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NATURAL ENVIRONMENT RESEARCH COUNCIL
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Modelling Passive Scalar Dispersion Within And Above An Urban Canopy

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Introduction

Air pollution is currently estimated to reduce average life expectancy in the UK by 7-8 months and cost in excess of £20 bn per year [1]. Both pollutant emissions and exposure are particularly elevated in urban areas. Buildings within the urban canopy exert a drag force on the flow field which modifies both the mean wind profile and turbulence characteristics. Representing these effects on pollution dispersion is challenging.

Air pollution over London with the BT tower in the foreground. (The Guardian, 10 April 2012)

An Urban Canopy Model

In this modelling approach the time-averaged Navier-Stokes and passive scalar equations are reduced to 1D (vertical) budgets by a formal spatial (horizontal) averaging procedure. This yields extra terms, including turbulent flux terms that are then parametrized, e.g. using mixing length models [2].

Triple decomposition of instantaneous velocity field

$$u = U + \underbrace{\tilde{u}}_{\text{Spatial fluctuation}} + u'$$

Space-time mean | Spatial fluctuation | Temporal fluctuation

Spatial average of Reynolds-averaged Navier-Stokes equation

$$\frac{DU_i}{Dt} + \frac{1}{\rho}\frac{\partial P}{\partial x_i} = -\frac{\partial}{\partial x_j}\langle \overline{u_i' u_j'} \rangle - \frac{\partial}{\partial x_j}\langle \tilde{u}_i \tilde{u}_j \rangle - D_i$$

Reynolds stress | Dispersive stress | Drag

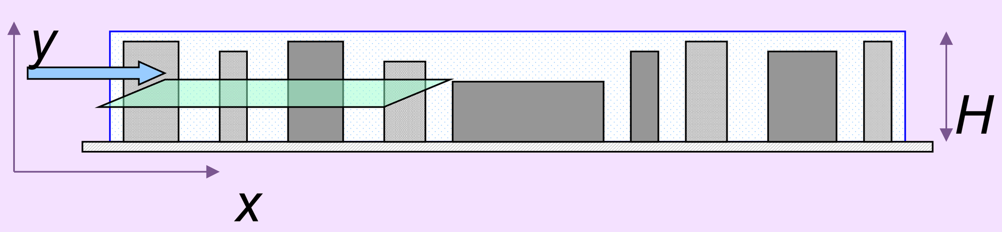

Figure 1. Schematic of spatial averaging process: horizontal heterogeneity at the building/street scale is removed, while vertical structure is resolved.

Comparison with DNS – Mean Velocity

Data from direct numerical simulations (DNS) of flow and passive scalar dispersion over regular arrays of cubes [3] are analysed to compare against the canopy model predictions.

