Non-local ventilation diagnostics for idealized and realistic urban domains

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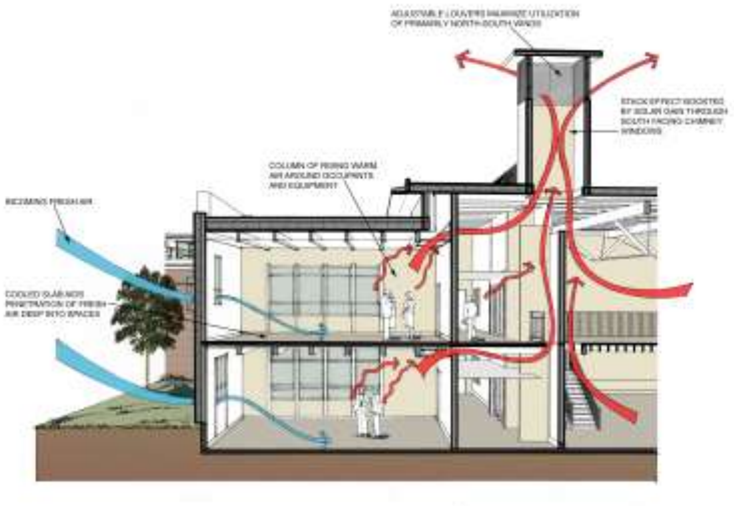
Motivation

- The health impact of air pollutants depends on pollutant exposure. Hence the health impact can be minimised in two ways:
  - Decreasing pollutant **concentration** via source control.
  - Decreasing exposure by improving the **ventilation**.
- Ventilation refers to the replacement of polluted air with fresh air or equivalently the escape of polluted air from a specific region.



Urban pollutant ventilation

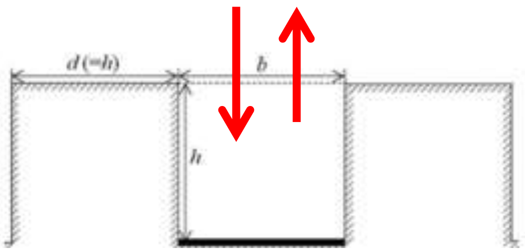
- In the urban environment, characterisation of the air and pollutant transport within cities is of great interest
- **Flux-based** diagnostics are based on rate at which pollutant escape from the domain

air exchange rate

$$ACH(t) = \int_{\Gamma} w'(t)|_{\text{roof}}\, d\Gamma$$

pollutant exchange rate

$$PCH(t) = \int_{\Gamma} w'(t)|_{\text{roof}} c(t)|_{\text{roof}}\, d\Gamma$$



Liu *et al*. (2011), Atmospheric Environment

- Limitations:
  - Limited information about **transport**
  - Less useful for strongly **inhomogeneous** flows

Timescale-based diagnostics

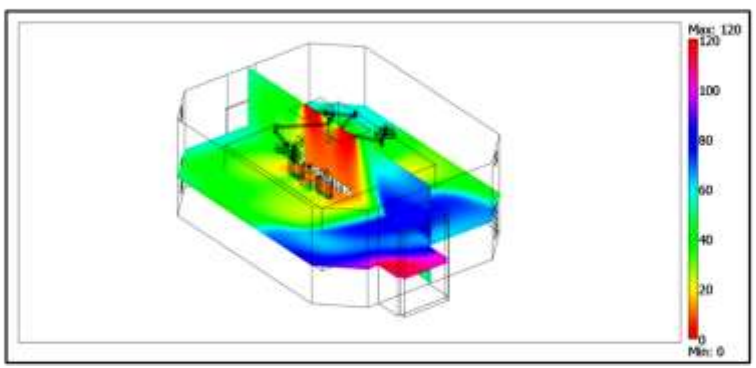
- Ventilation depends on the **time** required for pollutants to escape the domain
- These timescales relate a source location to a receptor location, i.e. they are effectively **Lagrangian** and **nonlocal**
- Age of air – measures the time elapsed since an air parcel entered a room or a region of interest
- Residence time, exposure time
- Issues
    - How should they be calculated?
    - Spatial and temporal dependence
    - Dependence on source and initial conditions

Local mean age of air

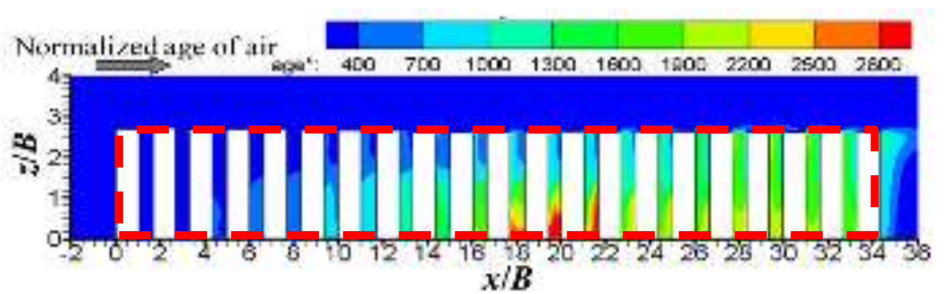
- For a homogeneous source, the local mean age of air is given by the time-mean concentration and source flux:

$$\tau = \frac{\overline{c}}{S}$$

- Originally developed for indoor building ventilation, it represents the turnover timescale
- Can be applied for the urban environment – more relevant for the effect of fresh air



