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On the pollutant removal, dispersion, and entrainment over two-dimensional idealized street canyons

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ABSTRACT

Pollutant dispersion over urban areas is not that well understood, in particular at the street canyon scale. This study is therefore conceived to examine how urban morphology modifies the pollutant removal, dispersion, and entrainment over urban areas. An idealized computational domain consisting of 12 two-dimensional (2D) identical street canyons of unity aspect ratio is employed. The large-eddy simulation (LES) is used to calculate the turbulent flows and pollutant transport in the urban boundary layer (UBL). An area source of uniform pollutant concentration is applied on the ground of the first street canyon. A close examination on the roof-level turbulence reveals patches of low-speed air masses in the streamwise flows and narrow high-speed downdrafts in the shear layer. Different from the flows over a smooth surface, the turbulence intensities are peaked near the top of the building roughness. The pollutant is rather uniformly distributed inside a street canyon but disperses quickly in the UBL over the buildings. Partitioning the vertical pollutant flux into its mean and turbulent components demystifies that the pollutant removal is mainly governed by turbulence. Whereas, mean wind carries pollutant into and out of a street canyon simultaneously. In addition to wind speed promotion, turbulent mixing is thus required to dilute the ground-level pollutants, which are then removed from the street canyon to the UBL. Atmospheric flows slow down rapidly after the leeward buildings, leading to updrafts carrying pollutants away from the street canyons (the basic pollutant removal mechanism).

1. Introduction

One of the most pronounced effects of human activities on micro-climate and air chemistry/quality is in cities (Landsberg, 1970; Minoura, 1999; Tu et al., 2007; Chang et al., 2009; Notario et al., 2012). Urban areas are the sites consisting of most anthropogenic pollutant emission (Piringer et al., 2007; Kim Oanh et al., 2008; Chen et al., 2009) where the vast majority of people live (United Nation, 2008). Yet, a greater population density could promote more efficient energy consumption and hence lower down per capita carbon footprint (Parrish and Zhu, 2009).

The scalar transport, such as heat, moisture, and pollutants, in the atmospheric boundary layer (ABL) is an attractive research topic with a range of application. Turbulent transport over a variety of natural terrain has been well explored. For example, the transport of atmospheric constituents in open, unobstructed, relatively flat and homogeneous terrain can be calculated well by the Gaussian plume model (Pasquill, 1983). On the other hand, urban morphology imposes radical changes in radiative, thermodynamic, and aerodynamic characteristics at the ABL bottom. It hence influences micro-climate, enhances turbulence, and modifies air pollutant mixing and transport (Mazzeo and Venegas, 1991; Baklanov, 2009), giving rise to the development of urban boundary layer (UBL). In the absence of any topography, buildings are the roughness elements of a city. The major flow characteristics in built areas result from building wakes, road intersections, and street canyon effects. Building wakes are largely due to the flows around an isolated building. Whereas, in building clusters, the wakes associated with individual buildings interact with each other resulting in the recirculating flows at the UBL bottom. Apparently, there

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is a knowledge gap in urban dispersion, in particular in the neighborhood scales with explicitly resolved buildings in which the most serious threats to urban inhabitants, including heavy vehicular exhaust and accidental toxic release, are posed.

Approaches to atmospheric transport in the UBL are broadly divided into field measurements (Roth, 2000), laboratory experiments (Ahmad et al., 2005), and mathematical modeling (Vardoulakis et al., 2003; Li et al., 2006) that complement each other. Focusing on a length scale in the range 1 km to 3.5 km, Britter et al. (2002) compared the accuracy of steady-state and unsteady-state pollutant transport models. Rotach et al. (2005) conducted the *Basel UrBan Boundary Layer Experiment* (BUBBLE) to measure turbulence and tracer over urban, sub-urban, and rural areas. Using the same UBL scenario in New York City, Hanna et al. (2006) tested five computational fluid dynamics (CFD) models which agreed well with the observed wind flows during a field experiment. Recently, *Dispersion of Air Pollution and its Penetration into the Local Environment* (DAPPLE), which was a major campaign focusing on the effects of city architecture and prevailing climatic conditions in North European, was carried out in London to examine the pollutant mixing and transport in a complex and dense urban environment (Wood et al., 2009).

