Atmospheric Environment 144 (2016) 47–59

Contents lists available at ScienceDirect

Atmospheric Environment

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

Effect of stable stratification on dispersion within urban street canyons: A large-eddy simulation

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HIGHLIGHTS

- Effects of stable stratification on street-canyon flow and pollutant are studied by LES.
- Stable stratifications reduce the flow and vertical transport of momentum and heat.
- Pollutants pool near the ground and much pollutant accumulates in street canyons.
- Pollutant transport mechanism under stable stratifications significantly changes.

ARTICLE INFO

Article history:
Received 1 February 2016
Received in revised form
18 August 2016
Accepted 23 August 2016
Available online 26 August 2016

Keywords:
Large-eddy simulation (LES)
Urban street canyon
Pollutant dispersion
Stable stratification

ABSTRACT

This study employs a validated large-eddy simulation (LES) code with high tempo-spatial resolution to investigate the effect of a stably stratified roughness sublayer (RSL) on scalar transport within an urban street canyon. The major effect of stable stratification on the flow and turbulence inside the street canyon is that the flow slows down in both streamwise and vertical directions, a stagnant area near the street level emerges, and the vertical transport of momentum is weakened. Consequently, the transfer of heat between the street canyon and overlying atmosphere also gets weaker. The pollutant emitted from the street level 'pools' within the lower street canyon, and more pollutant accumulates within the street canyon with increasing stability. Under stable stratification, the dominant mechanism for pollutant transport within the street canyon has changed from ejections (flow carries high-concentration pollutant upward) to unorganized motions (flow carries high-concentration pollutant downward), which is responsible for the much lower dispersion efficiency under stable stratifications.

1. Introduction

With the continuous global urbanization process, more and more research interests are directed to the interaction between human activities and the built environment. Special attention is paid to the roughness sublayer (RSL), the region at the bottom of the atmospheric boundary layer (ABL) where the presence of the canopy influences directly the characteristics of the turbulence and dispersion. The RSL extends from the ground to a height of about there times the canopy height and includes the canopy air space (Kaimal and Finnigan, 1994). One of the basic roughness elements in urban areas is the street canyon, a relatively narrow street in-between buildings that line up continuously along both sides. Models of urban street canyons remain the basis of the urban canopy model (UCM) in numerical weather prediction (NWP, e.g., Weather Research and Forecasting model) models to account for the effect of exchange of momentum, heat and scalars between the urban area and overlying atmosphere. It is therefore of practical importance to investigate the flow, turbulence and scalar transport within and above urban street canyons.

The stratification of the atmosphere has great impact on the turbulence and dispersion in urban areas. The nocturnal atmosphere is generally stably stratified, although in urban areas this is sometimes not true due to the urban heat island and strong turbulence. Compared with the convective boundary layer (CBL), theory and observations in the stable boundary layer (SBL) are

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http://dx.doi.org/10.1016/j.atmosenv.2016.08.069
1352-2310/

rather more complex. Turbulence production by shear is counteracted by buoyancy forces, resulting in generally low turbulence levels, or in very stable conditions, intermittent turbulence (van Dop and Axelsen, 2007). The numerical simulation of the SBL is more challenging since the size of turbulent eddies is limited. Therefore, the resolution of the numerical model should be much higher when studying the SBL. Under very stable stratification, turbulence can be intermittent and gravity wave may be generated, which further complicates the problem and makes numerical simulations inapplicable. The numerical simulation using large-eddy simulation (LES) has demonstrated that LES can adequately capture the characteristics of weakly to moderately stably stratified boundary layer (Jiménez and Cuxart, 2005).

Many numerical studies have been conducted for the urban street canyons under unstable and neutral stratification (e.g., Sini et al., 1996; Kim and Baik, 1999; Xie et al., 2006; Li et al., 2008, 2010a, 2012; Dallman et al., 2014; Hang et al., 2016; Cui et al., 2016), while only a few have been done under stable stratification (e.g., Cheng and Liu, 2011b; Xie et al., 2013; Boppana et al., 2014; Li et al., 2015; Tomas et al., 2015). Although stable stratification conditions occur less frequently in urban areas during nighttime than in their rural surroundings due to anthropogenic heat release and the enhanced turbulence by urban structures, the research of stable stratification is still very important from a practical point of view, since the reduced turbulence can lead to strong concentrations of contaminants, and the reduced downward heat flux can result in very low surface temperatures and eventual frost damage in cold regions (Flores and Riley, 2011). Previous research has shown that later at night, when the rural SBL is deeper than the building height, the city is then capped by a stable layer (Godowich et al., 1985). This paper therefore intends to explore the turbulence and dispersion characteristics within urban street canyons under stable stratification, and we will try to investigate the mechanism behind these characteristics, which makes this study distinct from previous studies listed above.