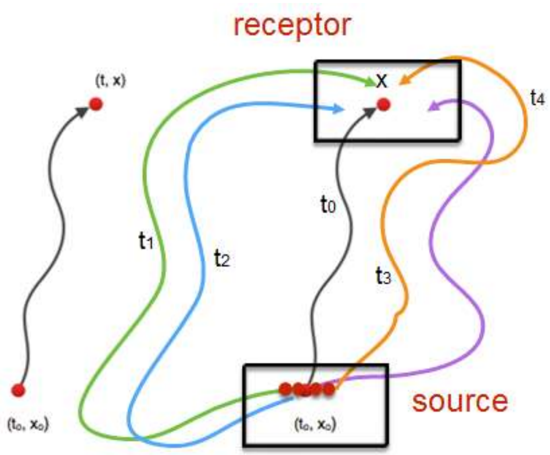
Balocco *et al.* (2004), Journal of Biomedical Science and Engineering



Hang & Li (2011), Atmospheric Environment

Tracer age spectrum

- Pollutant ventilation can also be characterised by the tracer age spectrum
- In this approach, the ventilation timescale is calculated directly from the evolution of the scalar field via the Green's function
- Does not assume a spatially homogeneous source – can be used for any arbitrary local source



Adapted from Hall & Plumb (1994), J. Atmos. Sci.

Tracer age spectrum

Green's function

$$\frac{\partial c}{\partial t} + \vec{u} \cdot \vec{\nabla} c = \kappa \nabla^2 c + \delta(\vec{x} - \vec{x}_0)\delta(t - t_0)$$

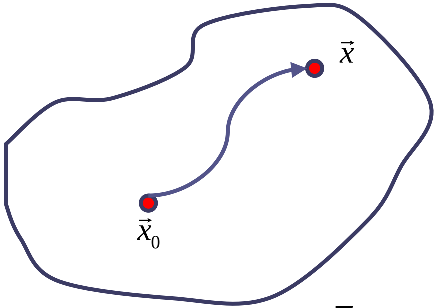
$$c(x,t) = \int_0^t dt_0 \int_\Omega G(\vec{x}, t | \vec{x}_0, t_0) S(\vec{x}_0, t_0) d\vec{x}$$

Age spectrum

$$Z_{age}(\vec{x}, \xi) = \frac{\int_\Omega G(\vec{x}, t | \vec{x}_0, t - \xi) S(\vec{x}_0, t - \xi) d\vec{x}_0}{\int_0^t dt \int_\Omega G(\vec{x}, t | \vec{x}_0, t_0) S(\vec{x}_0, t_0) d\vec{x}_0}$$

Mean tracer age

$$\tau_{age} = \int_0^\infty \xi Z_{age} d\xi$$



- **Physical idea:**
  There is a statistical distribution of ages or **age spectrum** connecting the source and receptor. The **mean tracer age** is the first moment of the distribution. The age spectrum is obtained from the **Green's function** of the advection-diffusion equation.

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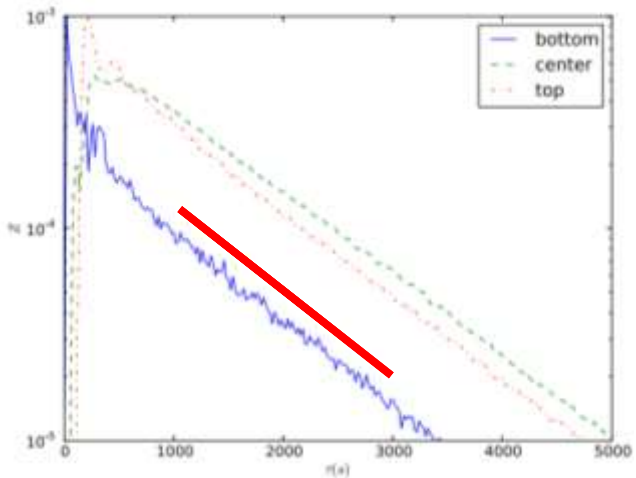
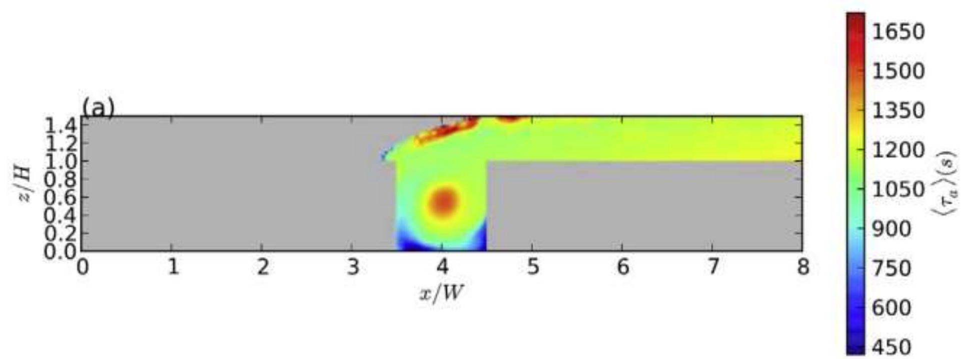
Urban ventilation using tracer age spectrum

- As tracer age spectrum represents a statistical distribution of ages, it can provide more insights regarding pollutant ventilation:
  - Higher mean tracer age implies poorer ventilation by means of, e.g. pollutant retention, trapping and re-entrainment
  - Effectiveness of ventilation can also be inferred from the gradient of the tracer age spectrum – larger slope (decay constant) implies better ventilation





