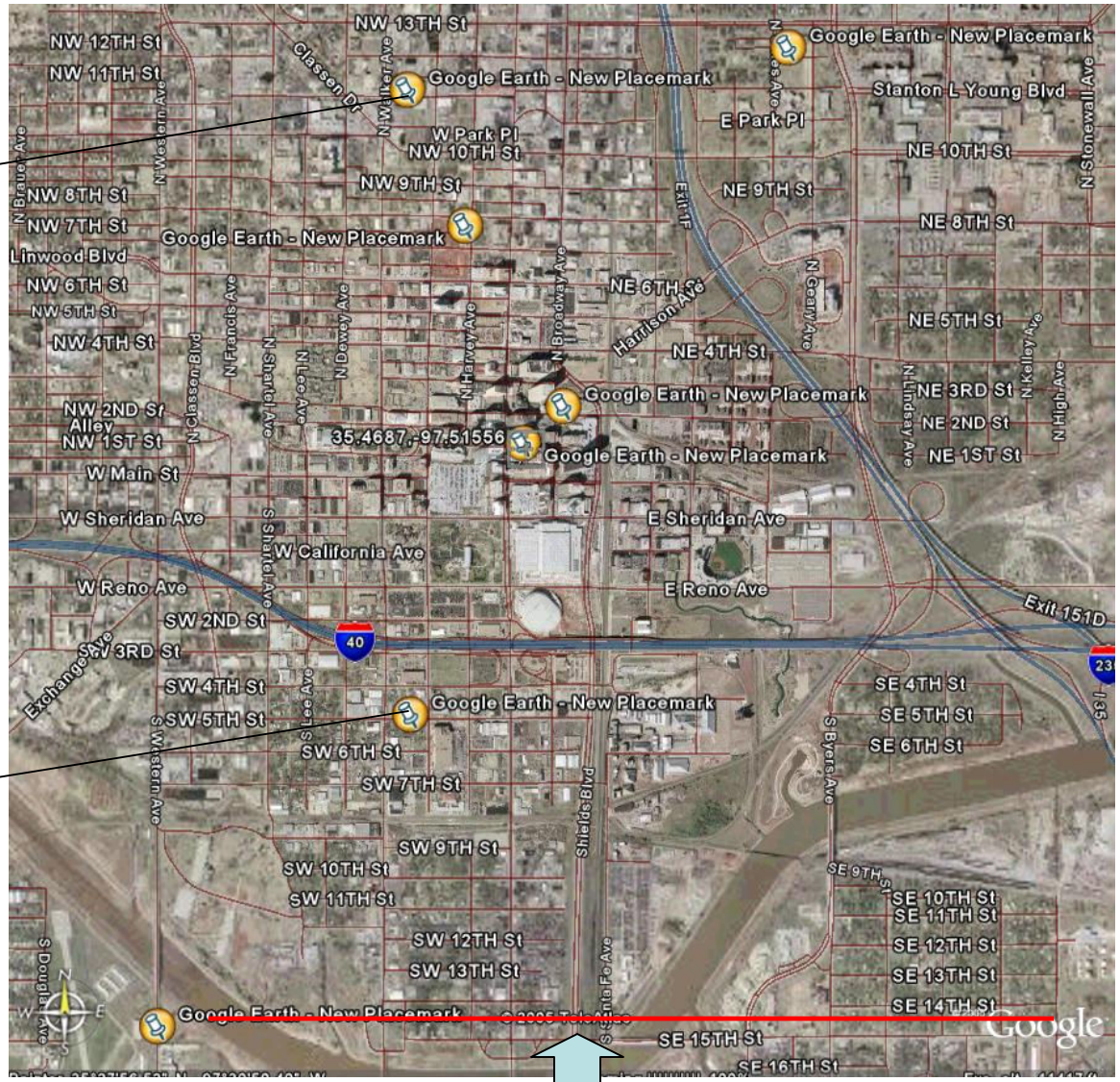






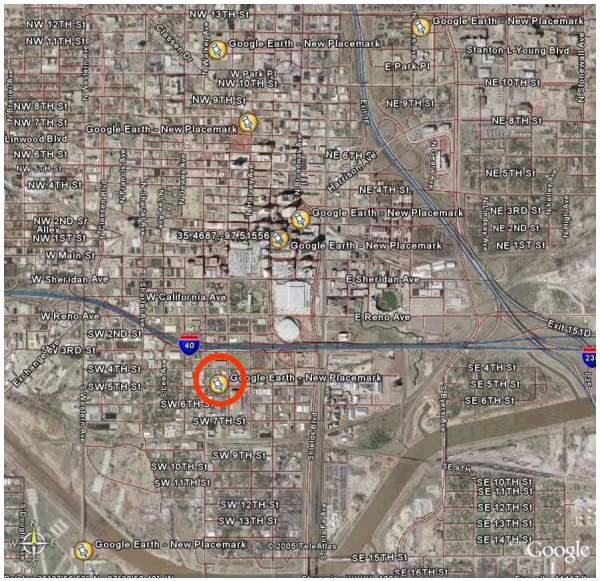
Comparison with Experimental Data

Location 2



