Neighbourhood-scale Urban Dispersion Modelling Using a Canopy Approach

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Lewis Blunn (NCAS and UoR)

Collaborators: Dr Omduth Coceal (NCAS), Prof Bob Plant (UoR), Prof Janet Barlow (UoR), Dr Humphrey Lean (Met Office), Dr Sylvia Bohnenstengel (Met Office) and Dr Negin Nazarian (UNSW)

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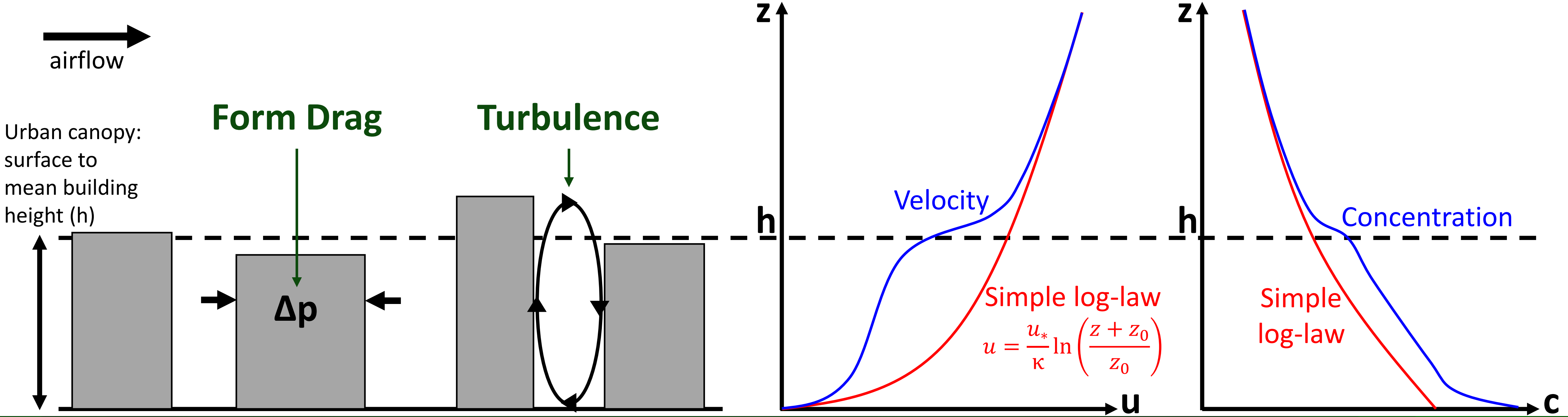
Motivation

- Numerical weather prediction (NWP) (e.g. UK Met Office 300m model) is heading towards the **"neighbourhood" scale** O(0.1-1 km)
  - Similar building geometry statistics
  - Accurate vertically resolved prediction of microscale processes at the neighbourhood scale?

- **Buildings** affect pollution dispersion and play a large role in determining **concentration** near the surface
  - Important since it is where we live



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Outline

- Introduce a **novel model** for 1D velocity and pollution concentration profiles in the urban surface layer (profiles represent the horizontal average of the neighbourhood)

- **Test** model using three different turbulence parametrisations against a high-resolution model of the 3D flow and dispersion (“truth data”)

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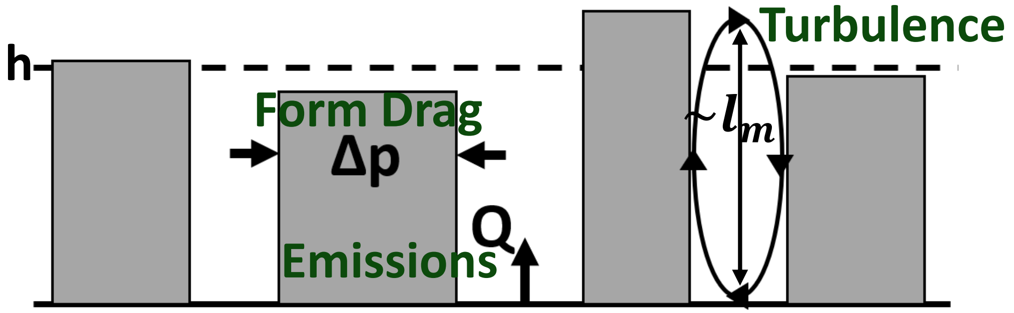
Urban Surface Layer Model (USLM)