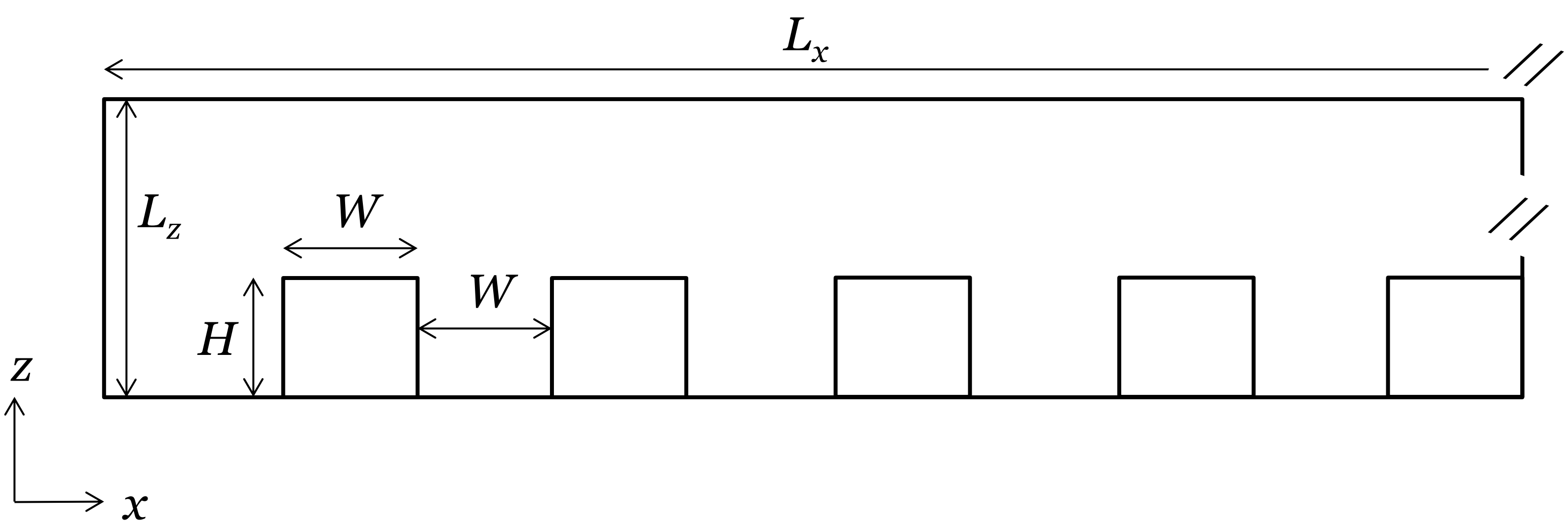
Lo & Ngan (2015), Atmospheric Environment

Numerical model

- Parallelized Large-eddy Simulation Model (PALM) is used (Maronga *et al.*, 2015)
- Two domains have been investigated in this study:
  - **Idealised** building array domain
  - **Realistic** domain (Mong Kok, Hong Kong)
- Boundary conditions
  - Spanwise: Periodic
  - Streamwise: Dirichlet-Radiation
  - Wall: No-slip
  - Domain top: Neumann
- Turbulence recycling is used to ensure sufficient turbulence at the inlet
- In all cases, the roughness Reynolds number $Re_{\tau} > 600$ where Re_{τ} is based on the building height

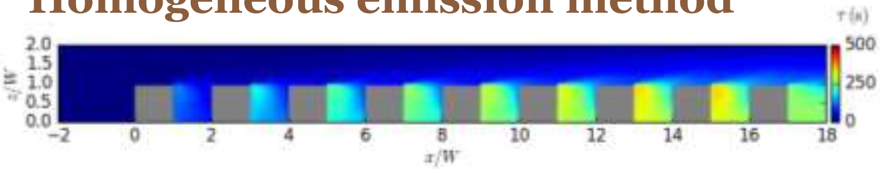
1. Idealized domain

- Cases studied:
  - Case U1: $H/W = 1$ (skimming flow)
  - Case U2: $H/W = 2$ (skimming flow)
- $H = 20$ m, $W = 20$ m, $L_x = 20W$, $L_y = 15W$, $L_z = 7.5H$
- Grid size: $\Delta x = 1$ m, $\Delta y = 1$ m, $\Delta z_{min} = 1$ m
  - Grid is uniform in the x- and y-directions; geometric expansion is used in the z-direction for $z > 2H$



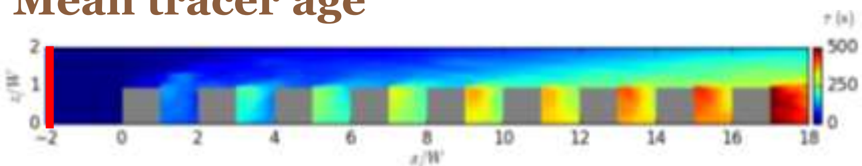
1.1 Mean tracer age vs. local mean age of air

