Lagrangian exposure and residence times for urban flows

Ka Wai Lo & Keith Ngan

School of Energy and Environment, City University of Hong Kong

Abstract

Effective policy for air pollution requires appropriate indicators for the potential health impact of pollutants. Current indicators are based mostly on time-averaged pollutant concentrations rather than the exposure. This poster describes the calculation of residence and exposure times for idealised and realistic domains (a single street canyon and two Hong Kong neighbourhoods, respectively). Using large-eddy simulation for the resolved fields and a Lagrangian stochastic model for subgrid-scale motions, it is found that probability distribution functions of the timescales have long exponential tails. Implications for regulatory policy are discussed.

1. Background

Conventional urban pollution diagnostics focus on the accumulation of pollutants. Ventilation of the urban canopy has been the focus of intense research interest. Yet the direct relevance of these diagnostics to health is unclear because the health impact of a pollutant depends on concentration and the time spent by the pollutant in a respirable region.

Timescales characterising pollutant ventilation and exposure are most easily calculated within a Lagrangian framework. Typically additional assumptions (e.g. homogeneity) are imposed when they are inferred from Eulerian data. Following work in indoor air quality **[1]** and oceanography **[2]**, the **residence time** is the time required for a particle to leave a domain while the **exposure time** is the total time spent by a particle in the region of interest. Mathematically

$$\frac{D\tau_r}{Dt} = 1 \qquad \frac{D\tau_e}{Dt} = \chi\,.$$

For the residence time, an absorbing boundary condition is applied at the roof level. For the exposure time, χ is an indicator function for the region of interest (i.e. χ=1 if the particle is inside, 0 otherwise).

The Lagrangian equations of motions are solved by advecting particles. In the coupled LES-LSM approach proposed by Weil et al. **[3]**, the velocity is divided into resolved and subgrid scales. In this poster, the resolved velocity comes from the large-eddy simulation model, PALM **[4]**, while the subgrid velocity comes from a Lagrangian stochastic model **[3]**. The LSM solves the Langevin equation

$$du_i = a_i dt + b_{ij} dW_i.$$

where dW_i is Gaussian noise (or more formally, an increment from a Wiener process). The deterministic case is recovered by setting the subgrid velocity to zero.

3. Residence and exposure times for an urban neighbourhood

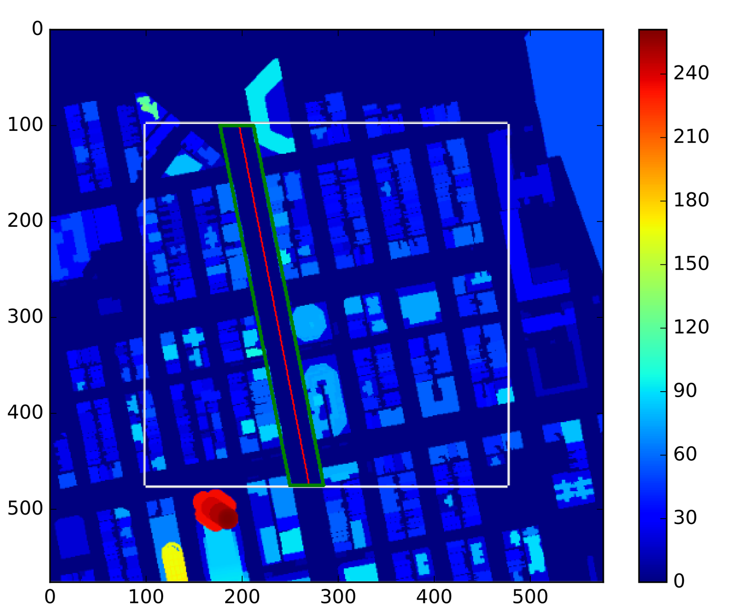

Fig. 2 Computational domain for a realistic urban area (Mong Kok, Hong Kong). The colours correspond to building heights.

