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Analysing urban ventilation in building arrays with the age spectrum and mean age of pollutants

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ABSTRACT

This study investigates the applicability and relevance of the Green's function and age spectrum to urban ventilation. Ventilation in an idealised urban environment is examined by characterising pollutant dispersion from the urban canopy layer. Air flow over regular uniform and non-uniform building arrays is computed using large-eddy simulation and pollutant removal is analysed via the age spectrum for localised sources. The age spectrum represents the probability distribution function of pollutant or tracer ages. Since the age spectrum is obtained directly from the evolution equation for the passive scalar, it is more effective for flows with high intermittency. This should be beneficial for studies of extreme pollution events in the urban environment such as accidental release of toxic gases and dust storms. It is demonstrated that the age spectrum is sensitive to the source release location, implying that pollutant removal depends on the initial conditions. Mean ages calculated using the homogeneous emission method and the age spectrum show qualitative similarities; however, there are quantitative differences in regions where the flow is highly unsteady and intermittent. The age spectrum indicates that ventilation decreases by ~70% when the aspect ratio (building height/street width) is increased from 1 to 4. Furthermore, the effect of fresh air entrainment increases by ~80% when the building heights are non-uniform.

1. Introduction

Air pollution has become an important environmental issue in recent decades. In the urban environment, local air pollution typically originates from vehicular emissions [1]. Particulate matter (PM) and gaseous pollutants in built-up urban areas constitute a major long-term health risk to children [2], seniors [3] and people suffering from respiratory diseases [4–6]. Apart from local air pollutants, severe air pollution episodes such as accidental release of toxic gases, dust storms and bushfire smoke [7–9] also pose acute risk to the environment and health of urban inhabitants. Ventilation, which refers to the process by which pollutants are removed by fluid flow, is thus very important for both outdoor and indoor air quality [10].

It is known that urban ventilation and pollutant dispersion are affected by factors such as building packing density [11], street width [12, 13] and inflow wind conditions [14, 15]. Numerous field studies [16], experimental work [17, 18] and numerical simulations [19–25] have mainly focused on idealised domains, e.g. street canyon [19–23], 26, 27] and building arrays [11, 28–31] (see for example the reviews by Vardoulakis et al. [32] and Belcher [33]). It has been found that urban street canyons are often linked to poor ventilation with high pollutant concentrations. In particular, the presence of closely packed tall buildings causes the air flow to stagnate, greatly hindering the removal of pollutants from the urban canopy layer (UCL) [17, 34–36].

In studies of urban ventilation and pollutant dispersion, it is common to adopt flux-based indices such as the volumetric flow rate and air change rate [30, 37], pollutant dispersion and exchange rate [19, 22, 26], and exchange velocity and city breathability [16, 38, 39]. As pointed out by Bady et al. [34], these flux-based indices mostly correspond to the mean exchange across the UCL boundary, rather than the local ventilation within the UCL. An alternative perspective comes from building ventilation theory commonly applied to evaluate indoor ventilation [34, 40] where timescale-based indicators have been used to characterise ventilation within the urban environment. An example is the local mean age of air τ_{air} [29, 41, 42] which can be used to examine how rural air is supplied and distributed within an UCL. Large values implies a poorly ventilated region and vice versa. To estimate the local mean age of air, the homogeneous emission method [41] which assumes a spatially uniform source is commonly applied: the local mean age of air is estimated from the time-mean concentration, thereby establishing a link between the pollutant concentration level and its removal timescale.

For a realistic urban area, the removal of pollutants is influenced by variability in the urban morphology [43], human activity [44] and

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Nomenclature

c	concentration field
g	gravity
H	building height
H_1	shorter building height (for non-uniform case)
H_2	taller building height (for non-uniform case)
k	turbulent kinetic energy
p^*	perturbation pressure
Q_c	scalar source
Re_H	Reynolds number based on the building height
S_1	street width (primary)
S_2	street width (secondary)
S_c	homogeneous source
T_c	canyon circulation timescale
t	time
(u, v, w)	velocity in the streamwise, spanwise and vertical direction, respectively
u_o	roof-level streamwise velocity
u_∞	free-stream velocity
V_c	volume of a canyon or channel unit
W	building width
x	horizontal direction
y	vertical direction
z	span-wise or lateral direction
Z	age spectrum
Z_y	spanwise-averaged age spectrum
Z_o	global maximum of the age spectrum
Δ	grid spacing
$\Delta\tau_{rel}$	relative difference between τ_{mta} and τ_{hom}
ξ	time lag
κ	scalar diffusivity
λ_p	building area density
ν	kinematic viscosity
π^*	modified perturbation pressure
Ω_y	spanwise vorticity
ρ	density
S_{ij}	strain tensor
τ_{mta}	mean tracer age
τ_{hom}	mean age (homogeneous emission)
$\Delta\tau$	difference between inlet-source and ground-source mean age
$\Delta\tau_{rel}$	relative difference between τ_{mta} and τ_{hom}
$\mathfrak{I}$	characteristic timescale of exponential decay
$\langle\rangle_c$	canyon or channel averaged field
$\langle\rangle_y$	spanwise averaged field

