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Statistical Models of a Tracer Plume in Complex Urban Canopies

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Motivation for new pollution dispersion modelling

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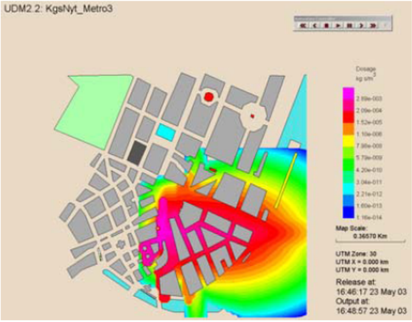
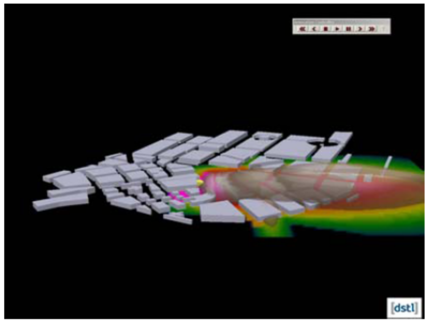
Operational aspects

- Industrial accidents (Chem, Rad, Bio)
- Counter–Terrorism (source backtracking)
- First responders (capacity planning)
- Troops activity in CBRN environment



S&T Challenges

- CFD models are still very slow and computationally intensive
- Need to have realistic model of complex flow in the canopy
- Need to have prediction for mean concentration as well as fluctuations



Urban Release Scenario
Torben Mikkelsen
2003

Need high fidelity models, based on physical ground that can be used in operational environment

What was done?

A simplified model for flow in the canopy:

- Log-law velocity profile above the canopy
- Distributed drag approach within the canopy
- Smooth match near the canopy top, inc continuous diffusivity

A new model for concentration profile:

- Power law approximation for velocity
- 3D analytical solution for concentration profile for boundary layer over a canopy
- Generalisation of this analytical solution to include local canopy effects

Experimental Data analysis and model validation:

- Data Analysis for Water Chanel experiment
- Validation of analytical model and parameter estimation

Model of Velocity Flow in the Canopy

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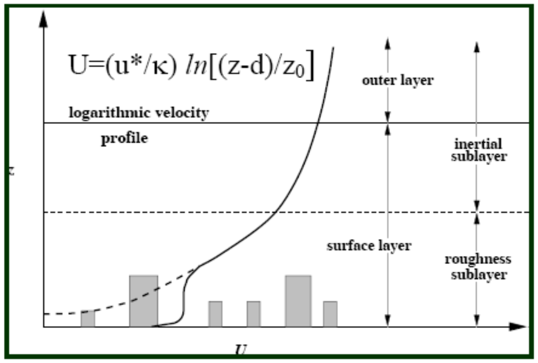
- Distributed drag approach for velocity within the canopy:

$$\frac{\mathrm{d}\tau(z)}{\mathrm{d}z} = \rho C_D a V_x^2(z)$$



By Neophytou and Britter, 2005

- Wind profile above canopy is known:

$$V_x(z) = \frac{v_*}{\kappa}\log\left(\frac{z-d}{z_0}\right)$$

- Parameters ***d*** and $\boldsymbol{z_0}$ can be determined from boundary conditions on the ground ($\boldsymbol{V_x = 0}$) and 'smooth' match.
- Similar to *J.Finnigan, S. Belcher, G. Katul* and others

Mean Velocity Profile

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- Analytical expressions for velocity and diffusivity

$$V_x(z) = \frac{v_*}{\gamma\kappa}\log\left(\frac{z-d}{z_0}\right) \qquad z \geq H \qquad\qquad \beta = \frac{2\epsilon}{\sigma}$$

$$V_x(z) = v_H\sqrt{\frac{\sinh\left(\frac{\beta z}{H}\right)}{\sinh(\beta)}} \qquad z < H$$