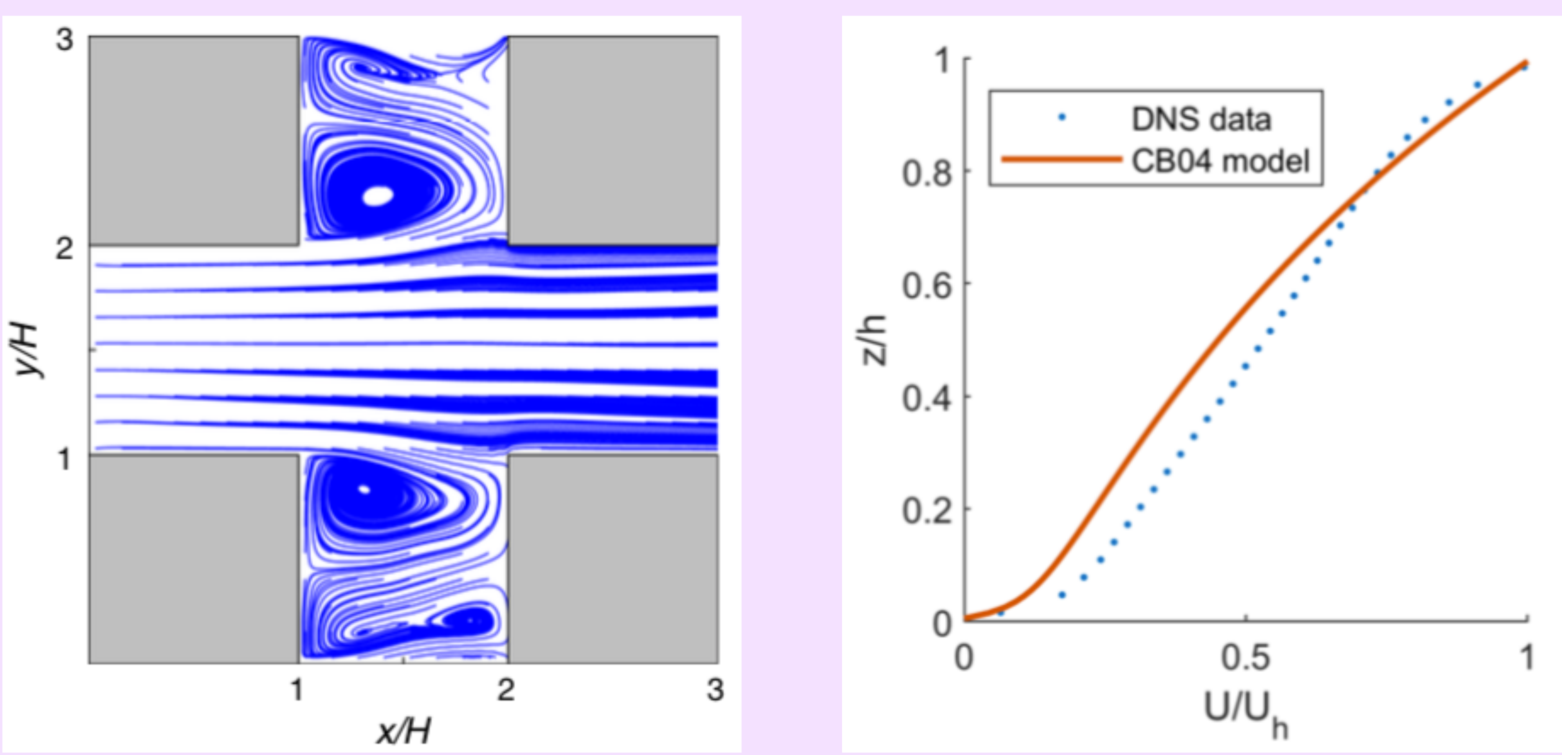

Figure 2. Left: Streamlines at z = 0.5H from the DNS of [3]. The mean flow is from left to right. Right: Comparison of spatially-averaged DNS velocity profile with that from canopy model (CB04) of [2].

Comparison with DNS – Concentration

The DNS [3] involved a point-source passive scalar release near the ground. A uniformly distributed source release was approximated by superposition.

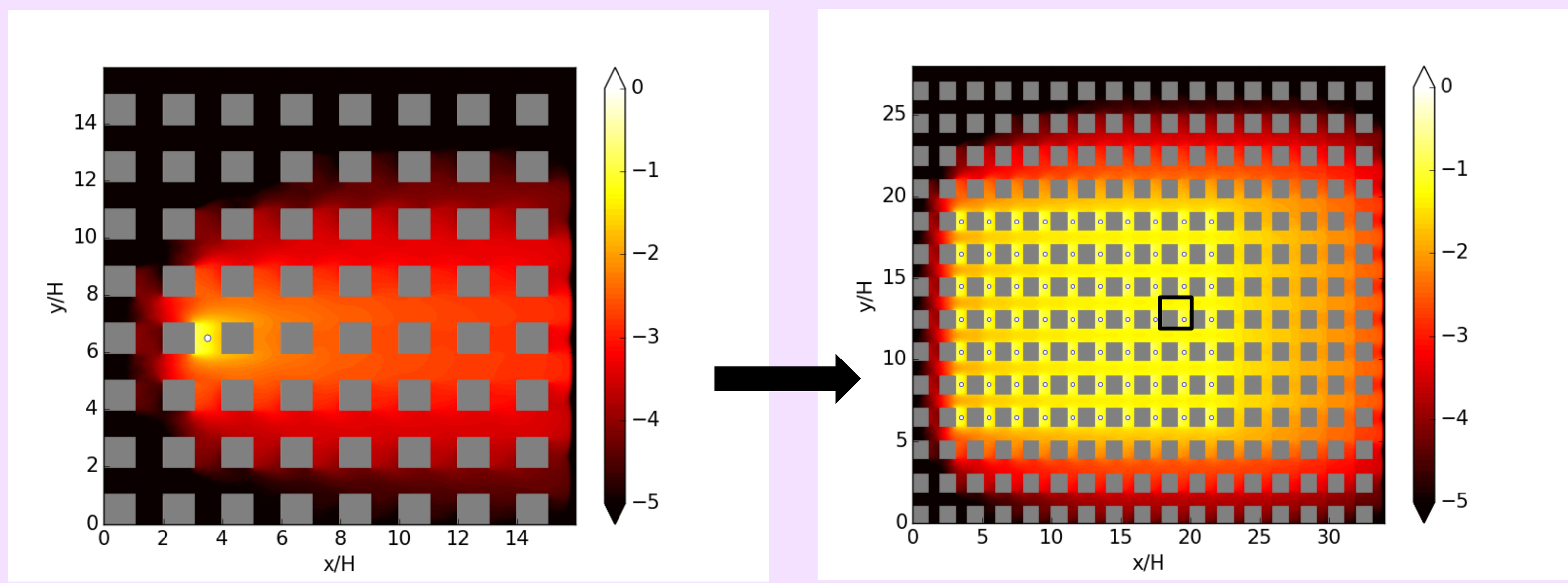

Figure 3. Left: DNS tracer concentration at z = 0.5H due to point source. Right: DNS tracer concentration at z = 0.5H from a superposition of the source shown in the left panel. The square annotation shows the unit square used for calculating the equilibrium concentration profile.