Subscripts

o	initial state
sgs	SGS component

Superscripts

$-$	time-averaged field
$\sim$	filtered field
$'$	fluctuating field

Abbreviations

LES	large-eddy simulation
PALM	Parallelized Large-eddy Simulation Model
RANS	Reynolds-averaged Navier-Stokes

external winds [45]. This implies that the airflow within these urban configurations is highly turbulent and possibly intermittent [20]. In addition, pollutant sources may be inhomogeneous particularly in cases of extreme pollution where the disturbances to the urban environment are essentially transient in nature. In these cases, evolution of the pollutant field and hence its removal timescale depend on the unsteady flow and source release locations (i.e. initial conditions). More generally, there exists a statistical variability in the pollutant removal. Such effects should be taken into account when evaluating pollutant removal timescales for inhomogeneous urban domains, yet studies examining this aspect of the problem are uncommon.

Recently, Lo and Ngan [46] applied the Green's function and age spectrum [47,48] to study ventilation for a single street canyon. The age spectrum represents a statistical or probability distribution function of tracer (or pollutant) ages. In this approach, the mean tracer age is calculated directly from the evolution of the scalar field as the first moment of the age spectrum; it encapsulates all the fluid dynamical processes that affect the distribution of a passive tracer. Since this approach does not require time-averaging or a spatially homogeneous source, the implication is that it can be used for localised sources and as an indicator to study inhomogeneity in urban ventilation. In this article, when there is no risk of ambiguity, we shall refer to the mean age of pollutant as the mean tracer age.

In this work, we aim to examine ventilation within inhomogeneous urban domains using the age spectrum and mean age of pollutants. The urban domains investigated are idealised city-like geometries with uniform and non-uniform aspect ratios (building height/street width). Applicability of the age spectrum in characterising ventilation is examined by comparing localised and homogeneous sources. Specifically, the flow conditions under which the age spectrum differs from the homogeneous emission method are discovered. The present work also attempts to examine sensitivity of the age spectrum to different initial conditions by considering source release locations at the ground level and inlet.

2. Methodology

2.1. Numerical model

The computational model is based on the non-hydrostatic and incompressible Navier-Stokes equations. To adequately resolve the turbulent structures, a large-eddy simulation (LES) approach was adopted in which the large-scale eddies are resolved explicitly and the small-scale eddies are filtered and modelled. This filtering operation, denoted by a tilde ($\sim$), is defined as

$$\tilde{\varphi}(x_i, t) = \int_D F(x_i, x_i')\varphi(x_i', t)dx_i', \tag{1}$$

where D is the flow domain, F is the filter function, and $x_j = (x, y, z)$ are axes of the Cartesian coordinate system. The equations for the conservation of mass, momentum and passive scalar, implicitly filtered over a grid volume on a Cartesian grid, read as:

$$\frac{\partial \tilde{u}_j}{\partial x_j} = 0 \tag{2}$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i\tilde{u}_j}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial \tilde{\pi}^*}{\partial x_i} + \nu\frac{\partial^2 \tilde{u}_i}{\partial x_j^2} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{3}$$

$$\frac{\partial \tilde{c}}{\partial t} + \frac{\partial \tilde{u}_j\tilde{c}}{\partial x_j} = \kappa\frac{\partial^2 \tilde{c}}{\partial x_j^2} - \frac{\partial s_j}{\partial x_j} + S \tag{4}$$

In Eqs. (2)–(4), $\tilde{u}_i = (\tilde{u}, \tilde{v}, \tilde{w})$ are the velocity components with location $x_i = (x, y, z)$, ρ_0 is the density of dry air, $\tilde{\pi}^* = \tilde{p}^* + \frac{2}{3}\rho_0 e$ is the