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Turbulent dispersion of pollutants in urban-type canopies under stable stratification conditions

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HIGHLIGHTS

- Development of a LES method is applicable to stably stratified turbulent flow.
- Patterns of the urban canopy flow are classified with varying plan area densities.
- Flow patterns inside the canopy are similar between neutral and stable conditions.
- Evolution of pollutant plumes are found to be affected by the stable stratification.
- Proportion of advection and diffusion in scalar flux depend on packaging densities.

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ABSTRACT

Large eddy simulation is performed for the dispersion of a passive scalar in the turbulent boundary layer over an urban-like roughness surface under neutral and stable stratification. Square arrays of cubical obstacles are used to model the urban canopy with a ground level point source located in front of the obstacle. We design cases for varying building intervals to investigate the relationship between flow patterns and dispersion processes for different plan area densities λ_p. It has been found (Shen et al. 2015) that flow patterns in a three-dimensional urban canopy can be classified into five basic regimes in neutral stratification: isolated roughness, external wake interference, internal wake interference, skimming flow and streets network. This classification still holds in the presence of moderately stable stratification. In area with large λ_p, the material released from the point source tends to be trapped by the leeward recirculation and is well-mixed inside the canopy. The mean concentration level within roughness canopies is high due to the reduced advection velocity. In area with small λ_p, the great part of the material is entrained into the horseshoe vortex wrapping around the obstacle and carried downwind. The material is concentrated in the lower region of the canopy with a relatively higher temporal fluctuation. In the presence of stable stratification, the spread of the plume is reduced and the temporal fluctuation is suppressed as well. For area of large λ_p, the advective part of the scalar flux is responsible for carrying the material at ground level aloft into the urban canopy layer.

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1. Introduction

In urban atmospheric environmental problems, man-made resources of pollutant, including motor vehicle exhaust and industrial waste gases, have become main factors of air contamination. In these problems regarding human health, understanding the airborne pollutant diffusion in urban areas is of great importance (Belcher, 1837). Dispersion models to predict the pollutant concentration is also required with the increasing concern related to the releases of hazardous gases due to terrorist attacks or accidental leakage events (Pontiggia et al., 2011). The process of scalar dispersion in urban canopies can be affected by factors from both underlying urban surface features and the overlying atmospheric conditions. These factors, e.g., buildings in the vicinity, topographic geometry around, incident wind direction and the thermal stability, increase the complexity of urban dispersion processes and the difficulty of pollutant modelling (Fernando et al., 2010).

Concerning factors of underlying urban surface, the major flow field in the lowest part of the urban boundary layer is dominated by wakes generated by buildings, such as leeward recirculation and

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vortex shedding, along with turbulent fluctuations (Britter and Hanna, 2003; Louka et al., 2000). These building wakes and turbulent fluctuations, steady or intermittent, might influence the dispersion process through advection and diffusion (Belcher et al., 2015). From a view of two-dimensional street canyon model, Oke (1987) identified three basic flow regimes which are known as *isolated roughness, wake interference* and *skimming flow,* as a function of the height-to-width ratio of the streets. In the isolate roughness regime, buildings are far enough that a recirculation bubble develops in the leeward face of the building whose length is about 6 times of the building height. In the wake interference regime, buildings are close to each other and wakes generated interact with the downstream buildings. In the skimming flow regime, buildings are so densely packed that there exists a steady recirculation region inside the canyon. This classification was further refined by Sini et al. (1996), taking into account the street geometrical aspect ratio and the thermal effect. These studies provided insights into the process of the urban diffusion and aided in the development of models for urban flow and dispersion (Vardoulakis et al., 2003). Soulhac et al. (2011) put forward a street network model, SIRANE, which explicitly modelled the scalar flux at intersections and was capable of providing a detailed concentration field at the street scale.

However, the flow pattern described in these models might not reveal the three-dimensional feature of flow and dispersion in the real urban canopy. Martinuzzi and Tropea (1993) performed flow visualization in channel experiments to investigate flow around obstacles of a variety of aspect ratios. Their experiments highlighted the fundamental difference between nominal two-dimensional and three-dimensional obstacle flow. One important characteristic of the three-dimensional obstacle flow is the persistent horizontally oriented vortices generated near the ground level upwind of the obstacle, which wrap around the obstacle and trail off downwind as a counter-rotating vortex pair. This feature is called the “horseshoe vortex” because of its shape. For obstacles with small aspect ratios, the horseshoe vortex coexist with the corner vortex behind the cube and the impinging mixing-layer in the wake. Mavroidis et al. (2003) investigated the dispersion in the vicinity of isolated obstacles of different shapes and the effect of orientation with respect to the approaching flow direction in scaled field and wind tunnel experiments. They found a portion of material in the plumes impinging on the obstacle was entrained into the horseshoe vortex, carried around the obstacle and further downwind of the recirculating region.