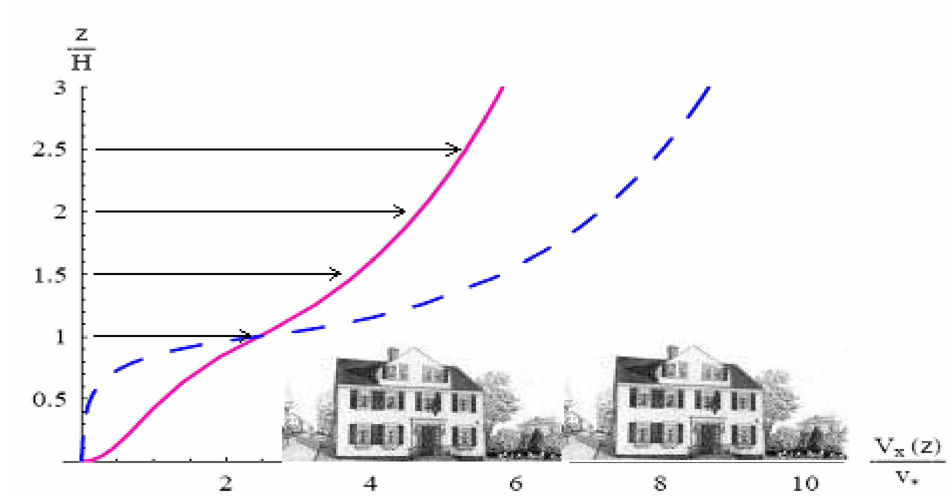
- The only parameter for the canopy: $\epsilon = C_D a H$

$$\frac{d}{H} = 1 - \frac{\sigma}{(\gamma\kappa)^2}$$

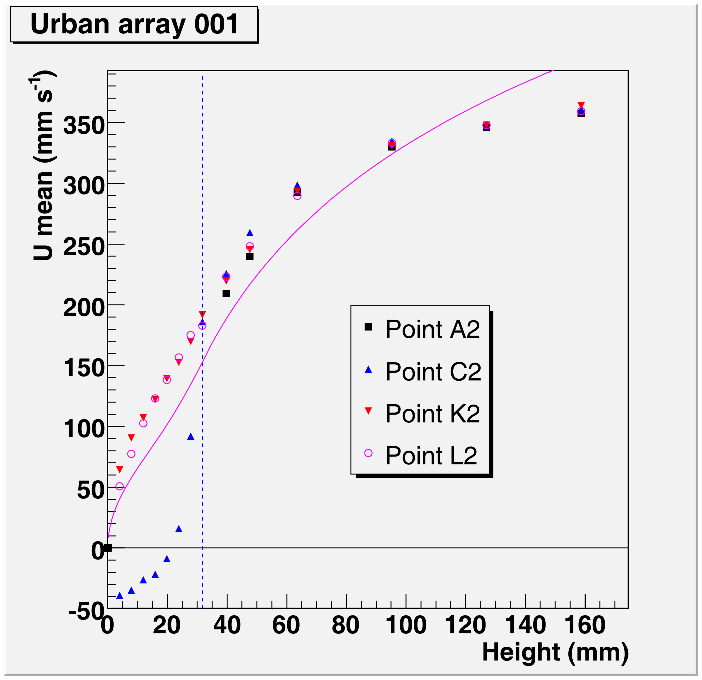
$$\frac{z_0}{H} = \frac{\sigma}{(\gamma\kappa)^2 e^1}$$

$$\frac{v_H}{v_*} = \frac{1}{\gamma\kappa}$$

$$\tanh\left(\sqrt{\frac{2\epsilon}{\sigma}}\right) = \frac{1}{(\gamma\kappa)^2}\sqrt{\frac{\epsilon\sigma}{2}}$$



Velocity Profile Water Channel Measurements



The match of our velocity model to our data is very good.