(Finnigan and Shaw, 2008 [1])

Double averaged momentum equation -> Velocity

$$-\overbrace{\frac{d\langle\overline{u'w'}\rangle}{dz}}^{\text{Reynolds flux}} - \overbrace{\frac{d\langle\tilde{u}\tilde{w}\rangle}{dz}}^{\text{Dispersive flux}} = \overbrace{\left\langle\frac{d\langle\bar{p}\rangle}{dx}\right\rangle}^{\text{Constant body force}} + \overbrace{\left\langle\frac{d\tilde{p}}{dx}\right\rangle}^{\text{Form Drag}}$$

$$\frac{d\left(\overbrace{l_m{}^2\left|\frac{dU}{dz}\right|\frac{dU}{dz}}^{\text{Momentum flux- 1st order closure}}\right)}{dz} = \left\langle\frac{d\langle\bar{p}\rangle}{dx}\right\rangle + \begin{cases}\frac{U^2}{L_{drag}}, & z \le h\\ 0, & z > h\end{cases}$$

$\langle\bar{u}\rangle$

Constant

Double averaged scalar equation -> Scalar concentration

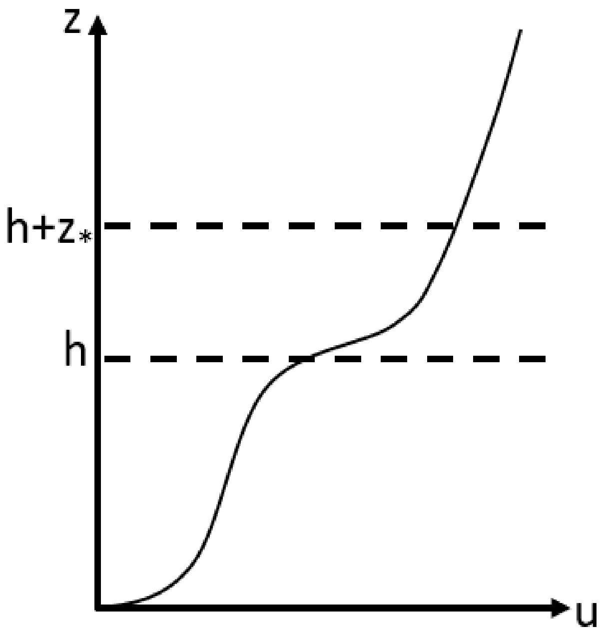
$$-\overbrace{\frac{d\langle\overline{w'c'}\rangle}{dz}}^{\text{Turbulent flux}} - \overbrace{\frac{d\langle\tilde{w}\tilde{c}\rangle}{dz}}^{\text{Dispersive flux}} = \overbrace{Q\delta(z)}^{\text{Scalar surface source}}$$

$$-\frac{d\left(\overbrace{\frac{l_m^2}{S_c}\left|\frac{dU}{dz}\right|\frac{dC}{dz}}^{\text{Scalar flux- 1st order closure}}\right)}{dz} = Q\delta(z)$$

