A numerical study of pollutant entrainment and dispersion in a street network

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Why does entrainment matter?

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Buncefield fire, North of London in 2005

Enormous quantities of PM10 released

Hypothetical street-level release in a city centre

Aerial view of DAPPLE site (central London) - www.dapple.org.uk
Superimposed visualization in a wind tunnel scale model

Basic questions & approach

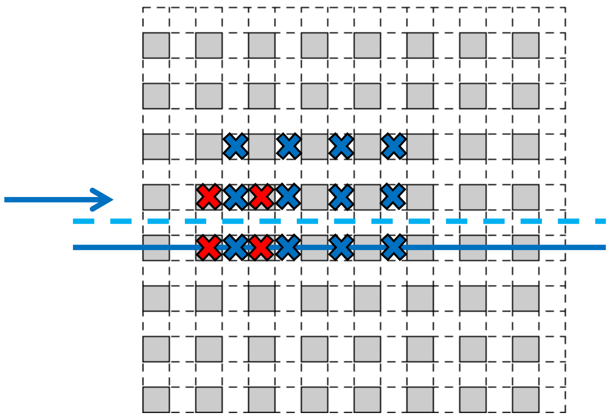
- When/where is entrainment important?
- What controls entrainment in an urban canopy?
- How can we model it in fast dispersion models?

Demonstrate entrainment using data from Direct Numerical Simulations (DNS)
Represent entrainment and other processes within a simple box–network framework
Explore qualitative and quantitative capabilities of the model

DNS results: ground vs. elevated source

Branford et al. (2011); Coceal et al. (2014)

0 deg simulation



Solid line: within/above canyons
Dashed line: within/above channel

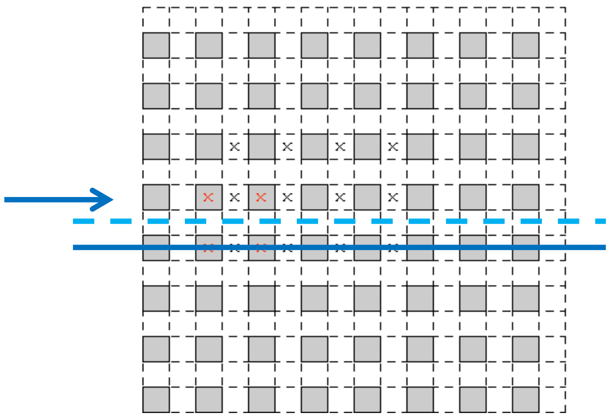
Crosses denote source locations (blue within array at ground level; red above array at 2h).

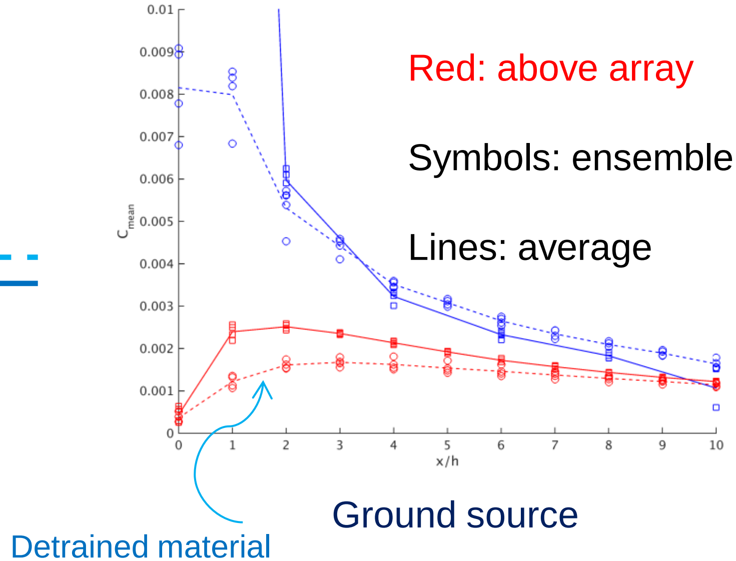
Arrow denotes wind direction.

$$\frac{dc}{dt} + \vec{u} \cdot \vec{\nabla} c = \kappa \nabla^2 c + S,$$

Continuous release of a passive scalar from an ensemble of point sources, advected by turbulent flow under neutral stability; periodic horizontal boundary conditions.