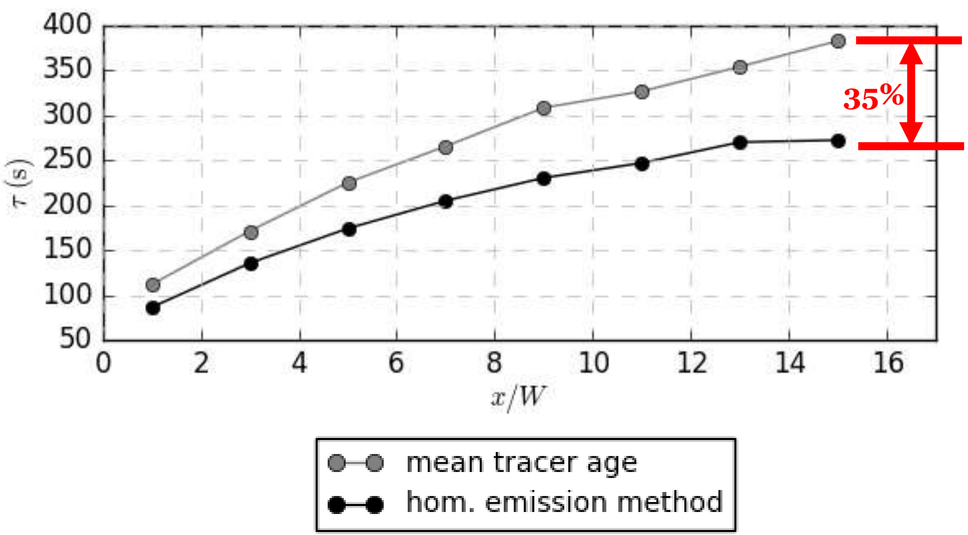
Homogeneous emission method



Wind direction

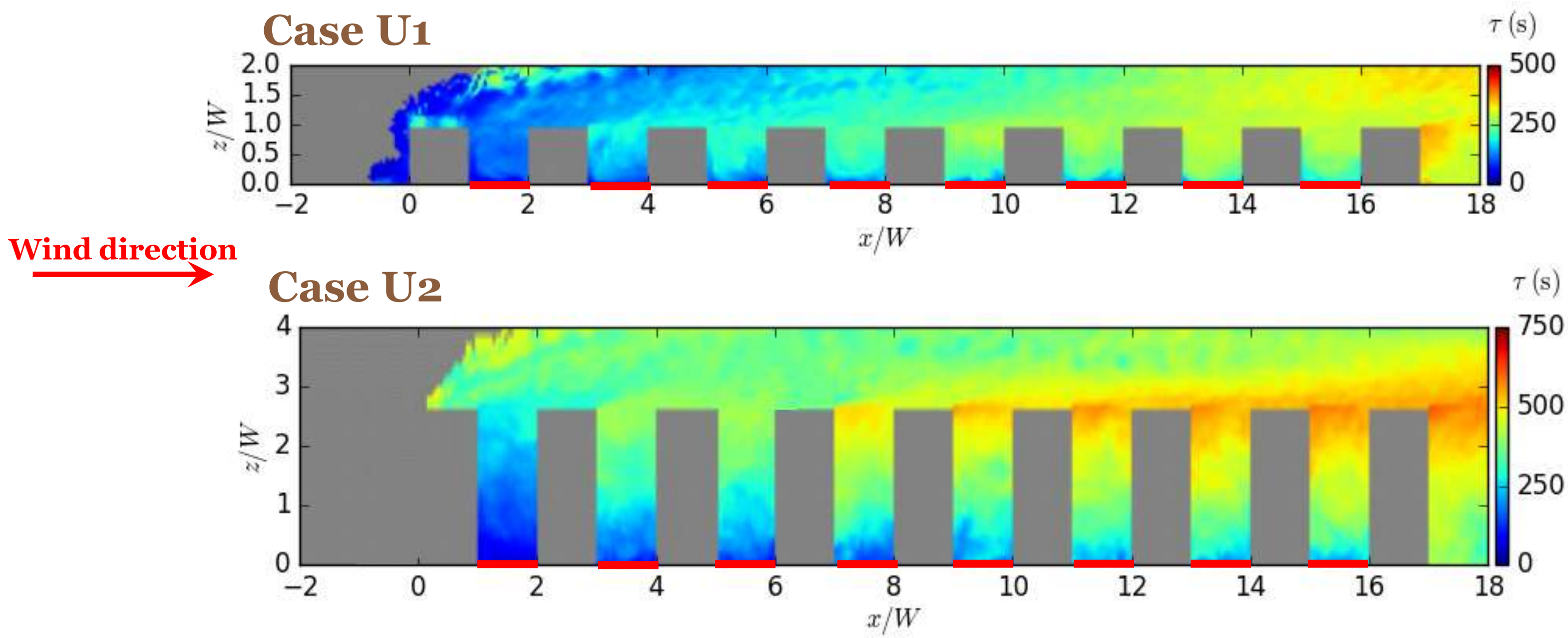
Mean tracer age





- Similarities
  - Qualitative similarities are observed in the spatial structure
  - Mean age is higher downstream as a result of re-entrainment of pollutants upstream.
- Key difference
  - **Magnitudes**: mean tracer age is generally **larger** than the local mean age of air.

1.2 Mean tracer age – Idealised domain



- Pollutant escape – ventilation is generally better in Case U1
- General trends
  - Mean tracer age is generally **larger** in **downwind canyons** – consistent with Hang and Li (2011)
  - Ventilation is poorer in downwind canyons – **re-entrainment** of upwind pollutants