The exception is for measuring velocity directly behind an obstacle, as expected (blue triangles)

The Plume Model

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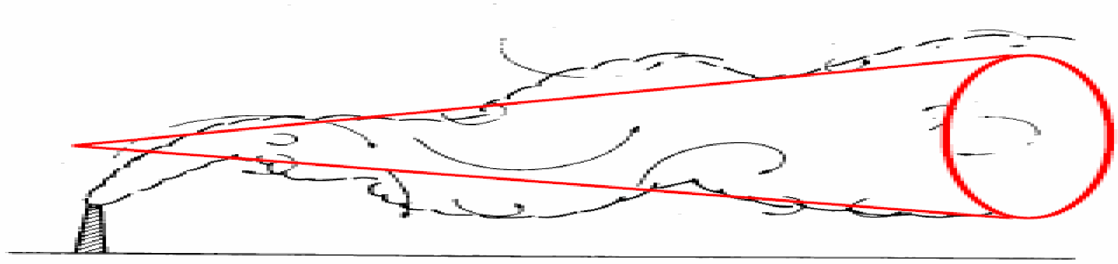

Insert Derived Velocity and Diffusivity profiles into Advection-Diffusion Equation

$$V_x(z)\frac{\partial C}{\partial x} = \frac{\partial}{\partial y}\left(K_{yy}(z)\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}(z)\frac{\partial C}{\partial z}\right)$$

Use *Barenblatt* approximation of mapping ABL log-law to a power law profile close to the ground

$$V_x(z) = a v_* \left(\frac{z-d}{z_0}\right)^m \qquad a = \frac{\ln Re}{\sqrt{3}} + \frac{5}{2}, \quad m = \frac{3}{2\,\ln Re}$$

The Plume Model: Use Stretch Exponential Solution

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$$C_z = \begin{cases} C_0 \exp(-B(\zeta_0^\alpha + \zeta^\alpha)) I_{-\nu}(2B(\zeta\zeta_0)^{\alpha/2}), & \text{if } z \geq d \\ C_z(d), & \text{if } 0 < z < d \end{cases}$$

$$C_0(x,z) = \frac{Q}{v_0 z_0}(\zeta(z)\zeta_0)^{\alpha\nu/2}\alpha B(x)$$

$$\zeta(z) = \frac{z-d}{z_0} \quad \zeta_0 = \frac{d - C_x X_H}{H},$$

$$B(x) = \frac{x_0}{x}$$

Stretch Exponential Solution for a raised source

Effective source height determined by model

d and z_0 determined by model

Constant C_z below d

C_y is Gaussian

Experimental model validation

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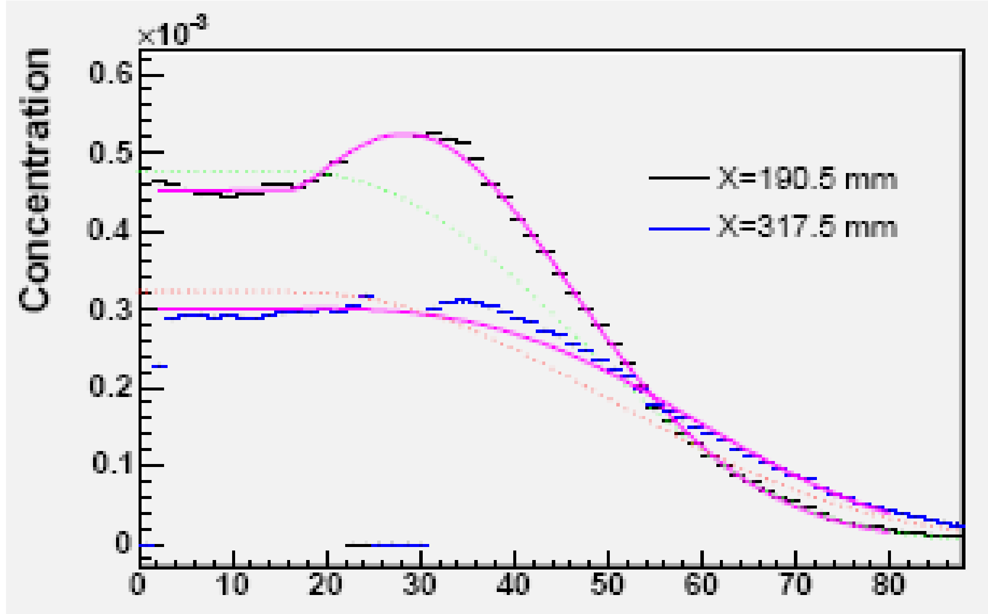
Image by Steve Walker, DSTL, UK



Plot of C_z as a func. of z at two distances downstream.