DNS results: ground vs. elevated source





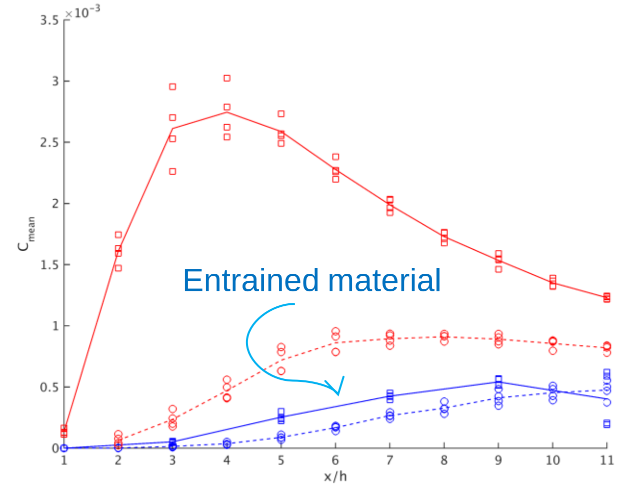
Blue: within array

Red: above array

Symbols: ensemble

Lines: average

Ground source



Elevated source

Lateral mixing is faster than vertical mixing

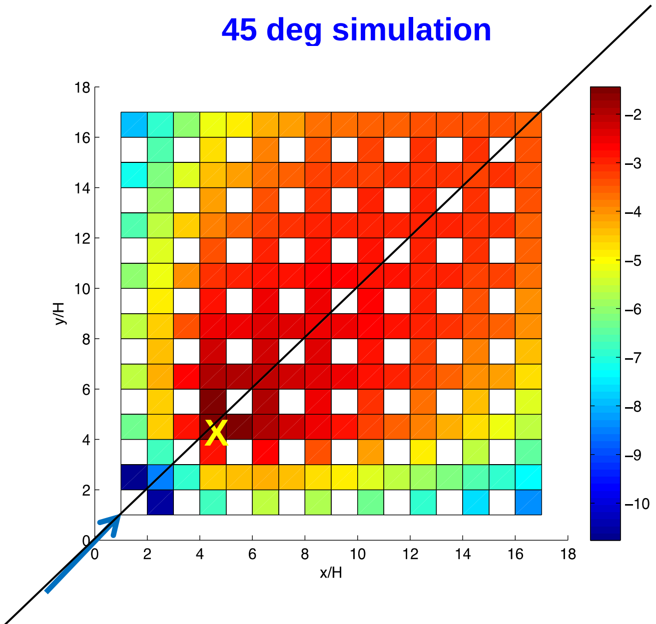
Both lateral and vertical mixing are quicker for ground sources

Material is entrained more gradually than is detrained

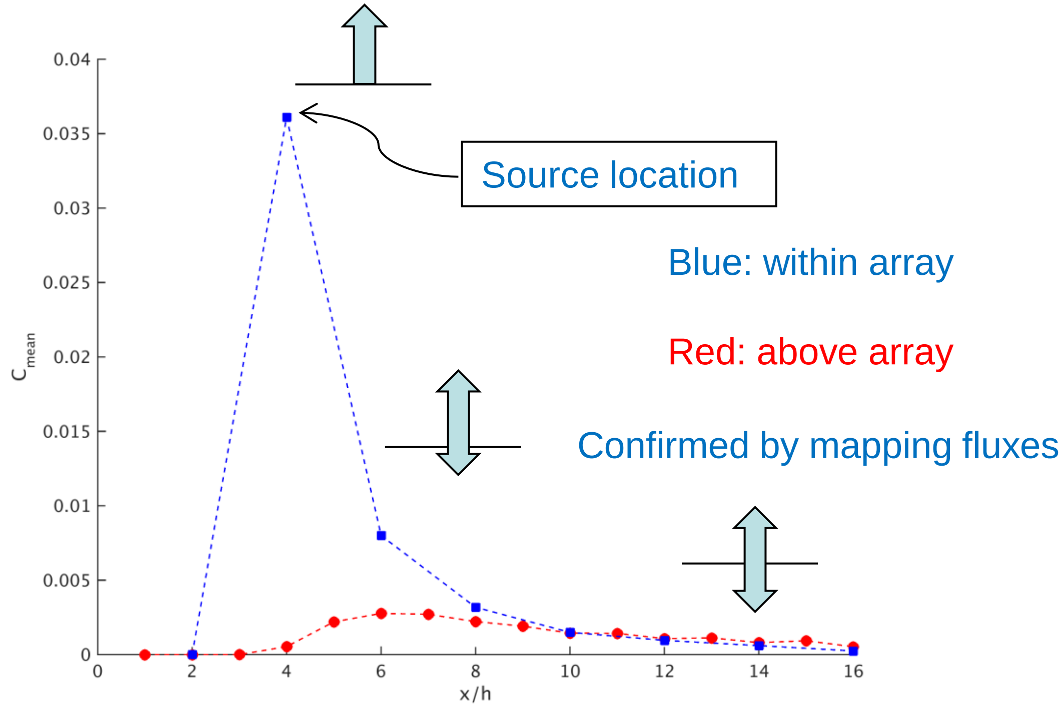
Entrainment starts quite soon after the release

