Atmospheric Environment 122 (2015) 611–621

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Characterising the pollutant ventilation characteristics of street canyons using the tracer age and age spectrum

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HIGHLIGHTS

- The ventilation of street canyons is analysed using the response to a point source.
- Ventilation timescales are defined from the distribution of transit times.
- Time averages can yield a misleading picture of the ventilation.
- An uneven, non-uniform building array improves ventilation.

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form
7 October 2015
Accepted 8 October 2015
Available online 22 October 2015

Keywords:
Age of air
Green's function
Large-eddy simulation
Pollutant dispersion

ABSTRACT

The age of air, which measures the time elapsed between the emission of a chemical constituent and its arrival at a receptor location, has many applications in urban air quality. Typically it has been estimated for special cases, e.g. the local mean age of air for a spatially homogeneous source. An alternative approach uses the response to a point source to determine the distribution of transit times or tracer ages connecting the source and receptor. The distribution (age spectrum) and first moment (mean tracer age) have proven to be useful diagnostics in stratospheric modelling because they can be related to observations and do not require a priori assumptions. The tracer age and age spectrum are applied to the pollutant ventilation of street canyons in this work. Using large-eddy simulations of flow over a single isolated canyon and an uneven, non-uniform canyon array, it is shown that the structure of the tracer age is dominated by the central canyon "vortex"; small variations in the building height have a significant influence on the structure of the tracer age and the pollutant ventilation. The age spectrum is broad, with a long exponential tail whose slope depends on the canyon geometry. The mean tracer age, which roughly characterises the ventilation strength, is much greater than the local mean age of air.

1. Introduction

Ventilation refers to the process by which polluted air is replaced by fresh air. It is an important topic in indoor air quality that has attracted much attention (Etheridge and Sandberg, 1996). Ventilation is also relevant to outdoor air quality as street-level air quality depends on the rate at which pollutants leave the urban canopy layer. It is widely recognized that urban air quality may suffer on account of poor ventilation; the 'street-canyon effect', in which the (streamwise) aspect ratio is large and the flow aloft decouples from the flow within the canyon (Britter and Hanna, 2003; Carruthers et al., 2012; Blocken et al., 2013), is the best-known example of this. Concrete information on ventilation timescales is valuable for end-users and researchers.

Various ventilation diagnostics have been developed and applied to numerical simulations of urban domains. Examples include the air and pollutant exchange rate (ACH and BCH respectively; Liu et al., 2005), normalised flow rate (e.g. Hang et al., 2009), and exchange velocity (Bentham and Britter, 2003). A detailed summary of outdoor ventilation diagnostics may be found in Ramponi et al. (2015).

Most outdoor ventilation diagnostics have focused on the roof level. Thus all the diagnostics listed above are based on roof-level fluxes. The ACH and PCH are defined from upward fluxes of mass and pollutant. The normalised flow rate is based on the mean mass

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http://dx.doi.org/10.1016/j.atmosenv.2015.10.023
1352-2310/

flux. The exchange velocity is defined using roof-level fluxes and characterises the velocity difference between the canopy and the overlying atmosphere.

These diagnostics reflect a traditional view of urban flow and dispersion. In accord with much of the research in the area, which highlights spatial and temporal averages (Vardoulakis et al., 2003; Li et al., 2006; Blocken et al., 2013), the ACH and PCH tacitly assume that the flow is spatially homogeneous and that the exchange velocity neglects the time-dependent ventilation process. These diagnostics, while providing a useful picture of the ventilation, have several flaws. First, ventilation is not necessarily uniform in space even though the ventilation of the canopy as a whole ultimately depends on exchange processes at the roof level (when pollutants do not escape from the sides). Second, time-averaged diagnostics do not quantify the timescales over which ventilation occurs. The latter concern is particularly important if urban computational fluid dynamics models are to be coupled to time-dependent mesoscale winds (Schlunzen et al., 2011).

These concerns have been addressed in a series of papers that apply concepts from indoor air quality. In building ventilation theory (Sandberg, 1981; Sandberg and Sjöberg, 1983; Etheridge and Sandberg, 1996), the age of a pollutant blob measures the time elapsed since it entered the domain. The age concept is attractive because it is directly relevant to the ventilation (escape or dilution) of pollutants from the urban canopy; however, the calculation of the mean age is not necessarily trivial. For a pollutant field $c(\vec{x})$ obeying the advection–diffusion equation

$$\frac{\partial c}{\partial t} + \vec{u} \cdot \vec{\nabla} c = \kappa \nabla^2 c + S, \tag{1}$$

the age of the pollutant at a given point in space will depend on the incompressible velocity field $\vec{u}(\vec{x})$, the diffusion due to the molecular (turbulent) diffusivity κ, and the (spatially varying) source flux $S(\vec{x})$.