Impact of group of buildings on the velocity and concentration field has been also addressed in numerous studies. Hajra and Stathopoulos (2012) showed the effect of downstream building on dispersion processes in wind tunnels. Davidson et al. (1995); Davidson et al. (1996) conducted field studies and wind-tunnel simulations of the dispersion of a plume released over ground level and blown onto a large array of equally sized obstacles downwind of the source. They analyzed the measurement of concentration and found that a number of mechanisms influenced the behavior of the plume: the deformation of the streamline of the mean flow and changes to the turbulent structures. Numerous experiments of similar layouts of obstacles were conducted on the building-influenced dispersion in wind tunnels and water channels (Hilderman and Chong, 2007; MacDonald et al., 1998; Yee et al., 2006), and the conventional Gaussian plume model was reported to work well in the far-field with suitably modified parameters. In a review of these experiments, Britter and Hanna (2003) pointed out that the increased turbulence levels within the urban canopies produced larger dispersion coefficients and reduced concentration, while the reduction in the advection velocity within roughness layers tended to increase concentration. The relative magnitude of these two factors determined the concentration level and dispersion process within urban canopies. Quantitative research on the effect of surface geometry have also been done through numerical simulation of canopy flow with different plan area densities λ_p (see section 2.2 for its definition) and building layouts (Coceal et al., 2007; Kanda, 2006; Kanda et al., 2004; Leonardi and Castro, 2010; Xie et al., 2008). The roughness sublayer parameters, including drag coefficients, roughness height and zero-displacement height were fitted as a function of λ_p, which is meaningful to the parameterization of urban models (Placidi and Ganapathisubramani, 2015). There have been urban dispersion models developed based on the effect of an individual building or a pack of buildings. Schulman et al. (2000) proposed a modified plume model for plume rise and building downwash. Belcher et al. (2015) developed a delicate street network model to model the short-range dispersion in city centers where buildings are packed relatively close. Their approach is able to captures the complementing roles of turbulent mixing and topological dispersion by dividing the airspace of streets and intersections into well-mixed boxes. In order to distinguish flow regimes in the built-up area from those in areas with sparse plan area densities, controlling parameters such as the plan area density λ_p is adopted as a threshold value, similar to the treatment in models like OSPM (Berkowicz, 2000) and SIRANE (Soulhac et al., 2012).

Atmospheric stability is another important factor in the dispersion processes as shown in field studies like the 2007 DAPPLE Project (Wood et al., 2009) and the CASE99 project (Poulos et al., 2002). The flow and dispersion around an isolated obstacle under varying thermal stability have also been studied through water channels and wind tunnels (Allegrini et al., 2013; Robins et al., 2001; Yassin, 2013; Zhang et al., 1996). Kanda & Yamao (2016) explored the thermal stratification effect on the passive scalar diffusion within modelled urban canopies, represented by arrays of rectangular blocks. The buoyant effects have also been addressed in recent advancements in numerical modelling of dispersion in urban canopies (Cui et al., 2016; Di Sabatino et al., 2013; Mavroidis et al., 2012; Xie et al., 2013). Although the enhanced mechanical mixing is considered to reduce the stable stratification effect in urban geometries, with higher friction velocity and artificial heat source, these researches still revealed non-negligible buoyant effects on dispersion processes. The impact of thermal stratification on the spatial evolution of the pollutant plume has been considered in present urban models through half-empirical laws or similarity relationship based on Monin-Obukhov theory (Soulhac et al., 2011).

Since urban areas are so diverse, a single regime is unlikely to be appropriate for all types of building shapes and layouts as well as varying plan area densities. Therefore, it is reasonable to identify the proper flow regime in a particular urban area of interest through some controlling parameters (Hunter et al., 1992). Following the Oke's idea, a trial of classification of the flow regimes from a three-dimensional view is drawn under neutral conditions by Shen et al. (2015). The existence of the horseshoe vortex and the lee recirculation cavity, referred to as the external wake and the internal wake respectively, are found to be dependent on the plan area density. Based on the inter-comparison of numerical simulations of flow over a regular array of cubes, flow patterns in urban canopies are classified into five types: *isolated roughness*, *external wake interference*, *internal wake interference*, *skimming flow* and *streets network* (see section 3.2). The influence of the flow pattern on the dispersion from a ground-level point source is also discussed through analysis of the concentration field.

Based on the previous work, we utilize the large eddy simulation (LES) to investigate the dispersion in urban-like canopies under different atmospheric stabilities. Here we consider the relationship between the flow pattern and the dispersion process in

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