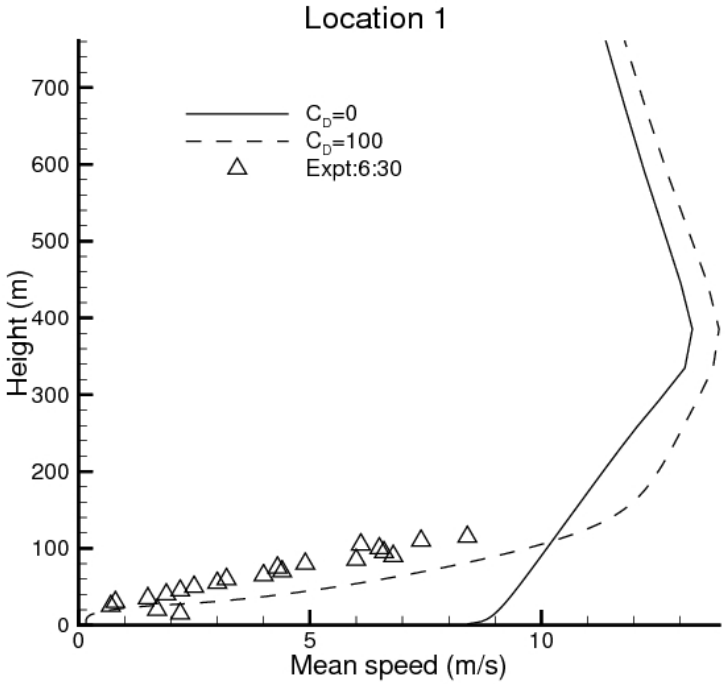
Location 1

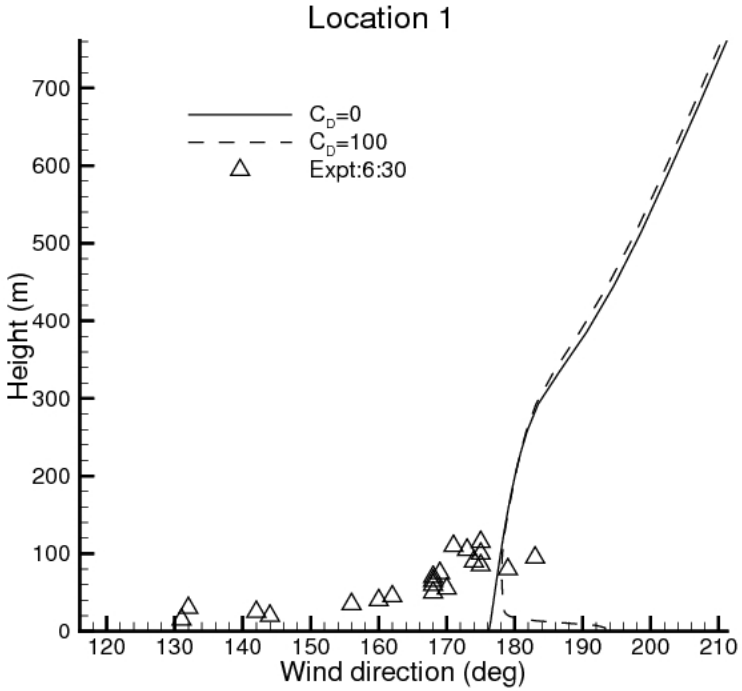
Mean wind speed and direction at Location 1