In order to simplify the analysis, it is sometimes assumed that the pollutant source is spatially homogeneous (Hang et al., 2009, 2013; Hang and Li, 2011). According to the 'homogeneous emission method', the local mean age is then given by

$$\tau_l = \frac{\overline{c}}{S} \tag{2}$$

where $\overline{c}(x, y, z)$ is the time-averaged concentration and S is the source or pollutant emission rate. Strictly speaking τ_l can be interpreted as a mean age only if the pollutant field is controlled by a spatially uniform source. If S is not uniform then the mean age also depends on the Lagrangian evolution of pollutants, i.e., on timescales for transport and mixing.[1] Differences between a 'turnover time', defined by the ratio of the mean mass or concentration to the source flux, and the mean age have been described in the building ventilation literature (Etheridge and Sandberg, 1996). Similar diagnostics have been considered by other investigators, e.g. the average residence time (Kato, 1988; Bady et al., 2008).

The general applicability of τ_l to urban pollution problems is unclear. In many problems of interest, the pollutants are released at street level rather than uniformly throughout the domain. For this reason studies applying the homogeneous emission method have focused on the so-called 'inhalation effect' (Lin et al., 2014), i.e. the complementary problem of fresh, unpolluted air penetrating the urban canopy. It has been shown that τ_l is a useful diagnostic for the 'breathability' of regular building arrays (Buccolieri et al., 2010).

An alternative approach has been developed in atmospheric science, where there has been great interest in characterising the transport and mixing of chemical constituents (e.g. Shepherd, 2002). For chemically inert species, such as SF_6, transport from the troposphere to the stratosphere is analogous to ventilation of the urban canopy. In stratospheric modelling, the age of stratospheric constituents has been calculated by exploiting the linearity of the advection–diffusion equation (Hall and Plumb, 1994; Waugh and Hall, 2002). The 'tracer age' refers to the age of air for prescribed tracer fluxes (see Sec. 2). As any solution can be expressed in terms of the associated Green's function (see Appendix 1 for details), the age of a pollutant follows from the Green's function or 'age spectrum'.

Although they may seem abstract and of limited practical relevance, the mean tracer age and age spectrum have been influential in atmospheric science. They are now standard tools for evaluating numerical models (Waugh and Hall, 2002). The great merit of this approach is that it is based entirely on the equations of motion; in the context of urban pollutant dispersion, this means that ventilation can be analysed without any a priori assumptions. A related benefit is that the mean tracer age and age spectrum can be directly compared to observations (Hall et al., 1999).

Despite the successful applications to stratospheric modelling, the Green's function approach has received little if any attention in the urban pollution literature. However, it is closely related to building ventilation theory. The mean tracer age obeys an equation that it is formally identical to one for the mean age (Etheridge and Sandberg, 1996; Holzer and Hall, 2000). This equation has not been explicitly solved in applications of building ventilation theory to urban pollutant dispersion; instead a simplified equation yielding Eq. (2) has been analysed instead.

In this paper we will investigate the applicability of the tracer age and age spectrum to numerical simulations of urban pollutant dispersion. The main objectives of this study are to (i) introduce new ventilation diagnostics based on the Green's function approach (Secs. 2 and 3) and (ii) use them to characterise the influence of the street-canyon geometry. The mean tracer age, standard deviation and age spectrum will be calculated from large-eddy simulations (Sec. 4). The diagnostics will be applied to an even (i.e. parallel) street canyon (Sec. 5) as well as the less familiar uneven, non-uniform street canyon array (Sec. 6), a configuration with streamwise and spanwise inhomogeneities (Gu et al., 2011). The advantages of the new diagnostics will be assessed in Sec. 7.

2. Tracer age and age spectrum

In atmospheric science the age of air has been defined using Eq. (1), which governs the evolution of a passive tracer. More precisely, the age of air is calculated from the associated Green's function; since the Green's function can be used to reconstruct any solution, this means that the approach is essentially exact (though, as explained below, simplifying assumptions are made in practice).

The main elements of the Green's function approach are summarized below. The presentation follows Holzer and Hall (2000) and Waugh and Hall (2002). Further details (and brief derivations) may be found in Appendix 1.

A tracer parcel is composed of irreducible elements that, owing to transport and irreversible mixing, experience different Lagrangian histories (Hall and Plumb, 1994; Waugh and Hall, 2002). These Lagrangian histories are encapsulated in the Green's function, which is nothing more than the solution to the advection–diffusion equation for a delta-function source. Physically the

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[1] To see this, consider two systems with identical τ_l and $\overline{c}$, one with a uniform source and the other with the source localised in a corner. In the latter case age depends on the size of the domain but in the former it is independent of space. Thus, in general, τ_l cannot be interpreted as a mean age when the source is not uniform.