DNS results: centreline concentration

Branford et al. (2011); Coceal et al. (2014)



Volume-averaged concentration



Centreline concentration

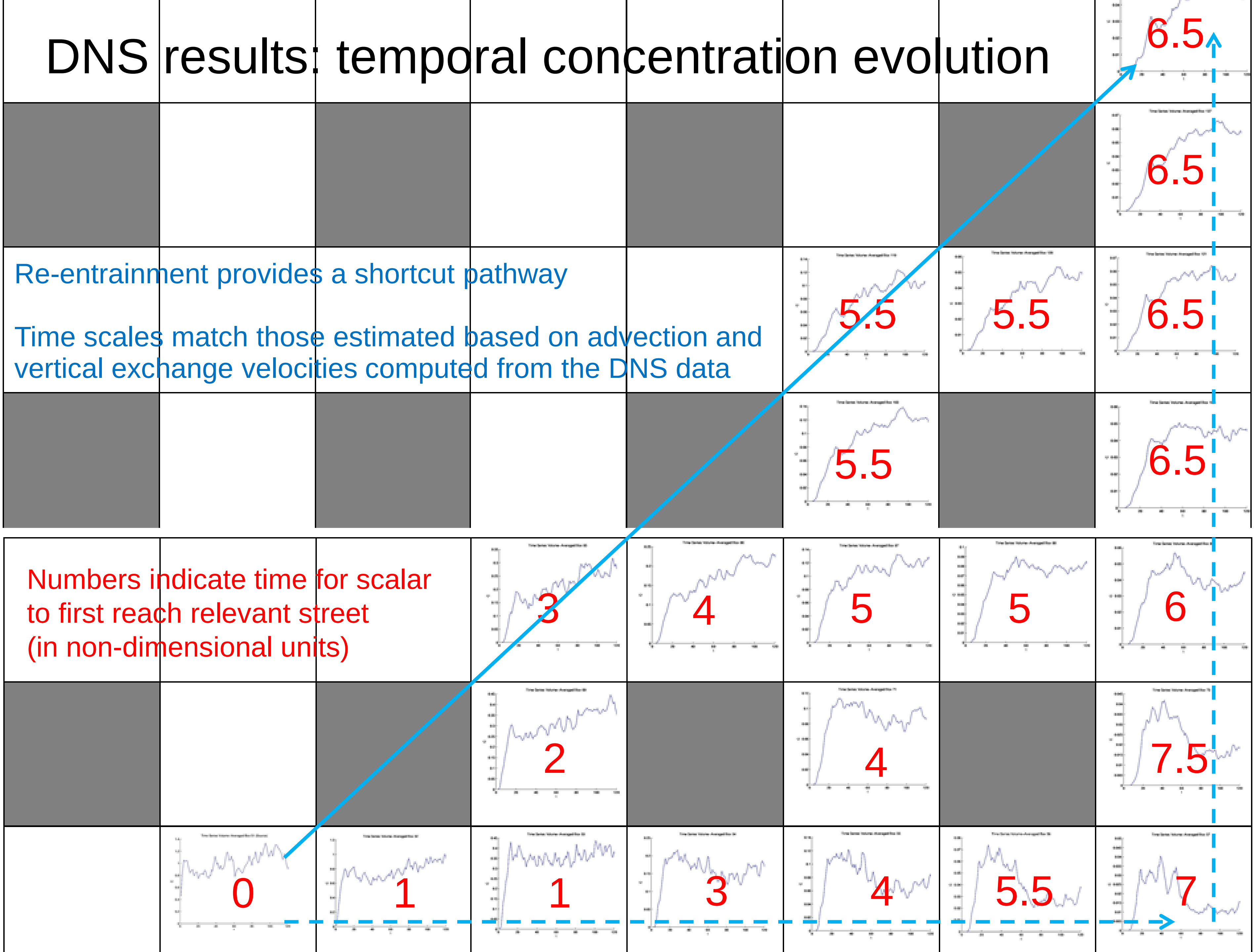
Cross denotes ground-level source location (within intersection)

Rapid decrease in concentration within array; slower decrease above.