The white box divides the simulation domain proper from the surrounding buffer region. Residence and exposure times were calculated within the green box so as to facilitate comparison with the simple street canyon; the average building height and aspect ratio are 50m and 1.4. The inflow wind speed was identical to that in the calculation for the single street canyon. Particles were released along the red line. Only the deterministic case was considered.

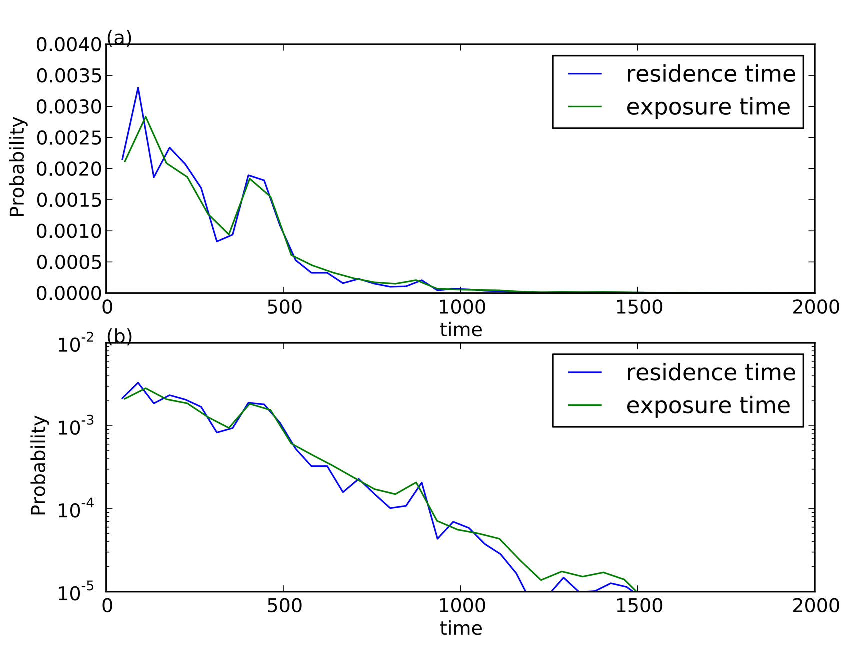

Fig. 3 Distribution of residence and exposure times. (a) linear; (b) log scales.

In the realistic urban domain, the tail of the PDF is no longer exactly exponential. Moreover, large fluctuations are superimposed on top of the decaying baseline. The mean residence and exposure times are 290 and 306s respectively and considerably shorter than for the idealised street canyon.

A. Validation of the Lagrangian model

The Lagrangian model was validated against tracer data from a wind tunnel experiment **[11]**. The concentration values agree well and the spatial variation is similar.

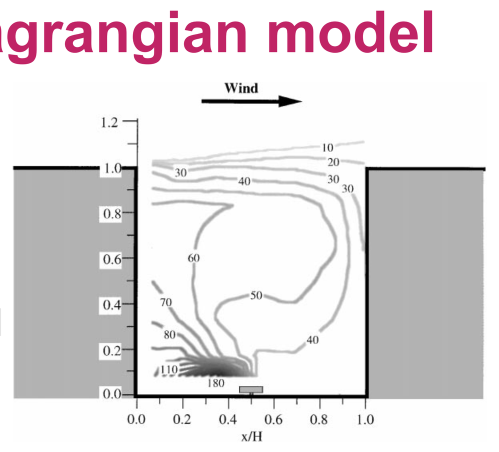

Fig. 5 Wind tunnel experiment

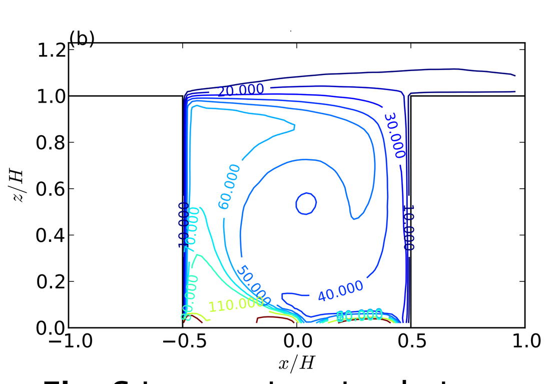

Fig. 6 Lagrangian simulation

2. Lagrangian residence and exposure times for a street canyon

Turbulent flow within a single street canyon was simulated using PALM **[5,6]** following **[7]**. Particles were released at the bottom of the canyon (about 140000 particles in total).