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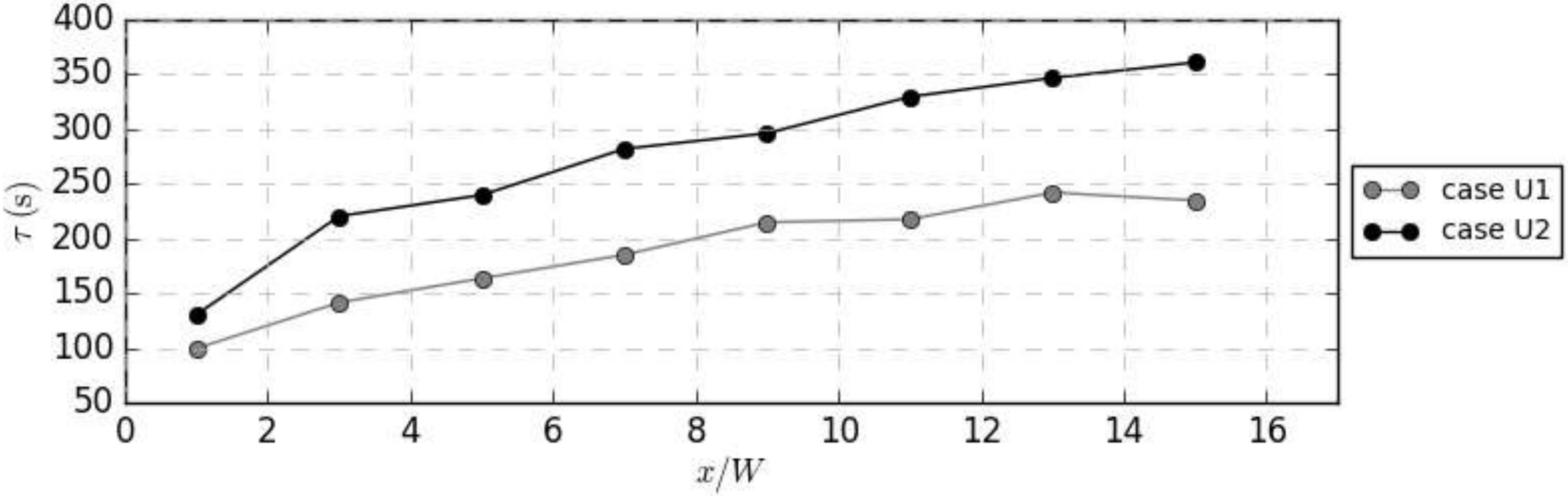
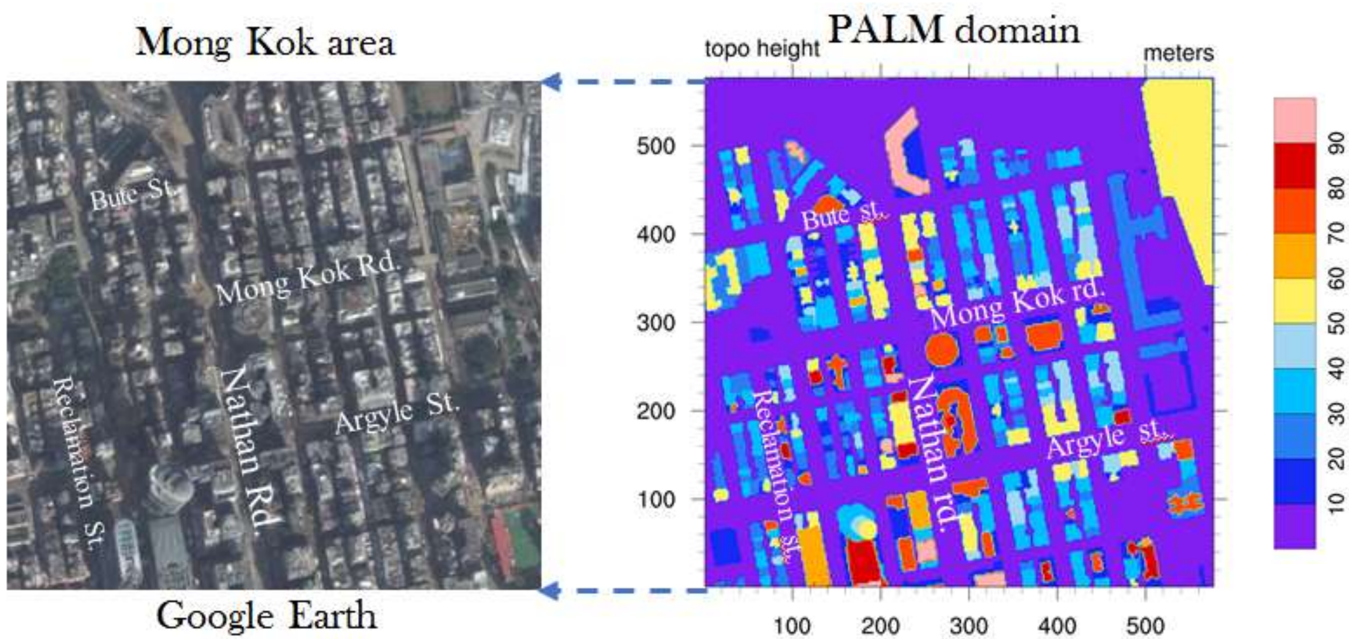
1.2 Mean tracer age – Idealised domain



- General trends
  - Canyon-averaged mean tracer age is larger in downwind canyons
  - For $H/W = 2$ (Case U2), mean tracer age is about 50% higher than in Case U1
  - Ventilation is poorer in Case U2 – insensitive to small-scale turbulence

2. Realistic domain – Mong Kok, Hong Kong



- Building height data obtained from the *Hong Kong Lands Department*
- Domain size: 576 m × 576 m × 384 m
- Δx = 2 m, Δy = 2 m, Δz_{min} = 2 m
  - Grid is uniform in the x- and y-directions; geometric expansion is used in the z-direction for $z > 2H$