$\langle\bar{c}\rangle$

$S_c = l_m/l_c$

Turbulence Closure- three parametrisations of l_m, l_c



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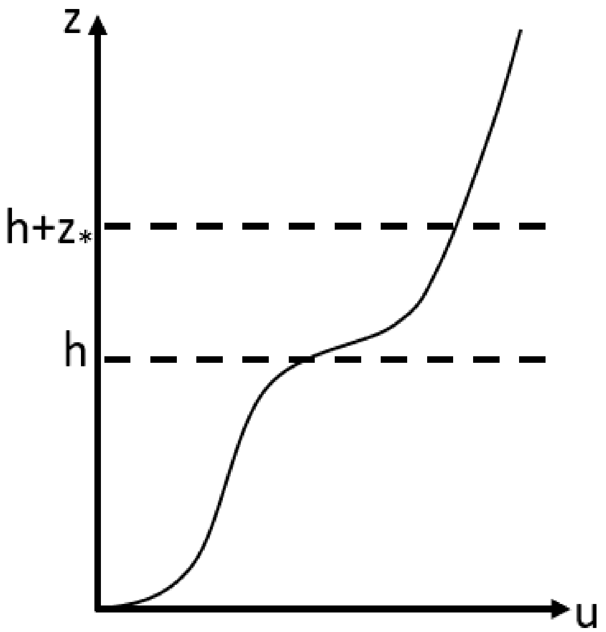

Within canopy:

1) constant+HF08:

l_m = constant -> velocity has an exponential solution.

$S_c = 0.5.$

Turbulence Closure- three parametrisations of l_m, l_c

USLM

Inertial sublayer: $l_m = \kappa(z-d)$.
S_c= 0.85.

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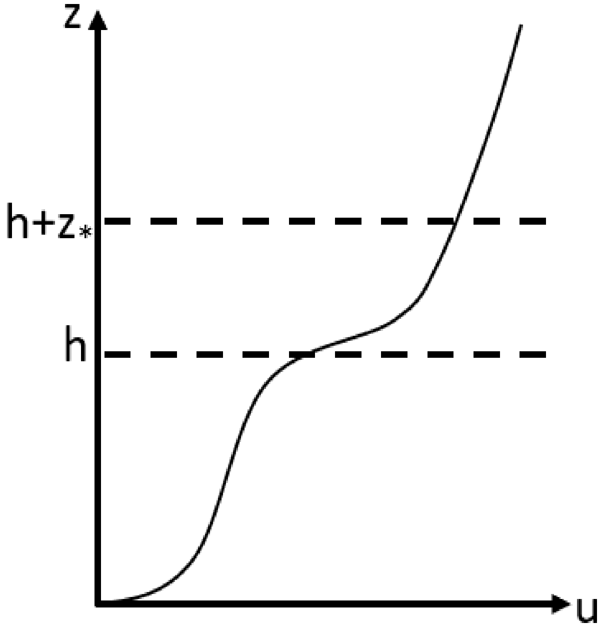

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Roughness sublayer:

l_m and S_c blend between canopy below and inertial sublayer above. Based on Harman and Finnigan, 2008 (2).

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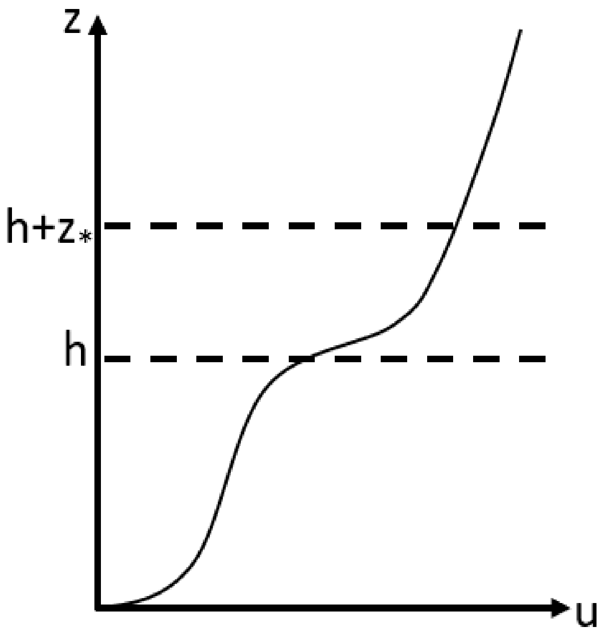