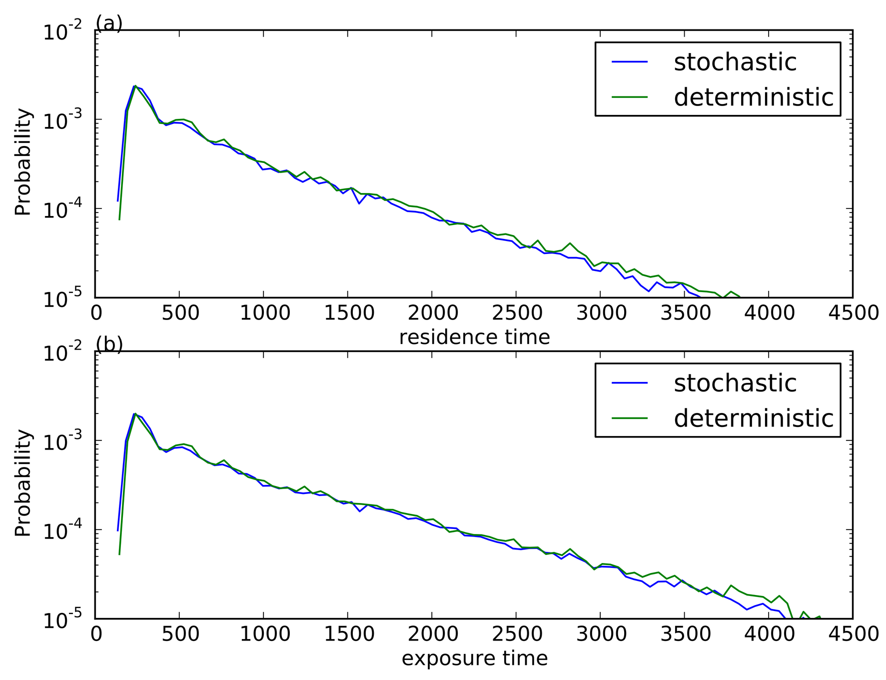

Fig. 1 Probability distributions of the residence time (*top*) and exposure time (*bottom*) for the entire canyon.

i) The PDFs show little sensitivity to the presence of stochastic subgrid motions.
ii) The PDFs are approximately exponential. This is consistent with the first exit time for Brownian motion **[8]**.
iii) The behaviour at the pedestrian level is quite different (not shown). The mean exposure time is much shorter.

Table. 1 Summary statistics for the residence and exposure times. All the measurements are in seconds.

	deterministic	stochastic
mean RT	783	737
mean ET	943	892
sd RT	690	660
sd ET	831	793
decay RT	771	732
decay ET	917	890

i. The mean exposure time is about 20% greater than the mean residence time on account of re-entrainment.
ii. The re-entrainment is relatively weak. This has been confirmed by calculating the visitation frequency (not shown).
iii. The stochastic and deterministic models agree well.
iv. The decay timescales were obtained by fitting the tails to an exponential.
v. Since the PDFs are approximately exponential, the mean and decay timescales are nearly identical. This supports the widespread use of the decay timescale **[9]**.

4. Application to air pollution regulation

Extended exposure to pollutants can lead to adverse health effects. Air quality is usually regulated with respect to the time average-concentration, but this is insufficient as information about exposure is missing. The European guidelines for fine particulates illustrate this problem: while the nominal safe value of 25 μg/m^3 applies to the annual mean, the risk posed by long-term exposure is greatly increased even for pollutant concentrations below 20 μg/m^3 **[10]**.