Although the models are necessarily simplified, a few field measurement campaigns using reduced-scale building blocks have been performed to test the sensitivity of UBL pollutant transport to building geometry and dimensions. Measuring the pollutant plume dispersion from the source in the first or second row over an array of cubes of size 2 m, Davidson et al. (1995) found that the mean vertical plume extent increases by 40% to 50% compared with that over open and flat terrain. Employing another array consisting of over 100 rectangular blocks of size 1.10 m × 1.10 m × 1.15 m (length × width × height), Macdonald et al. (1998) investigated how the density of roughness elements affects the plume dispersion behind a ground-level point source. The horizontal plume coverage is about 2 to 4 times wider than that over an open and flat terrain. Using a series of reduced-scale field measurements, and wind tunnel and water channel experiments, Yee et al. (2006) consistently found that urban obstacles modify pollutant plume dispersion substantially in which the plume spread is promoted by a factor of 2 to 4.

To test the sensitivity of pollutant dispersion to turbulence in a controllable manner, a number of laboratory experiments using wind tunnels or water channels have been carried out to examine pollutant transport in UBL. Meroney et al. (1996) implemented the technique using line sources to simulate the vehicular pollutant transport in street canyons. A street canyon is the basic unit constructing a city. An elucidation of its transport processes can enrich the fundamental understanding of pollutant removal in entire urban areas. The flows over an isolated building and building clusters were found to exhibit different pollutant dispersion behaviors. Afterward, the spatial distributions of mean and root-mean-square (RMS) pollutant concentrations were measured by Pavageau and Schatzmann (1999) in details that has been serving as a major dataset for the validation of mathematical models. Earlier theoretical studies outlined the vertical profiles of (decreasing) pollutant concentration in a street canyon. Likewise, Kastner-Klein and Plate (1999) measured the pollutant concentration distributions on the leeward and windward facades that are in line with the vertical profiles of decreasing pollutant concentration as found in early theoretical studies. Louka et al. (2000) used field measurements to demonstrate the importance of intermittent recirculating flows to street-level ventilation. A series of sensitivity tests were performed by Chang and Meroney (2001) and Chang and Meroney (2003) to study how the dimensions of buildings and streets affect pollutant transport. Jiang et al. (2007) applied flow visualization in a water channel, illustrating the pollutant transport behaviors in step-up and step-down notch street canyons. The aforementioned field measurements and laboratory experiments lay down the foundation of urban structures for atmospheric dispersion in the UBL.

Similar to other turbulence researches, mathematical modeling has been playing a major role in probing the flows and pollutant transport in urban areas. Using large-eddy simulation (LES), Liu and Barth (2002) and Liu et al. (2005) studied the turbulent pollutant transport inside a street canyon, and compared the pollutant distribution in street canyons of aspect ratios 0.5, 1, and 2. Cui et al. (2004), focusing on the LES-calculated turbulence characteristics in and over a street canyon, attempted to determine the turbulence scales. Afterwards, the pollutant transport from a line source (vehicular pollutant) or an area source (heat transfer) was examined in Cai et al. (2008). Letzel et al. (2008) recently realized the functionality of Kelvin–Helmholtz instabilities related to urban pollutant dispersion formulating the hypothesis of the pollutant removal by turbulence rather than mean flows.

Although the pollutant dispersion in urban areas has been examined in numerous studies, for example, the use of quadrant analysis in Cheng and Liu (2011), a number of key questions remain unclear. In this paper, we attempt to use LES with coherent structures to address the mechanism of pollutant removal from two-dimensional (2D) idealized street canyons and the pollutant transport aloft in the UBL. Moreover, a detailed analysis on the turbulent flows is carried out to differentiate the role of mean wind and turbulence in pollutant removal and entrainment. This section outlines the problem background. The modeling details are described in Section 2. A comprehensive diagnosis is conducted in Section 3. Apart from the properties of flows and pollutant transport below the canopy level (Section 3.1) and in the UBL over the buildings (Section 3.2), a thorough analysis on the pollutant removal mechanism is performed in Section 3.3. Afterward, we look into the coherent structures of flow and pollutant transport in Section 3.4 to reveal their coupling. Finally, the conclusion is drawn in Section 4.

2. Methodology

2.1. Governing equations

LES in the open-source CFD code (OpenFOAM, 2013) is used in this study. The flow is assumed to be isothermal and incompressible that consists of the continuity

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

and the filtered Navier–Stokes equation, written as

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\overline{u}_i\overline{u}_j = \frac{\Delta \mathrm{P}}{\Delta x}\delta_{i1} - \frac{\partial \overline{\pi}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} \tag{2}$$