2. Realistic domain – Mong Kok, Hong Kong

- Inflow winds obtained from a high-resolution WRF model are used as inflow boundary condition (UTC 0350 11-Jan-2017) – more details can be found in Ganbat & Ngan.
- Coupling between the mesoscale profiles and the LES model is achieved via Newtonian relaxation i.e. nudging:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial \overline{u}_i \overline{u}_j}{\partial xj} = -\frac{1}{\rho_0}\frac{\partial \overline{\pi}^*}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + g_i + F_N$$

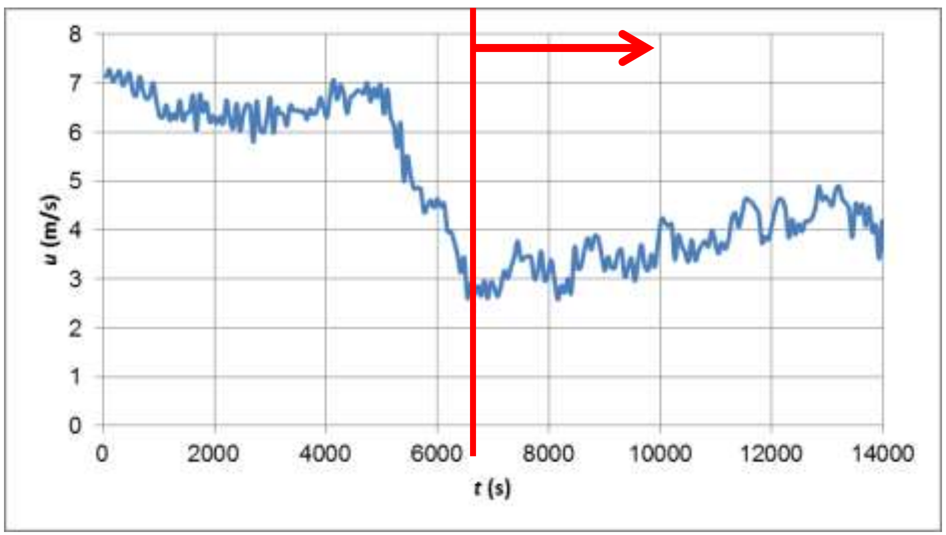
$$F_N = C_0 e^{-x/l}\left(\vec{u} - \vec{u}_{meso}\right)$$

C_0 = nudging coefficient

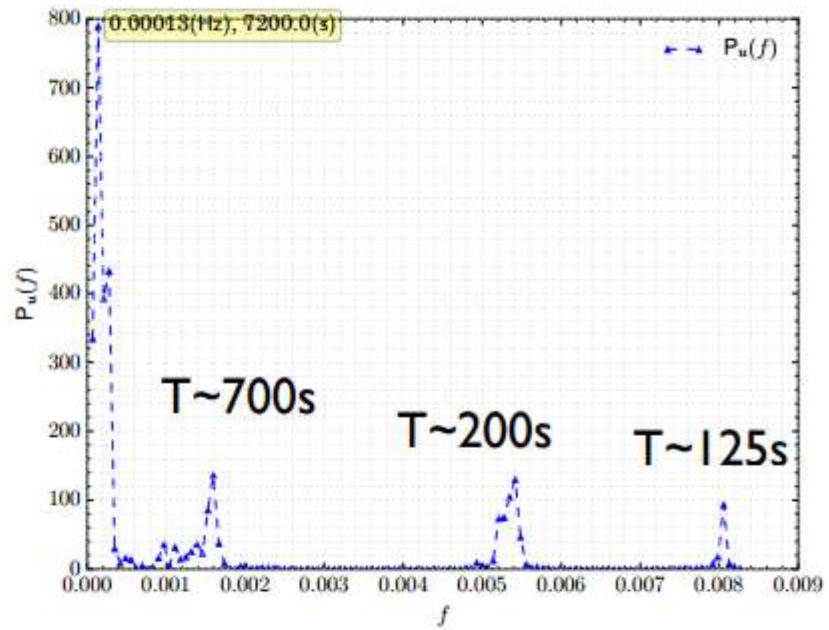
Perturbations are restricted to the inflow

2.1 Inflow profile

- A time period is chosen with relatively calm wind, i.e. 2 – 4 m/s.
- Output frequency of WRF is 1 minute.
- Validation has been carried out with radiosonde measurements from HKO (Ganbat & Ngan).



