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Multilayer urban canopy modelling and mapping for traffic pollutant dispersion at high density urban areas

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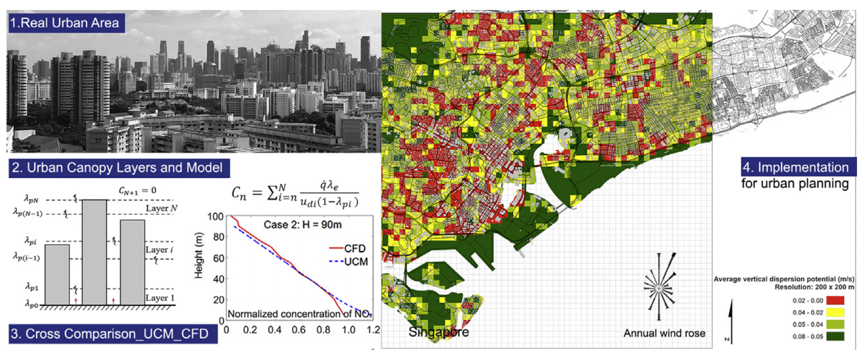
HIGHLIGHTS

- We create a practical model to estimate vertical pollutant dispersion potential.
- The model is derived based on understandings of mass and momentum conservation.
- Friction velocity, representing momentum flux, is modeled and validated.
- We clarify the effect of heterogeneous urban spatial characteristics on air pollutant dispersion.

GRAPHICAL ABSTRACT



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ABSTRACT

A semi-empirical multilayer urban canopy model is developed to estimate the vertical dispersion of traffic emissions in high density urban areas. It is motivated by the heterogeneity of urban morphology in real urban cities and the need of quick urban design and planning. The urban canopy is divided into multiple layers, to include the impact of building height variance on pollutant dispersion. The model is derived by mass conservation within each layer through adopting a box model. To validate the model, results in several cases with uniform and non-uniform building height distributions are compared with CFD simulations. The validation study indicates that the assumption of zero pollutant concentration over the modeled canopy and no horizontal pollutant transfer has increasingly negligible influence with increasing urban densities. The new multilayer model performs well to model the vertical pollutant transport, and modelling results can mostly follow the trend of the CFD simulations. The present paper conducts two case studies in metropolitan areas in Singapore and Hong Kong to illustrate how to implement this multilayer urban canopy model in the planning practice. With an in-house GIS team using available data, the multilayer model provides planners a way to understand air pollutant dispersion in high-density urban areas.

1. Introduction

Air pollution is a growing environmental concern in urban living. Given the involuntary exposure of urban inhabitants, especially in

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such confined spaces as the street canyon, air pollution has been linked to serious public health issues (Künzli et al., 2000, World Health Organization (WHO), 2008, European Environment Agency (EEA), 2012, Schachter et al., 2016). Increasing traffic emission is one of the major pollutant sources in highest density urban cites, and the stagnated airflow due to closely packed tall buildings makes the air pollutant dispersion difficult. Such a coupled problem leads to frequent reports of higher air pollution concentration in the urban canopy. Field measurement by the Hong Kong Environmental Protection Department (2011) from 1995 to 2015 indicates that the concentration of NO_2 measured at the roadside, i.e. pedestrian level, is significantly higher than that above the rooftops, due to the lower removal efficiency in the street canyon. Therefore, directly using ambient pollutant concentration data (e.g. the data from rooftop stations) could underestimate the effect of traffic emission on health and urban living. Consequently, modelling traffic pollutant dispersion in the urban canopy is a critical component in urban planning and design to establish a healthy urban environment.

To discuss air flow and dispersion through and above urban areas, Britter and Hanna (2003) suggested a classification of regional scale (100–200 km), city scale (10–20 km), neighborhood scale (1–2 km), and building scale (100–200 m). Different numerical models have been developed to estimate air pollutant concentration at different spatial scales. MM5/WRF models are at regional scale, in which the horizontal grid size in the nested domain is from about 50 km to 5 km. Yim et al. (2010) coupled CALMET with MM5 to downscale modelling results to the city scale, i.e. in the resolution of 500 m × 500 m. But the city scale model, i.e. MM5/CALMET model, can only estimate pollutant concentration above the urban canopy layer. As Britter and Hanna (2003) indicated, the buildings are normally treated statistically in the city-scale modelling, and the modelling process pays little attention to the flow and dispersion in the street canyon. Consequently, even though the modelling results in this scale are necessary as the input boundary condition for the next scale modelling (i.e. neighborhood scale) and useful to evaluate the city visibility (Yim et al., 2010), they are not suitable to evaluate air quality in urban areas. It is important to bridge this gap and investigate the pollutant dispersion in the urban canopy layer to evaluate the effect of air pollutants on public health.

The heterogeneity of urban morphology makes it difficult to model the pollutant dispersion beneath the rooftop. Wind engineers can reconstruct the detailed urban geometries through numerical and physical modelling methods, i.e. CFD simulations (Baik et al., 2007; Hang et al., 2012; Tominaga and Stathopoulos, 2012; Yuan et al., 2014; Dai et al., 2018) and wind tunnel experiments (Ranade et al., 1990; Meroney et al., 1999; Leitl and Schatzmann, 2010; Mo and Liu, 2018). However, both numerical and physical models require intensive technical support, and the former incurs high computational cost, especially in city and neighborhood scale, and therefore is not suitable for quick design and planning processes. To deal with this issue, the semi-empirical morphological method has been developed as an alternative solution, and has been broadly documented to model the traffic air pollutant dispersion in the urban canopy. By parameterizing the mass and momentum transfer in and between the urban canopy layer and the upper layer, spatially-averaged concentration can be solved by many existing models, such as the Canyon Plume-Box Model (CPB) (Federal Highway Administration, 2002), SIRANE models (Soulhac et al., 2011), ADMS Urban (Owen et al., 1999) or AERMOD (Cimorelli et al., 2004). However, most of these models are based on simplified parametric models and, particularly, most of them assume that the building height is uniform. Fig. 1 shows the real heterogeneous urban areas at Singapore, in which the building height variance normalized by average building height is about 2.0. This means that the basic assumption, i.e. uniform building height, cannot appropriately represent the real urban areas.

This study aims to develop a new semi-empirical model to evaluate the effect of heterogeneous urban morphology on air pollutant dispersion. Contrasting with conventional models that treat the street canyon from the ground to the average building height as a single layer, the study first introduces the theory behind multi-layer urban canopy representations (Section 2), and elaborates on the development of governing equations based on mass conservation (Section 3). The box model, in which the mass of pollutant that is horizontally transported into and out of the target area is assumed the same, is applied to simulate the vertical dispersion, given that vertical pollutant dispersion is thought to be able to remove the pollutant from cities, i.e. urban canopy layer, to the overlying atmosphere. Results from the new semi-empirical model are validated by CFD simulation, and corresponding planning suggestions are developed (Section 4). Last, two case studies at metropolitan areas in Singapore and Hong Kong are constructed to illustrate how to apply this semi-empirical model in real high density urban areas (Section 5).

2. Multilayer urban canopy structure

Pollutant dispersion in urban areas is strongly affected by the complex turbulent flow above and within the urban canopy at various time and length scales. One of the main transport mechanisms is turbulent transfer between the street canyon and the overlying atmosphere,

Fig. 1. Central Business District (CBD) and Residential areas at Singapore. (Source: authors).