Match to Model is very good. The constant region is predicted well.

The peak due to an effective raised source predicted as well.

Effects of the canopy

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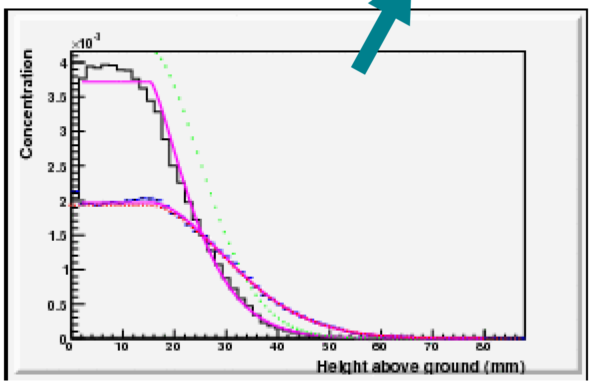
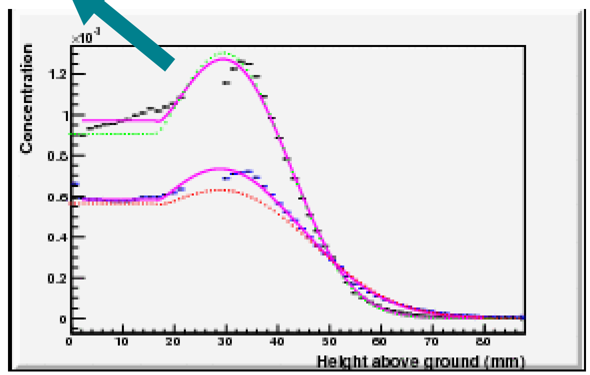
Identical except for location of source

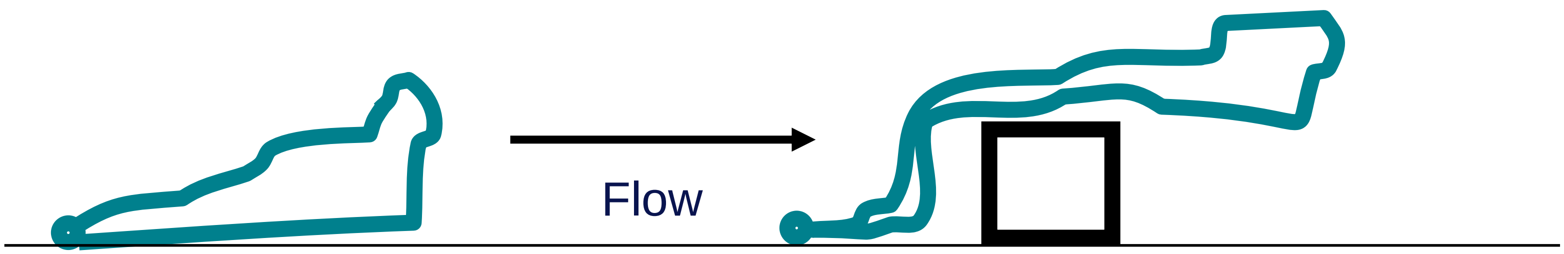
Urban
Array



Source in “canyon”



source in front of an obstacle



“pseudo” source height
Above ground level

Use stretch exp. form for non-zero release height (e.g Monin + Yaglom)

Extra-time: Effects of the canopy: elevated source (data fit)