△ Expt data

Drag force

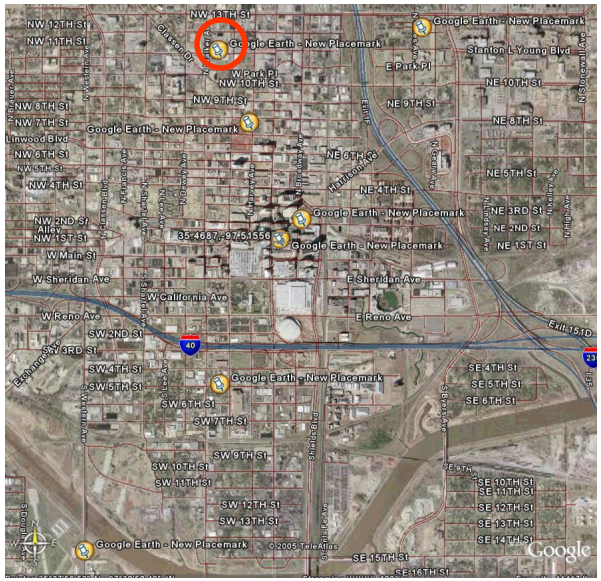


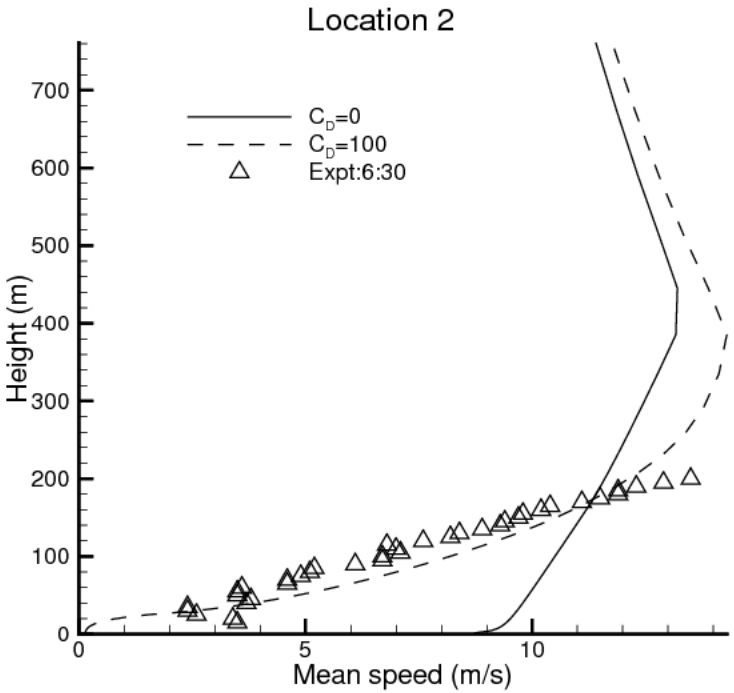


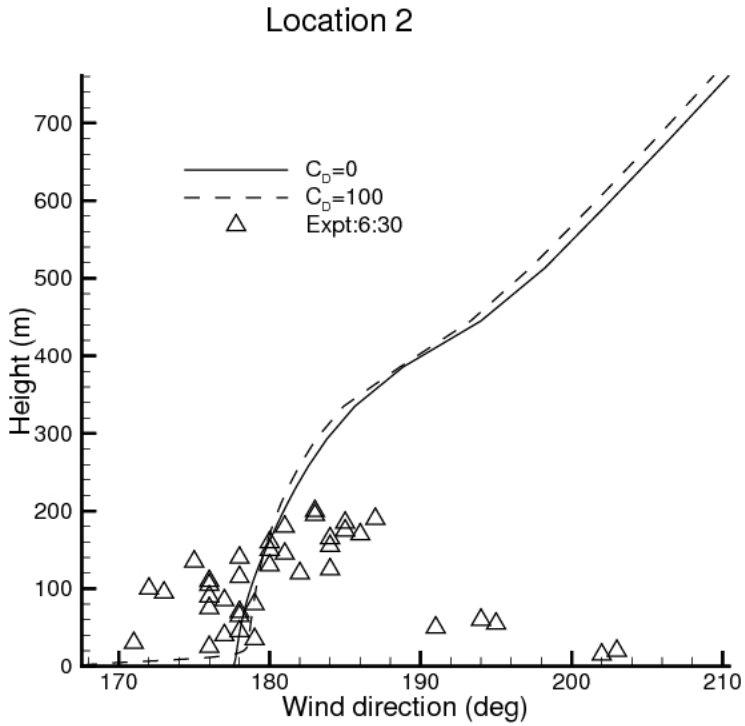
Mean wind speed and direction at Location 2