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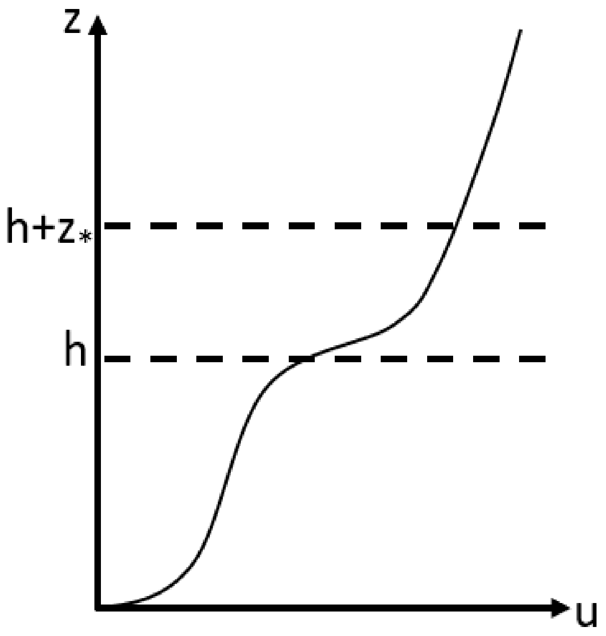

Within canopy: 1) constant+HF08:
l_m = constant -> velocity has an exponential solution.
$S_c = 0.5$.

2) Log-law:
$l_m = \kappa(z+z_0)$ -> velocity has a log-law solution when height distributed drag is neglected.
S_c= 0.5 in and S_c= 0.85 above.

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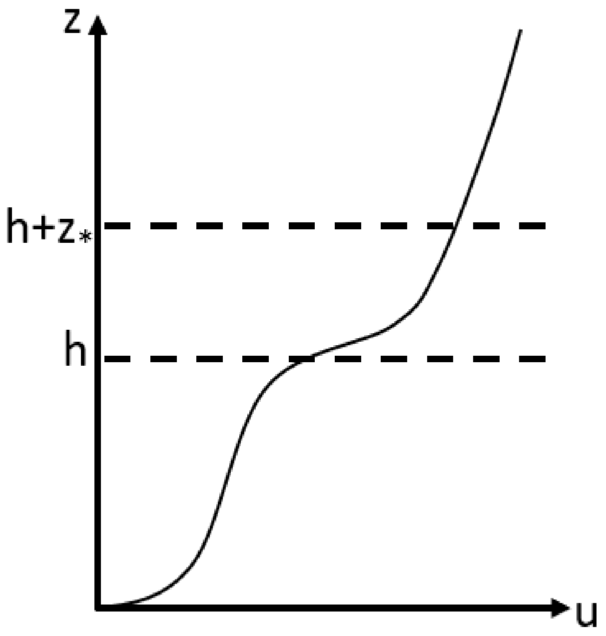

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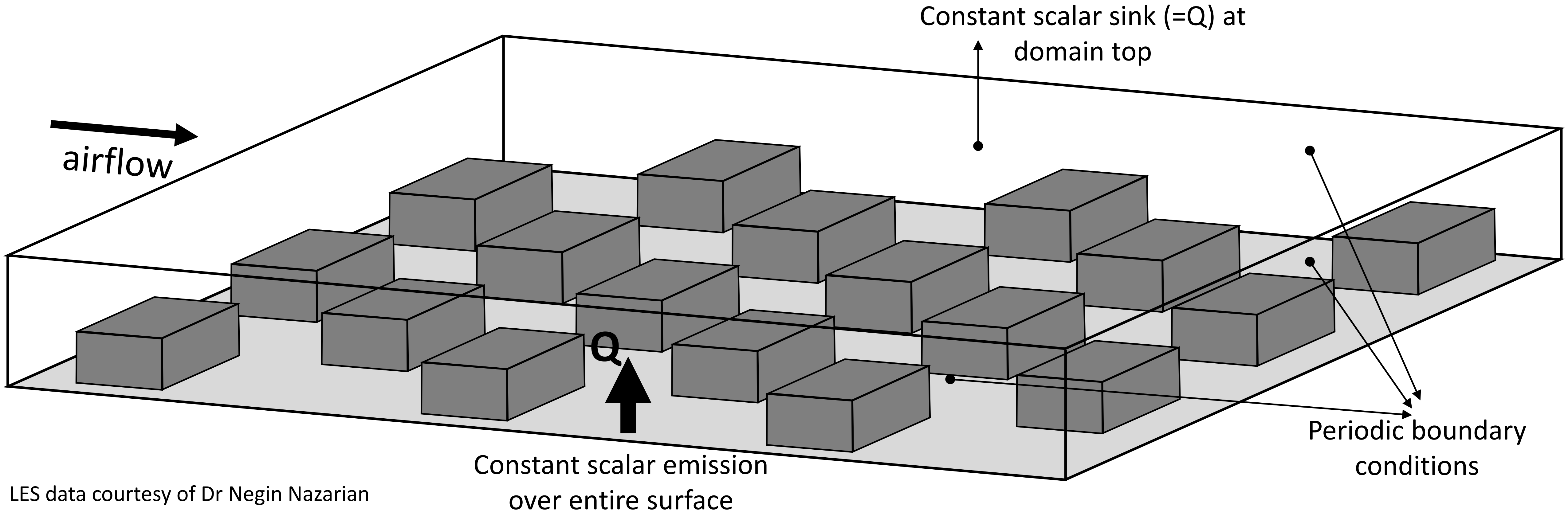
3) Derived from LES ("truth data"):
l_m and S_c are derived from a high-resolution 3D dataset.