By the third intersection concentration within and above are virtually equal.

Proportion of downward flux of material increases until equilibrium is achieved

DNS results: temporal concentration evolution



A box-network framework for dispersion

$$\dot{C}\ V = q + \sum_k \Phi_k$$

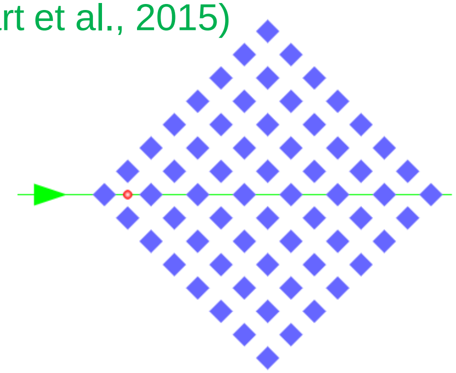
$$\Phi_k = F_k + f_k$$

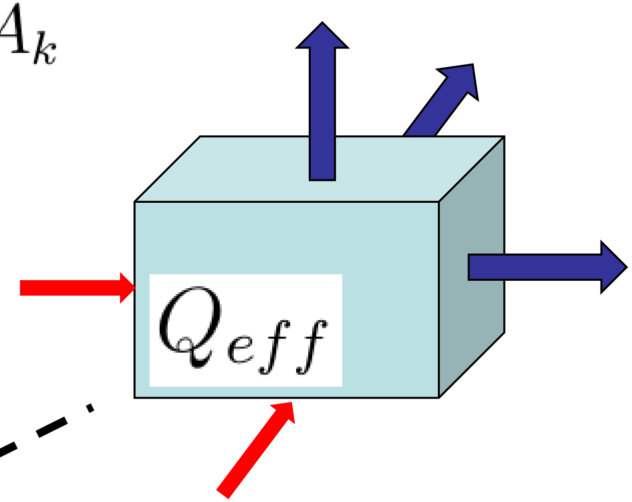
$$f_k = \Delta C\ E_k\ A_k$$

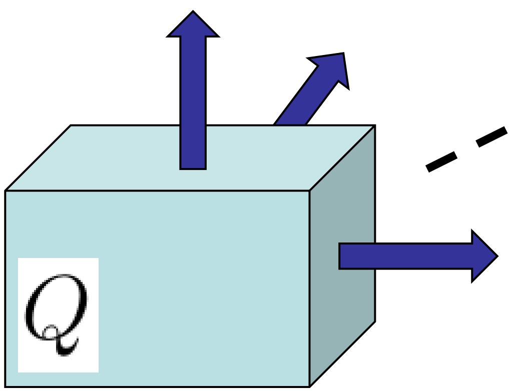
← Key assumption

$$F_k = C\ \overrightarrow{U_k}\ A_k$$

Treat each street as a well-mixed box (Goulart et al., 2015)