The concentration profile due to a uniformly-distributed tracer release is calculated using a repeating unit downwind where the concentration has reached equilibrium.

Canopy equations for scalar concentration

$$0 = -\frac{1}{\rho}\frac{\mathrm{d}F_c}{\mathrm{d}z} + S \qquad F_C = -\rho K_c \frac{\mathrm{d}C}{\mathrm{d}z} \qquad K_c = l_c l_m \left|\frac{\mathrm{d}U}{\mathrm{d}z}\right|$$

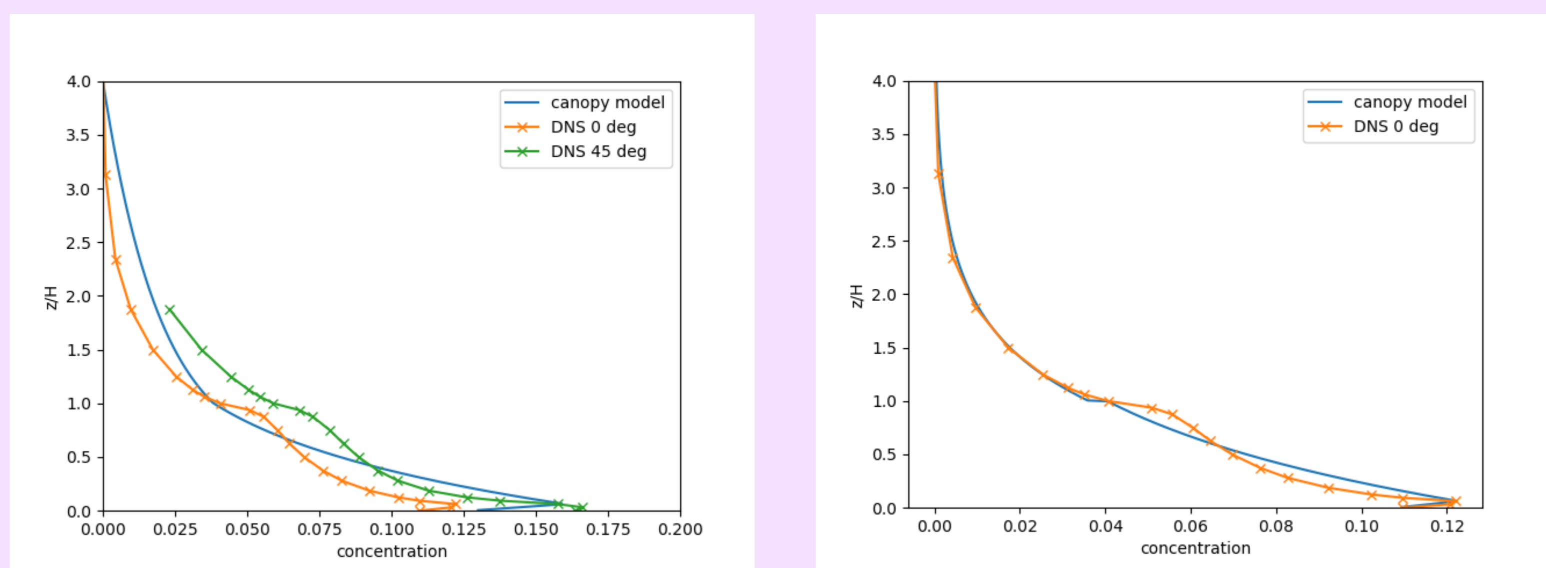

Figure 4. Left: Canopy model concentration profile compared against DNS data for 0 deg and 45 deg flow. The mixing lengths l_m and l_c are constant within the canopy and linearly-varying above. Right: Canopy model comparison against DNS data for the 0 deg flow, using different constant mixing lengths l_m and l_c above the canopy.

Conclusions

- **A canopy modelling approach can yield reasonable estimates of the spatially-averaged concentration as well as velocity profile.**
- **Uncertainties in the mixing lengths (particularly scalar) limit its practical application; DNS can provide guidance on suitable parametrizations.**
- **DNS results suggest that scalar and momentum mixing lengths are different.**
- **Mixing across the shear layer needs to be better represented.**

References

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[3] Branford S, Coceal O, Thomas TG, Belcher SE, 2011. Dispersion of a point-source release of a passive scalar through an urban-like array for different wind directions. *Boundary-Layer Meteorol.* **139**, 367–394.

Acknowledgments

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