Large Eddy Simulation (LES) – "truth data"

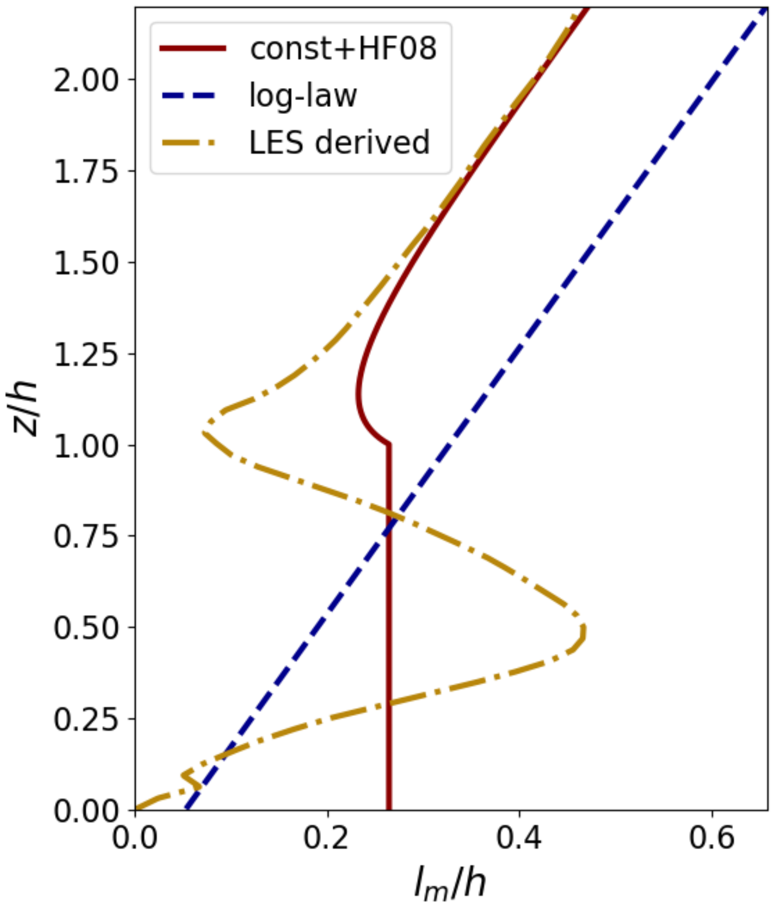
- High resolution simulation of the 3D flow and dispersion in a staggered array of cubes (λ_p=0.25)
- 0^0 flow and neutral atmospheric stability