△ Expt data

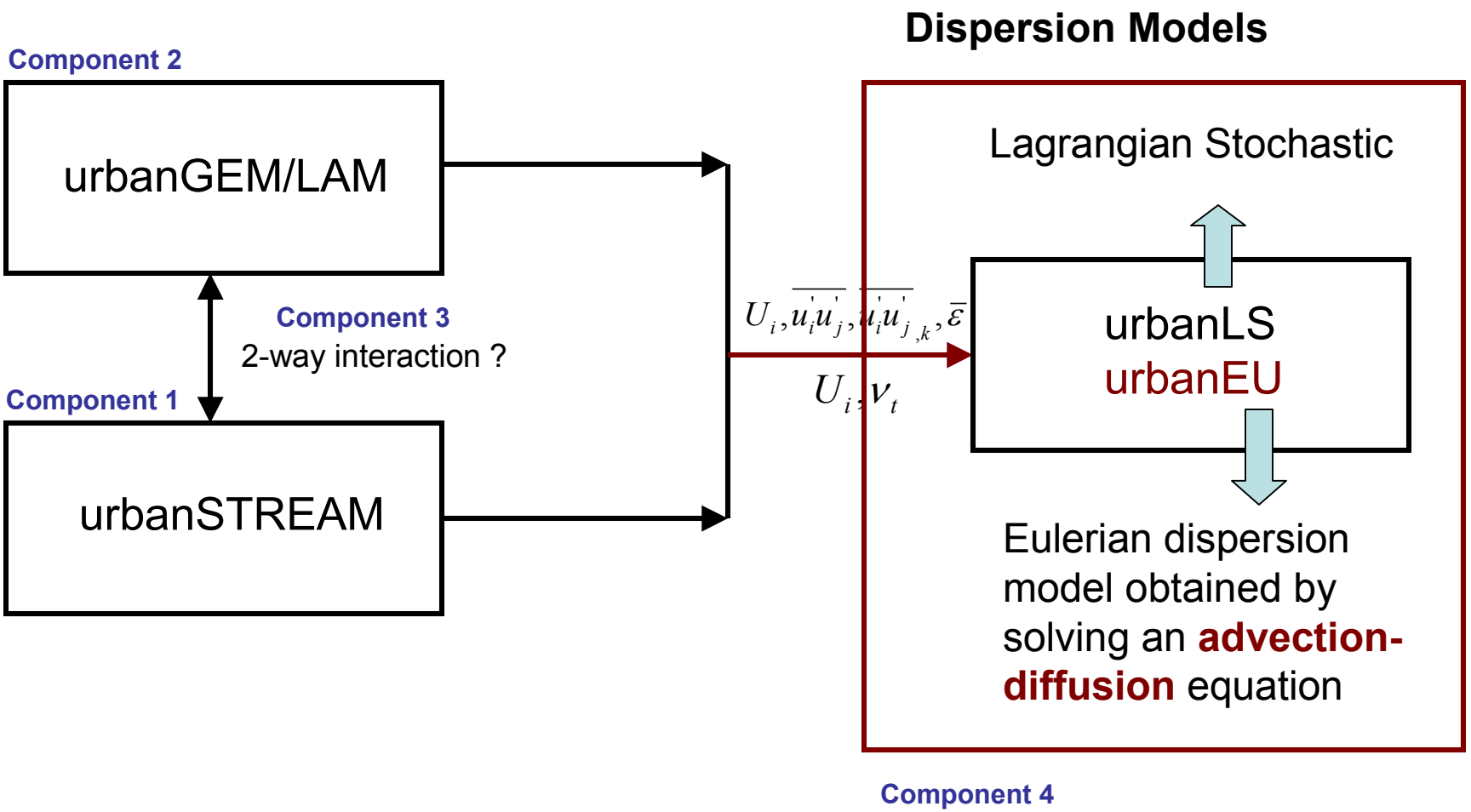
---------- Drag force







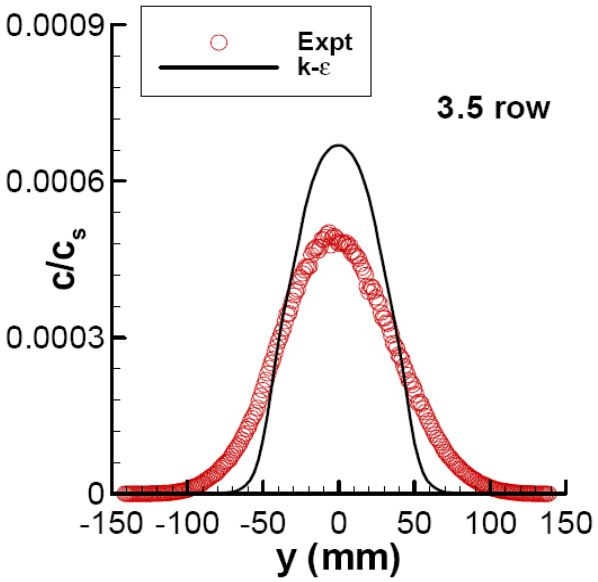
urbanEU: Eulerian Dispersion Model



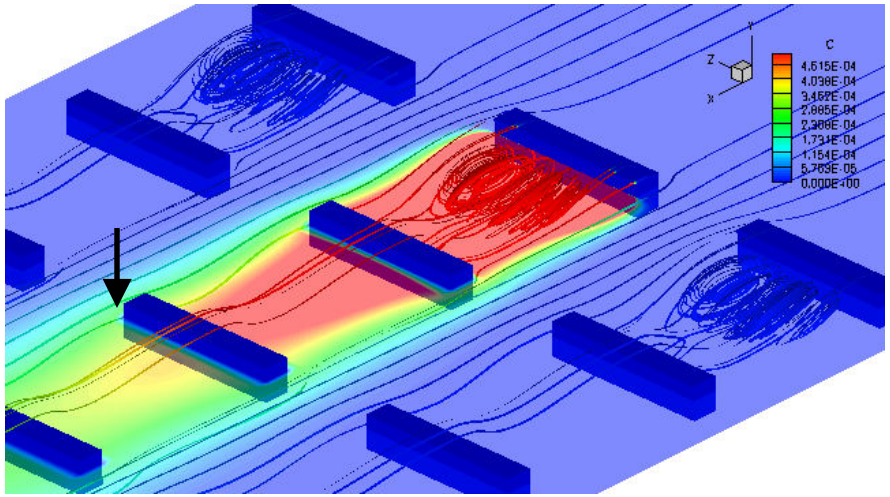
Governing Equations for Dispersion

$$\frac{\partial \overline{c}}{\partial t} + \frac{\partial}{\partial x_j}\overline{u}_j\overline{c} = \frac{\partial}{\partial x_j}\left(D\frac{\partial \overline{c}}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\overline{u_j' c'} + S$$

where $\overline{u_j' c'} = -\frac{\nu_t}{\sigma_c}\frac{\partial \overline{c}}{\partial x_j}$,