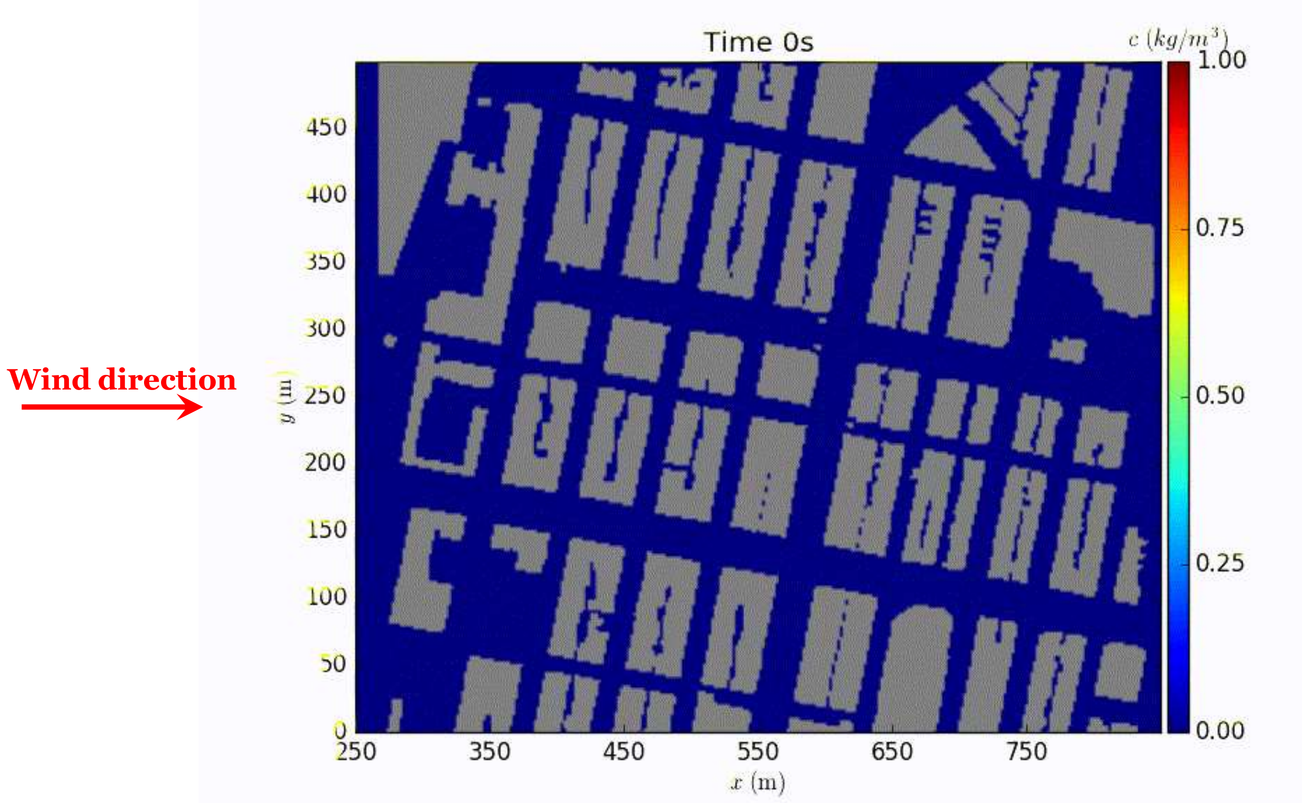
u-velocity signal at pedestrian height obtained from WRF (innermost domain ~300 m)



Frequency spectrum shows peaks at *T*~200 s

2.2 Passive scalar field – Realistic domain

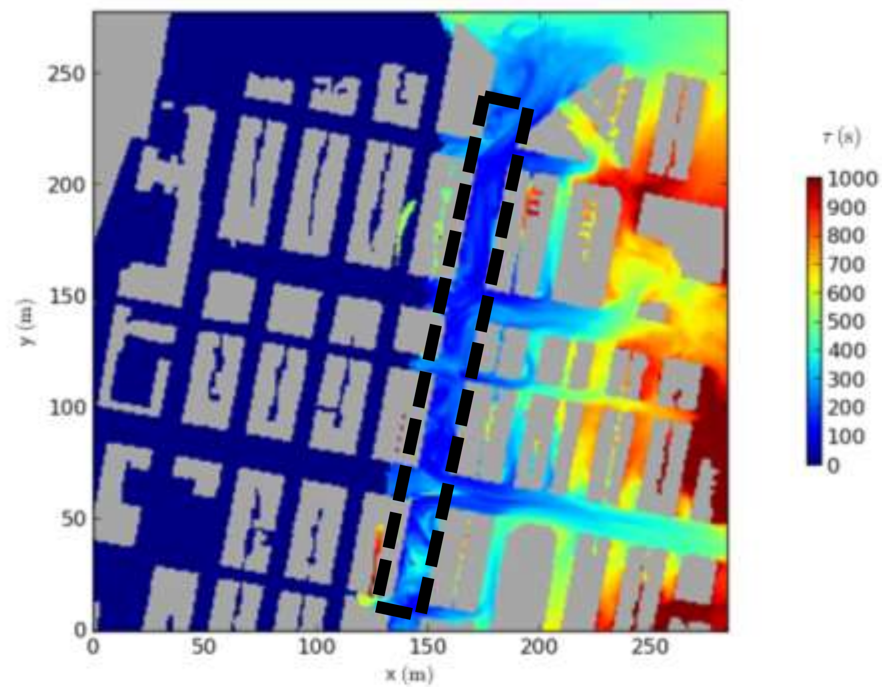
- Pollutant is released as a source flux on Nathan Road.
- Trapping of pollutants is observed in tight street canyons



2.3 Mean tracer age – Realistic domain

x-y cross-section at pedestrian level

Wind direction



- General trends
  - Mean tracer age is greater in **narrow street canyons**
  - **Trapping** of pollutants
- Ventilation of control region is generally better compared to idealised domain

2.3 Mean tracer age – Realistic domain

- Canyon-averaged mean tracer age is computed in both idealised and realistic cases:

Case	τ (s)
U1	250
U2	350
MK	280

- Generally, ventilation is poorer in deeper street canyons, e.g. in cases U2 and MK.
- However, comparing cases U2 and MK shows that ventilation is enhanced in the realistic case, as a result of inhomogeneity found in the flow.