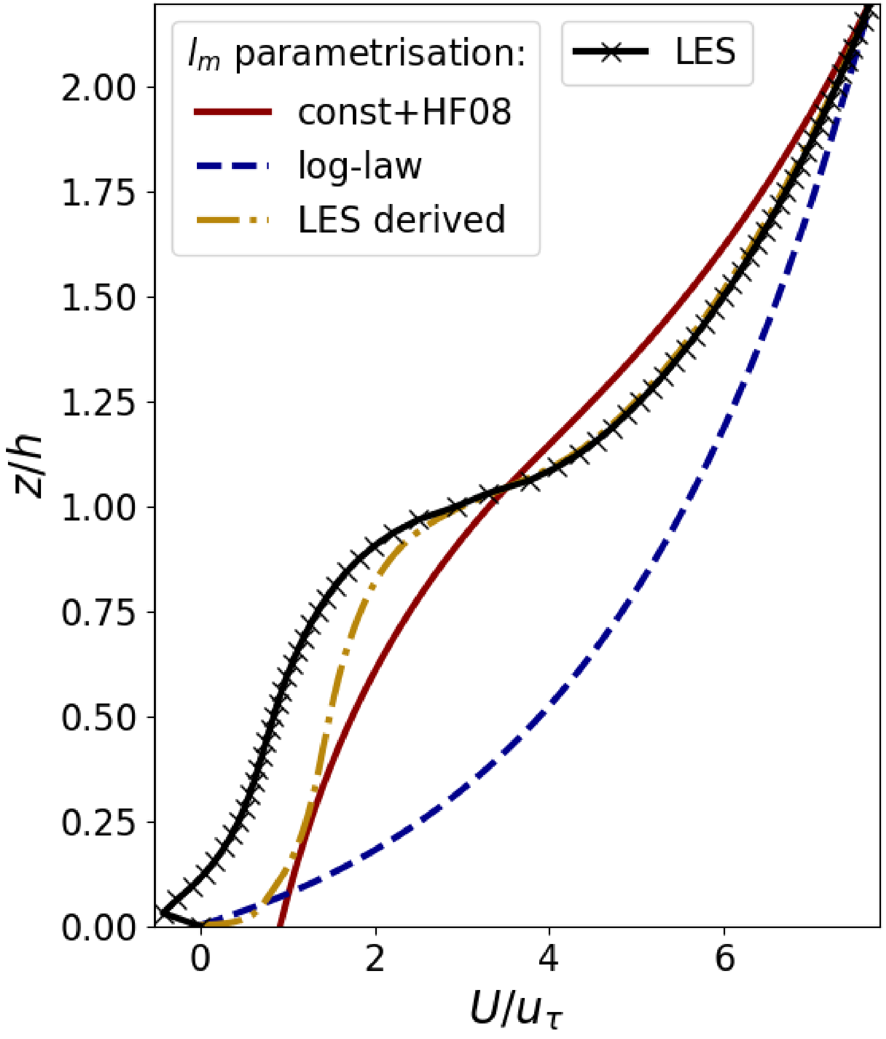


LES data courtesy of Dr Negin Nazarian

Velocity: model vs "truth"