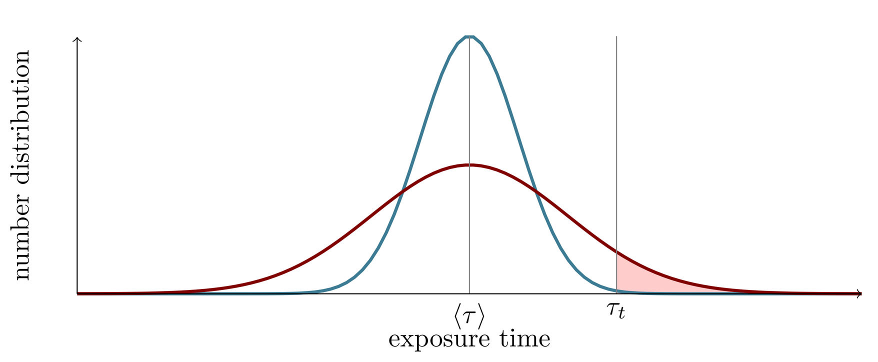

Fig. 4 Hypothetical exposure-time distributions.

Even though the two distributions have the same mean value $\langle\tau\rangle$, only the wide one has significant area lying beyond the threshold value, τ_t. Knowledge of the exposure-time distribution could provide additional information on potential health impacts.

Table 2 Pedestrian-level exposure statistics for two Hong Kong neighbourhoods, Mong Kok (MK) and Tsim Sha Tsui (TST). The assessment regions cover both neighbourhoods.

exposure time	MK	TST
≤200s	72%	61%
200-400s	14%	21%
400-600s	2.1%	9.9%
600-800s	4.0%	2.9%
800-1000s	2.0%	1.4%
≥1000s	6.3%	4.0%

The mean exposure times are 296s and 311s for MK and TST respectively. Although the mean exposure time is shorter in MK, a larger percentage of pollutants have long exposure times. Hence the potential health impact could be greater in MK.

References

[1] Bady, M., Kato, S. & Huang, H., 2008. Towards the application of indoor ventilation efficiency indices to evaluate the air quality of urban areas. Building and Environment 43, 1991 – 2004.
[2] Delhez, EJM., 2006. Transient residence and exposure times. Ocean Science, 2, 1--9.
[3] Weil, JC, Sullivan, PP & Moeng, C.-H., 2004. The use of large-eddy simulations in Lagrangian particle dispersion models. Journal of the Atmospheric Sciences 61, 2877–2887.
[4] Maronga, B et al., 2015. The parallelized large-eddy simulation model (PALM) version 4.0 for atmospheric and oceanic flows: model formulation, recent developments, and future perspectives. Geoscientific Model Development Discussions 8, 1539–1637.
[5] Raasch, S. & Schroter, M., 2001. PALM --- a large-eddy simulation model performing on massively parallel computers. Meteorologische Zeitschrift 10 (5), 363–372.
[6] Maronga et al., 2015. The parallelized large-eddy simulation model (PALM) version 4.0 for atmospheric and oceanic flows: model formulation, recent developments, and future perspectives. Geoscientific Model Development 8 (8), 2515–2551.
[7] Lo, KW & Ngan, K, 2015.: Predictability of turbulent flow in street canyons. Bound. Layer Meteorol. 156, 191—210.
[8] Schuss, Z., 2010. Theory and applications of stochastic processes, Springer.
[9] Lee, I & Park, H, 1994: Parameterization of the pollutant transport and dispersion in urban street canyons. Atmos. Environ. 28, 2343—2349.
[10] Beelen, R. et al. 2014. Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre escape project. The Lancet 383, 785–795.
[11] Pavageau, M. & Schatzmann, M.,1999. Wind tunnel measurements of concentration fluctuations in an urban street canyon. Atmospheric Environment 33, 3961–3971.

School of Energy and Environment, City University of Hong Kong
Tat Chee Avenue, Kowloon, Hong Kong SAR
Phone: +852 3442 6702
Email: keith.ngan@cityu.edu.hk