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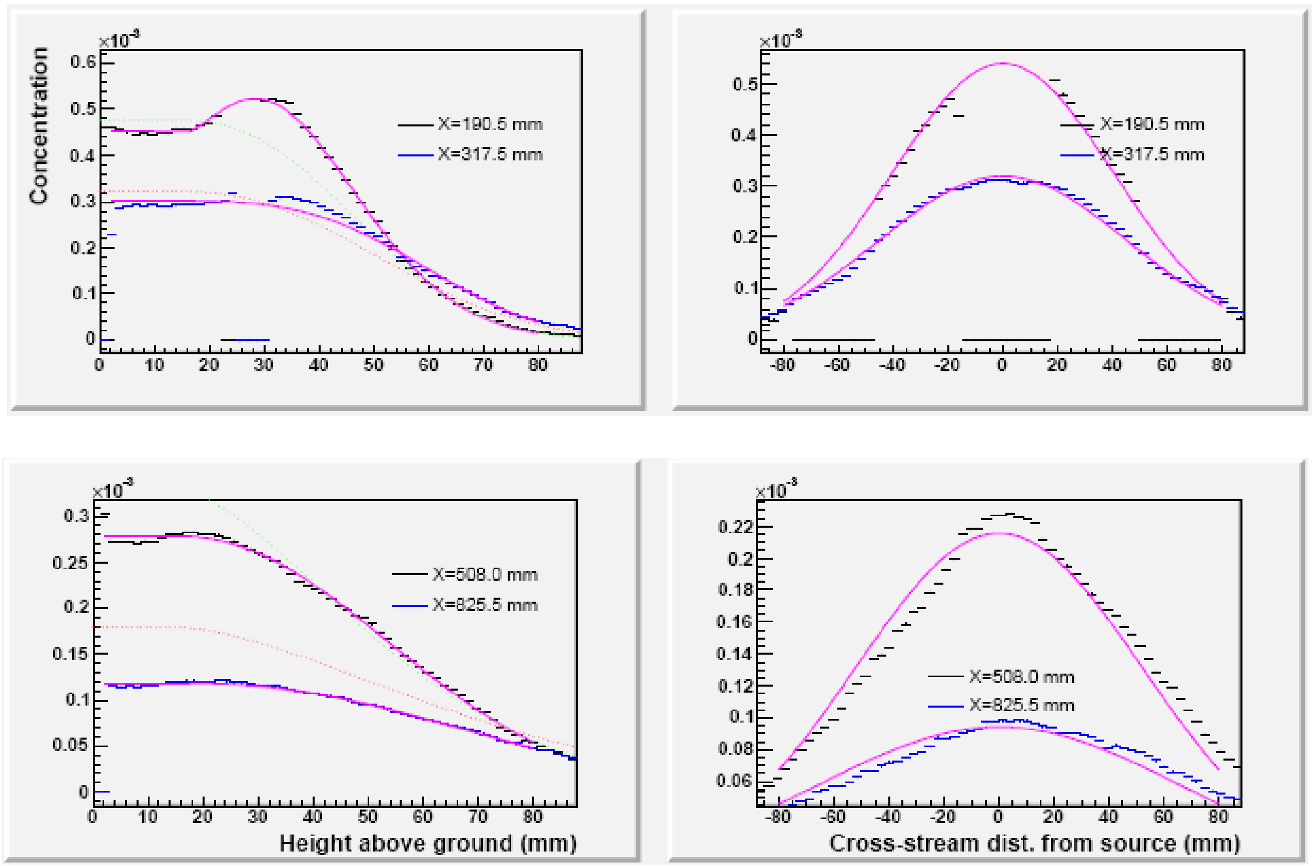

C vs *z (vertical)*, progressively further downstream

C vs *y (horizontal)*, progressively further downstream

Further from source, effects of initial effective displacement fade

Conclusions and Future Directions

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- Have a plume model that describes plumes in canopy densities typical in an urban environment.
- To take into account Atmospheric Boundary Layer stability conditions.
- Use to improve our formulation of plume fluctuations.
- Use in plume tracking and source determination via sensor networks.

QUESTIONS?