Momentum flux = $l_m{}^2 \left|\frac{dU}{dz}\right| \frac{dU}{dz}$





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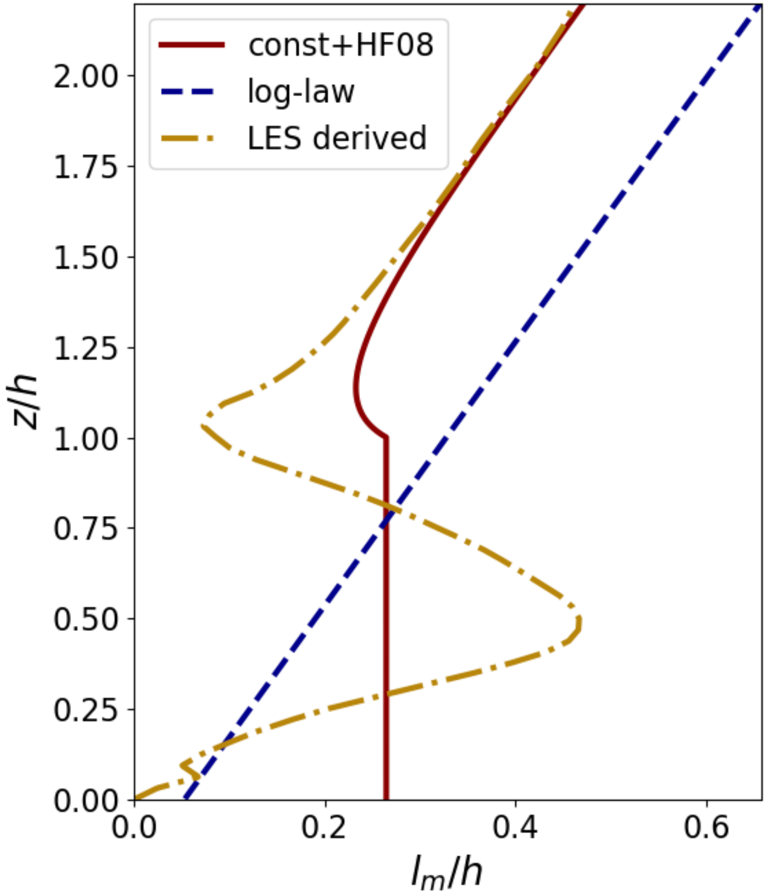
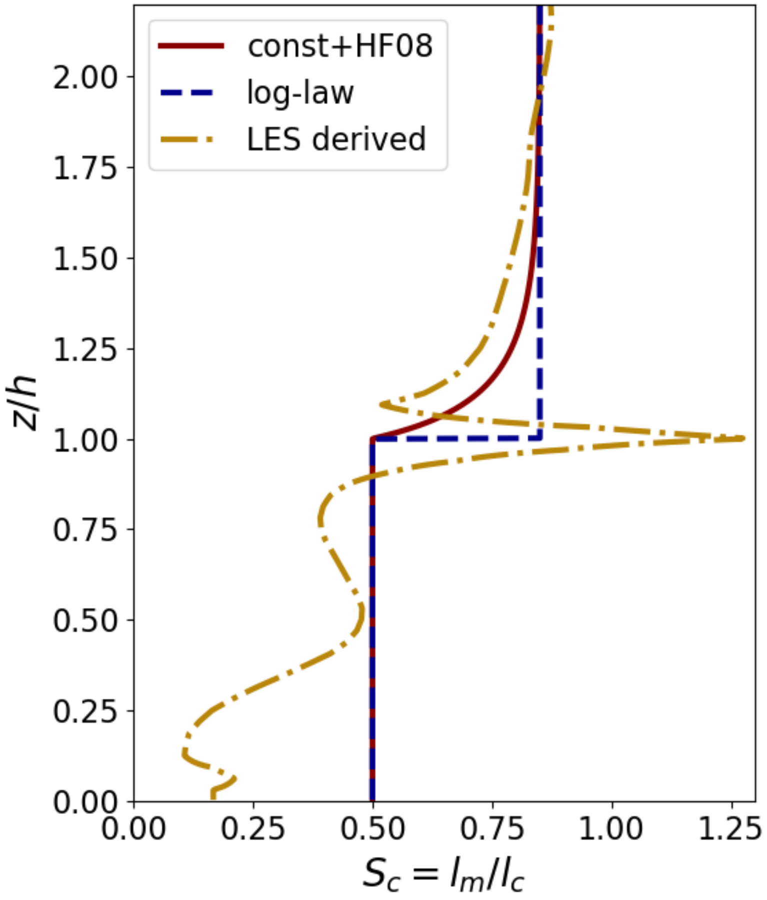
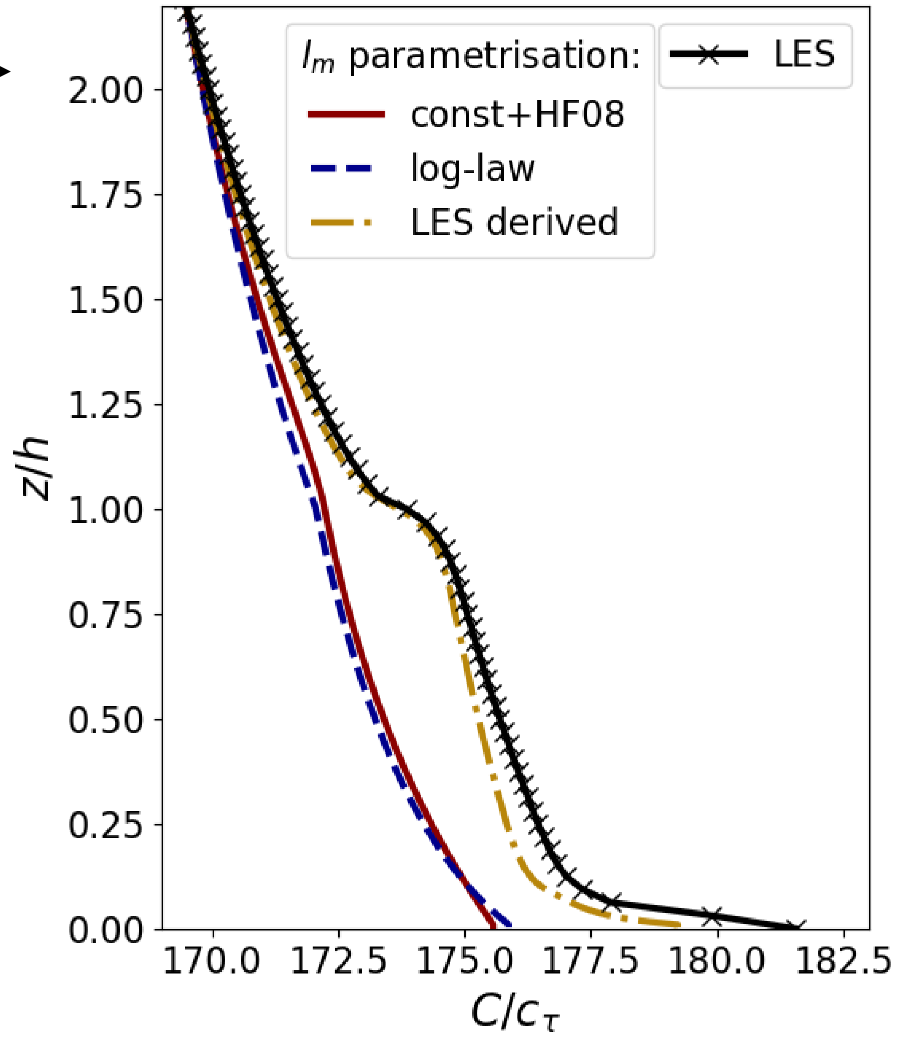
Scalar Concentration: model vs "truth"

Scalar flux $= \frac{l_m^2}{S_c}\left|\frac{dU}{dz}\right|\frac{dC}{dz}$ →







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Conclusions

- Demonstrated that accurate prediction of velocity and (for the first time) scalar concentration can be made in the urban surface layer using a canopy approach
  -> promising for real geometries

- Improved velocity prediction with mixing length given by derived from LES compared to using a log-law (used in most NWP) and const+HF08 (constant l_m used in current multi-layer canopy models)

- Only mixing lengths derived from LES accurately predict scalar concentration

- Schmidt number varies significantly in the canopy and is crucial for accurate scalar prediction

- Future work: use LES of more building geometries to inform development of a new l_m, S_c parametrisation.

Thank You

References:

(1) Finnigan, J. J. and Shaw, R. H. (2008), Double-averaging methodology and its application to turbulent flow in and above vegetation canopies. Acta Geophysica, 56: 534-561.

(2) Harman, I. N. and Finnigan, J. J. (2008), Scalar concentration profiles in the canopy and roughness sublayer. Boundary-Layer Meteorology, 129: 323-351.