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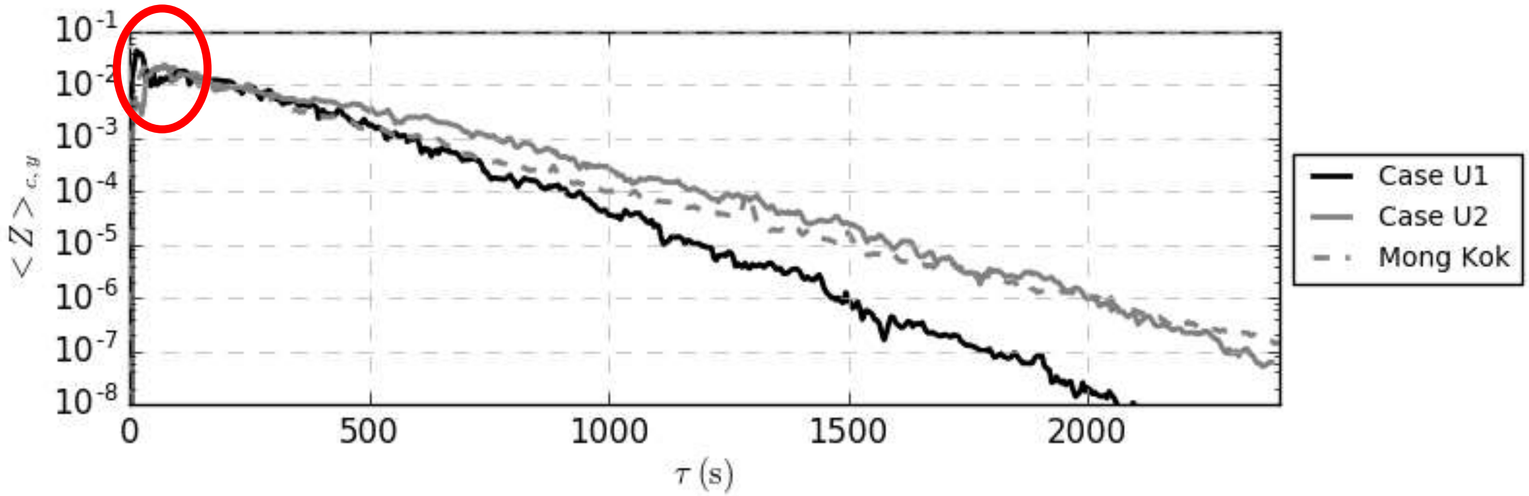
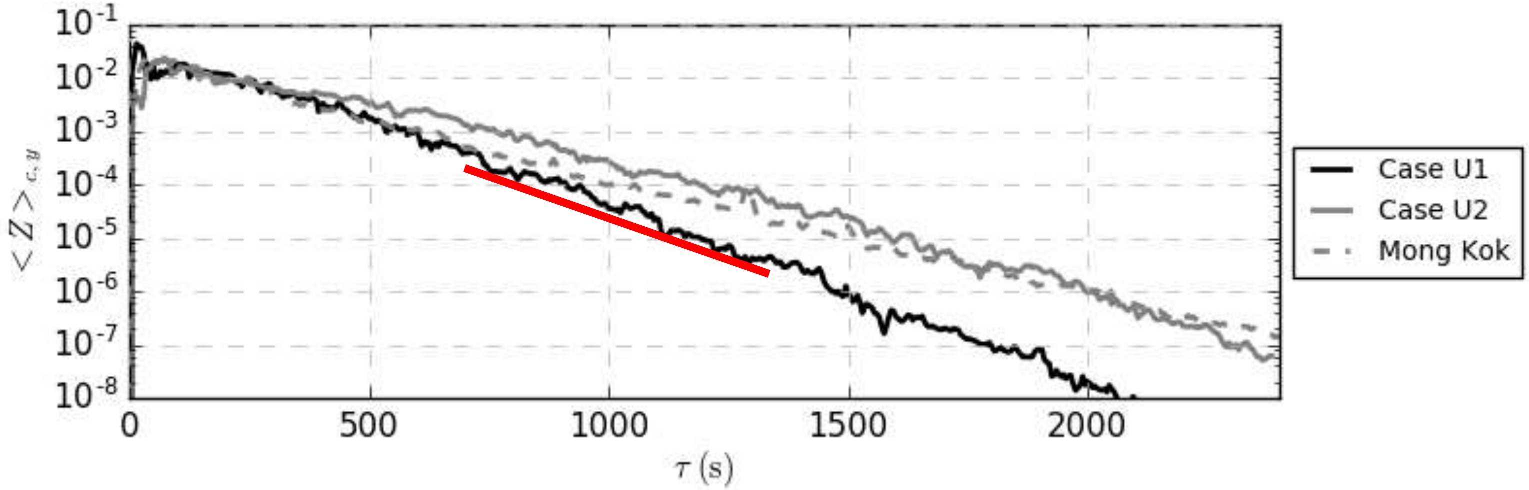
3. Tracer age spectrum



- There is a broad distribution of tracer ages.
- Tracer age depends on advection and diffusion. Peaks at the instant pollutant is released.
- Tail of the distribution is exponential, i.e.

$$Z = Ae^{B\tau}$$

3. Tracer age spectrum



- Effectiveness of ventilation (escape) can be directly related to the slope:

$$Z = Ae^{B\tau} = Ae^{-\tau/t_d}$$

Case	t_d (s)
U1	173.5
U2	247.2
MK	175.6

Conclusion

- The tracer age (age of air) can be defined precisely without *a priori* assumptions by adopting an effectively Lagrangian framework.
- Comparison between local mean age of air and mean tracer age indicates qualitative similarities, but there are differences in magnitudes.
- For the idealised domain, it is found that ventilation is poorer for:
  - Deeper canyons
  - Downstream canyons
- For the realistic domain, inhomogeneity in the turbulence results in enhanced ventilation.
- Decay timescale exhibits similar trends as the mean tracer age, but is lower than the latter.

Extra slides

Turbulence recycling