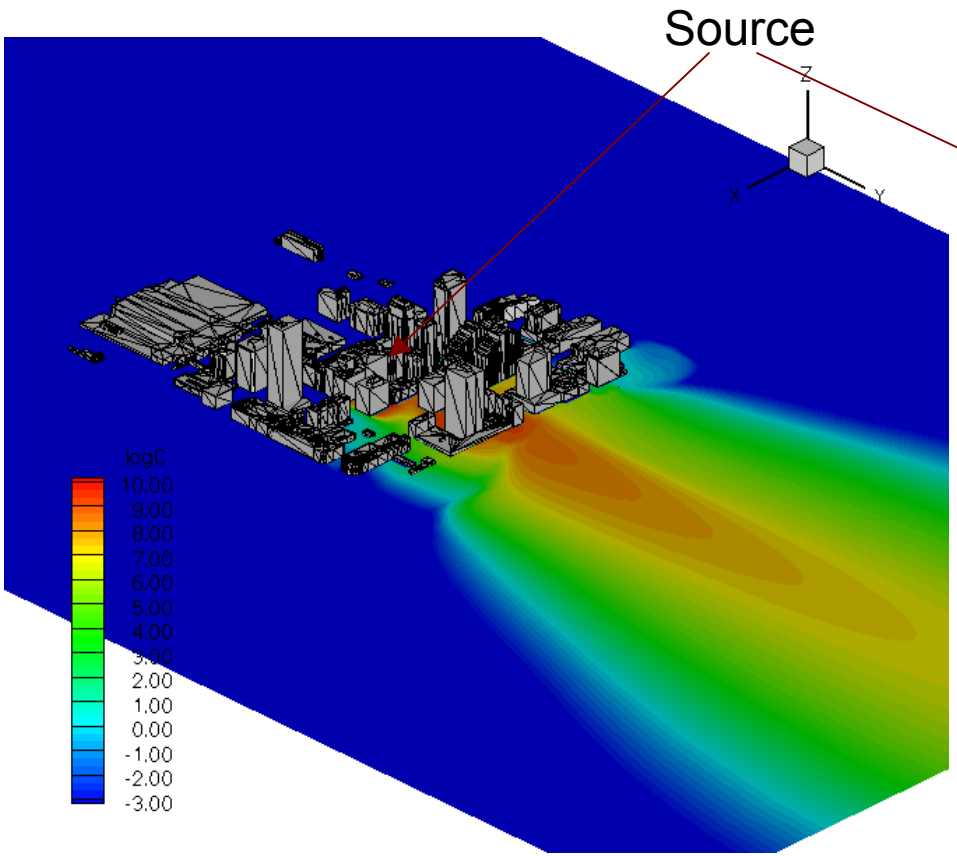


Horizontal Concentration Statistics at z/H=0.75



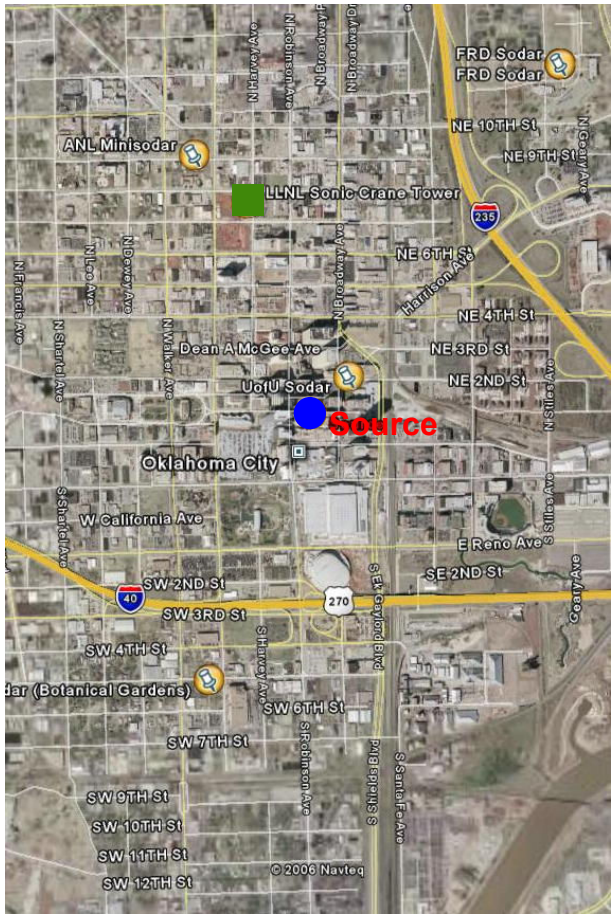
MUST Array

Concentration Field in Oklahoma City

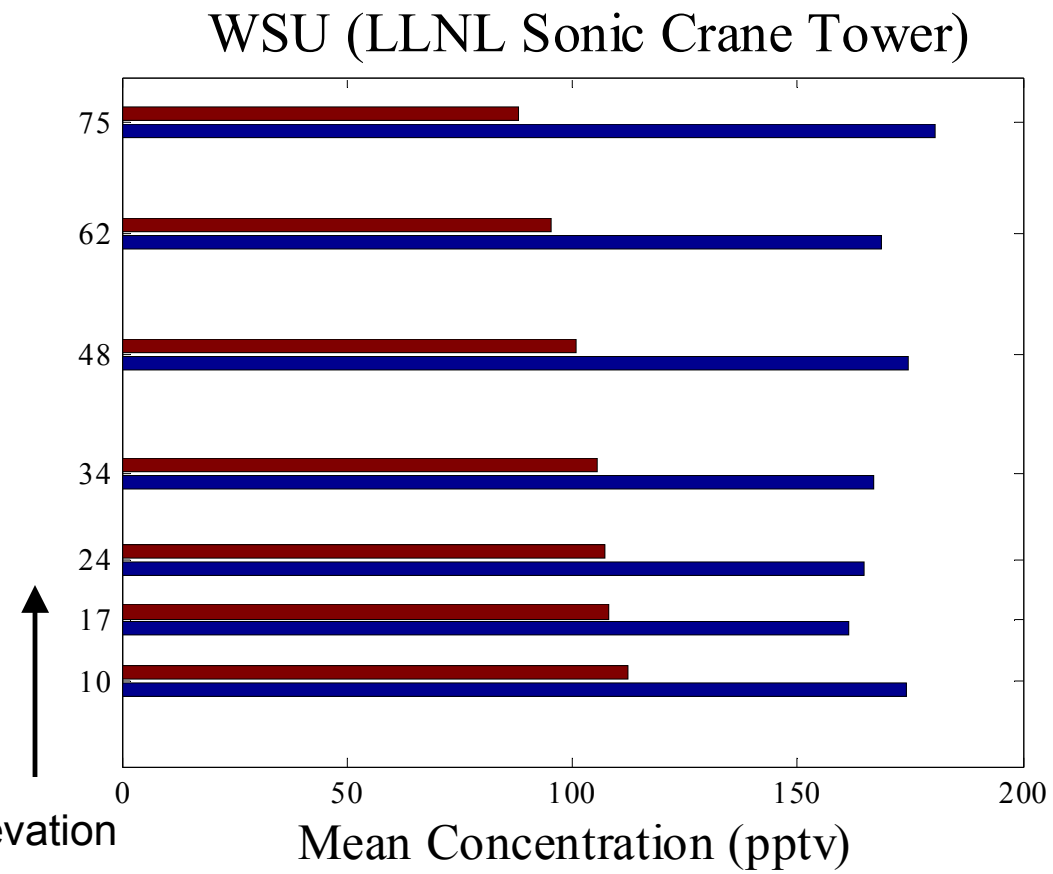


Source Location: South side of Park Avenue
35.46871667 ° N, 97.51556667 ° W

Concentration Prediction for Oklahoma City



Vertical profile of mean concentration



Experimental

urbanEU

Conclusions

1. Preliminary results obtained with the proposed resolution control parameter F_{RCP} within the framework of PRNS are promising
2. An integrated multi-scale modeling system for simulating urban flows and dispersion is presented and results are validated against field experiment in Oklahoma city [JU2003 database]
3. **Inverse source determination problem will be presented by E. Yee in WB1 on Wednesday**

Thanks and Questions?