$$\dot{C} = Q - \frac{C}{\tau}$$

Total loss rate →

$$\frac{1}{\tau} = \sum_k \frac{1}{\tau_k}$$

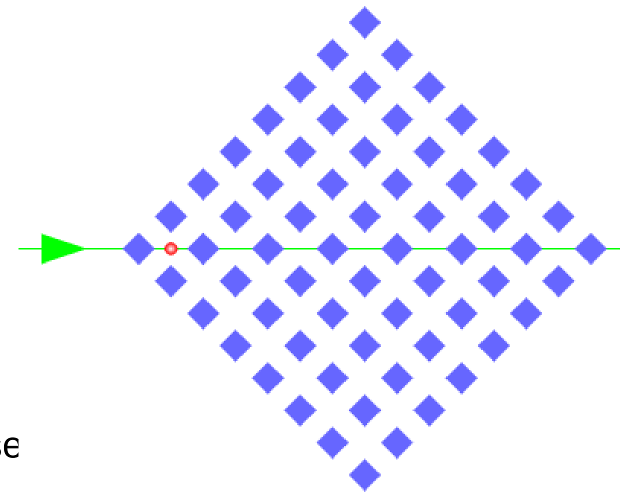
Depend on geometry, flow

$$\tau_k \equiv l_k / u_k$$

Belcher et al. (2015) ← Analytical solutions exist for a regular street network

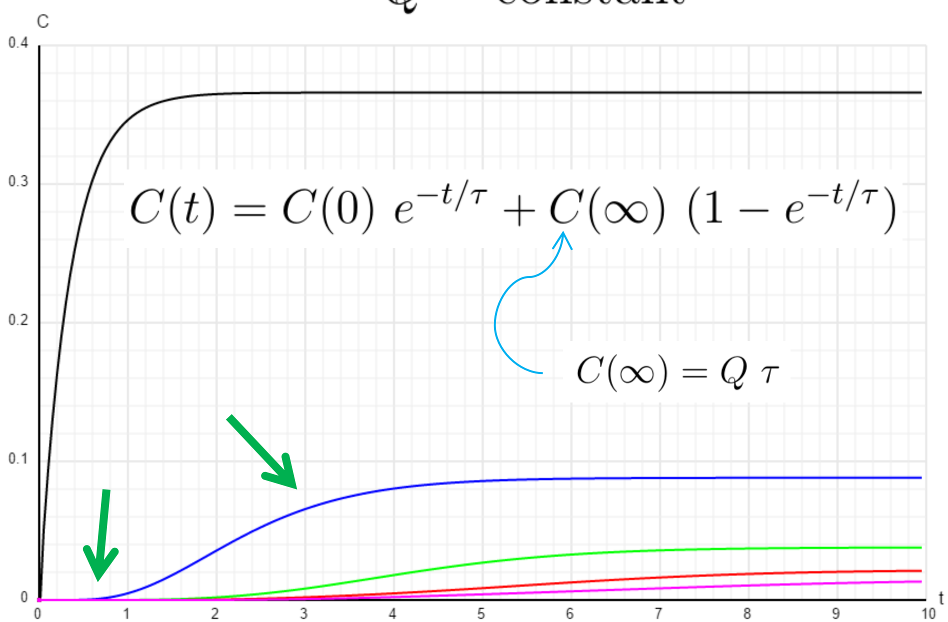
Time evolution through a network

$$\dot{C} = Q - \frac{C}{\tau}$$



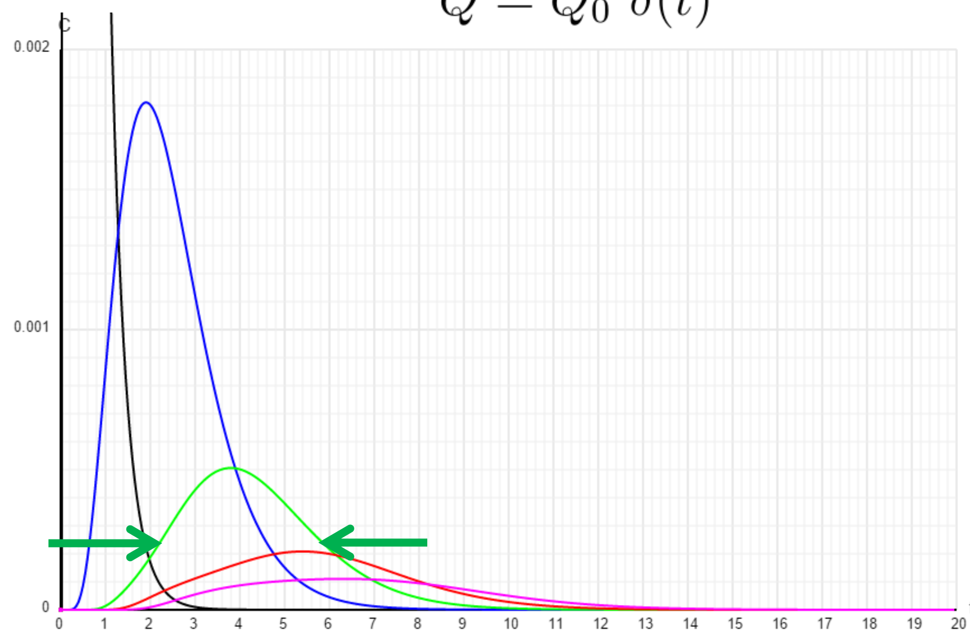
Continuous release

$$Q = \text{constant}$$

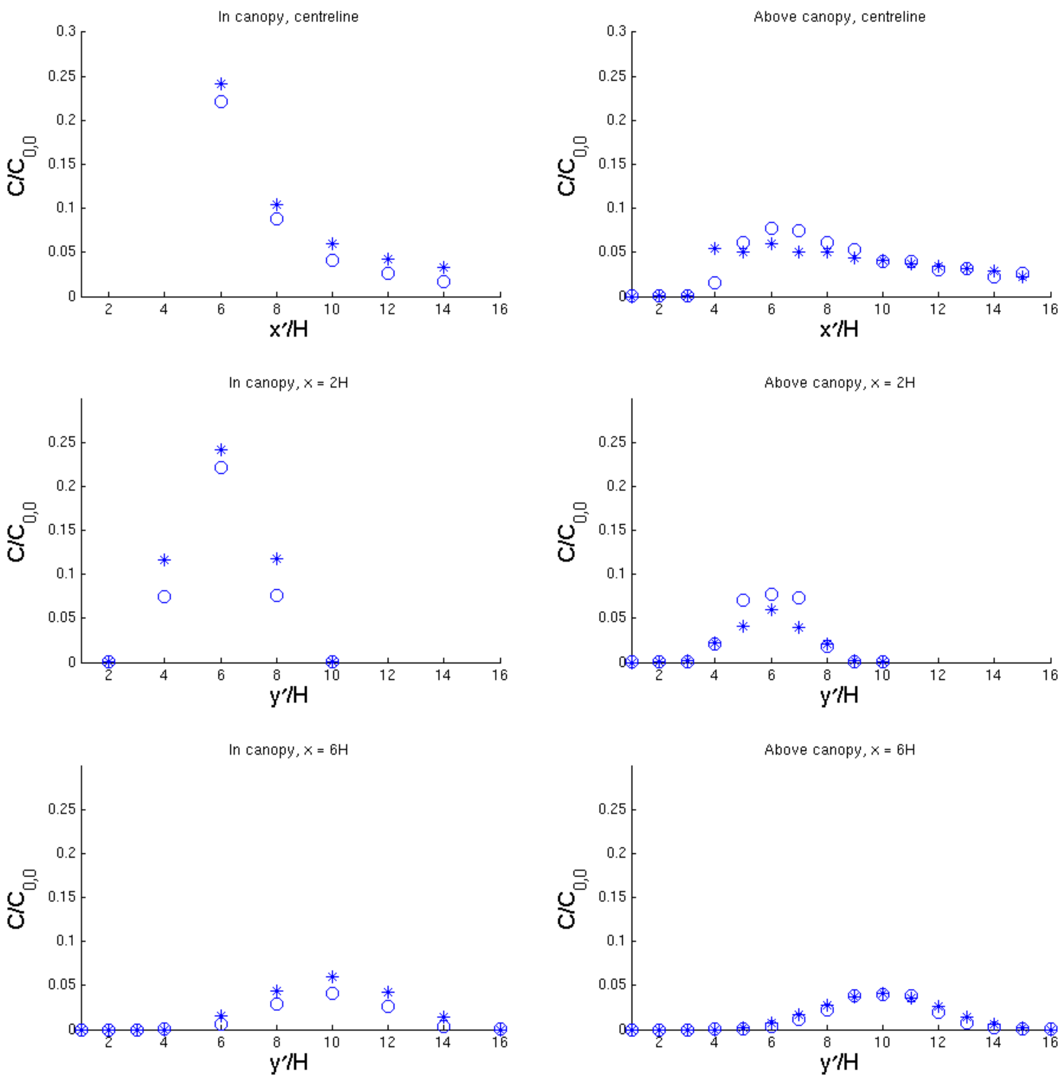


Puff release

$$Q = Q_0\ \delta(t)$$



Comparison of mean concentrations with DNS



Cicles: DNS. Asterisks: Network model

LEFT: Centreline and lateral profiles in array

RIGHT: Profiles above array

Reproduces well the decay in mean centreline concentration within and above the array.

Magnitude and width of plume well captured by simple model.

Increasing the detrainment rate does not change concentration in far field.

Network model is (extremely) simple and (extremely) fast!

Conclusions

- Entrainment in a street network becomes important after the first few streets downstream of a release.
- Re-entrainment can provide a quicker pathway for material than advection through the street network.
- Enhanced initial detrainment is compensated by higher subsequent re-entrainment.
- Dispersion is governed by effective transfer time scales, which depend on the geometry and flow.
- A simple box-network model captures concentration pattern and evolution quantitatively/qualitatively.

Further questions

see poster

Explored in more detail in the DIPLOS project (Dispersion of Localised Releases in a Street Network: www.diplos.org)

- Pathways for entrainment
- Relative proportion of material via different pathways
- Effect of wake trapping and tall buildings
- Lagrangian simulations

References

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