The urban street canyon geometry in this study is essentially a two-dimensional (2D) due to the periodic boundary conditions prescribed in the along-axis direction (see Section 2). According to Vardoulakis et al. (2003) and Li et al. (2006), street canyons might be classified into short ($L/b \leq 3$), medium ($3 < L/b < 7$) and long ($L/b \geq 7$), where L is the street length and b is the street width (see Section 2). When L is infinite, this corresponds to a 2D street canyon; otherwise, a three-dimensional (3D) street canyon geometry must be considered. The flow and pollutant dispersion in 3D urban-like models with thermal effects or under neutral stratification have been investigated in the literature (e.g., Santiago et al., 2014; Hang et al., 2015).

The rest of the paper will be organized as follows. The numerical method and simulation setup will be described in Section 2. Section 3 will present the results of turbulence and pollutant dispersion, followed by a conclusion in Section 4.

2. Methodology

This study employs the LES code (Li et al., 2010a, 2012) developed for incompressible turbulent flow based on a one-equation subgrid-scale (SGS) model.

2.1. *Governing equations*

The equations for the evolution of the filtered velocity field are derived from the Navier-Stokes equations for incompressible flow, with the buoyancy effect taken into account by Boussinesq approximation. The reference length scale h (the building height of the street canyon), the reference velocity scale U (free-stream velocity) and the reference temperature θ_a (the ambient temperature) are used to make the governing equations dimensionless. The dimensionless, filtered (resolved-scale) conservation equations for momentum, heat and mass read, respectively

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{\partial \pi}{\partial x_i} - \frac{\partial P}{\partial x_i}\delta_{i1} - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{1}{Re}\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \frac{gh}{U^2}\bar{\theta}\delta_{i3}, \tag{1}$$

$$\frac{\partial \bar{\theta}}{\partial t} + \frac{\partial \bar{\theta}\bar{u}_i}{\partial x_i} = -\frac{\partial \tau_{\theta i}}{\partial x_i} + \frac{1}{RePr}\frac{\partial^2 \bar{\theta}}{\partial x_i \partial x_i}, \tag{2}$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \tag{3}$$

where

$$\pi = \frac{\bar{p}}{\rho} + \frac{1}{3}e, \quad \tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j - \frac{2}{3}e\delta_{ij},$$

$$\tau_{\theta i} = \overline{u_i \theta} - \bar{u}_i \bar{\theta}, \quad e = \frac{1}{2}\left(\overline{u_i^2} - \bar{u}_i^2\right),$$

$\bar{u}_i$ is the resolved-scale velocity in the i-th direction, π is the modified pressure normalized by constant density ρ, $-\partial P/\partial x_1$ is the mean streamwise pressure gradient prescribed to drive the atmospheric flow, $\bar{\theta}$ is the resolved-scale (potential) temperature, g is the gravitational acceleration, and δ is the Kronecker delta. The Reynolds number is defined as $Re = Uh/\nu$ and Prandtl number Pr is taken as 0.72. The subgrid-scale (SGS) or residual momentum flux τ_{ij} and heat flux $\tau_{\theta i}$ are modeled using the eddy-viscosity assumption as

$$\tau_{ij} = -2\nu_T \bar{S}_{ij}, \quad \text{and} \quad \tau_{\theta i} = -2\nu_\theta \frac{\partial \bar{\theta}}{\partial x_i},$$

respectively, where

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right).$$

The turbulent viscosity for momentum $\nu_T$and diffusivity for heat ν_θ are modeled as $\nu_T = C_k \ell e^{1/2}$ and $\nu_\theta = (1 + 2\ell/\Delta)\nu_T$, respectively, where C_k is a constant (see below), ℓ is the length scale (or filter width), and $\Delta = (\Delta_x \Delta_y \Delta_z)^{1/3}$ is the local grid size.

The transport equation for SGS turbulent kinetic energy (TKE) e reads

$$\frac{\partial e}{\partial t} + \bar{u}_i \frac{\partial e}{\partial x_i} = \mathscr{P} + \mathscr{B} - \varepsilon + \frac{\partial}{\partial x_i}\left(\frac{2}{Re_\mathrm{T}}\frac{\partial e}{\partial x_i}\right), \tag{4}$$

where

$$\mathscr{P} = -\tau_{ij}\bar{S}_{ij}, \quad \mathscr{B} = -g\nu_\theta \frac{\partial \bar{\theta}}{\partial z},$$

$$\varepsilon = C_\varepsilon \frac{e^{3/2}}{\ell}, \quad Re_\mathrm{T} = Uh/\nu_\mathrm{T}.$$

The $C_k = 0.03$ and $C_\varepsilon = 1.0$ are model constants (Li et al., 2010b). The length scale l is defined as (Moeng, 1984; Saiki et al., 2000)