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Large-eddy simulations of ventilation for thermal comfort — A parametric study of generic urban configurations with perpendicular approaching winds

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ABSTRACT

This study investigates ventilation performance in parametric urban scenarios using a large-eddy simulation (LES) model called the Parallelized LES Model (PALM). With various combinations of planning parameters, air flows and pedestrian-level velocity ratios in a total of 48 scenarios are investigated. Major findings and recommendations are: First, ground coverage ratio (λ_p) is the most important factor for good ventilation. Second, in cases of homogeneous building heights, a power regression between velocity ratios and aspect ratios of parallel street canyons can be derived, which suggests that good understanding of local microclimate, especially prevailing wind directions in summer, is needed in urban planning. Third, the effects of building height differentials on urban ventilation are connected to urban density. In low-density scenarios, inhomogeneous building heights give worse ventilation performance compared to homogeneous cases. In high-density scenarios, inhomogeneous building heights result in better ventilation performance than homogeneous cases. Inhomogeneous building heights generate more vertical momentum fluxes in street canyons and have a negative (positive) effect on velocity ratios of low-density (high-density) parametric urban fabrics. The application of this point is that homogeneous building heights are recommended when low density is present, and inhomogeneous building heights may be better in cases of high density.

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1. Introduction

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has noted that warming of the climate system is unequivocal; 1983–2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere, and it is likely that the frequency of heat waves has increased in large parts of Europe, Asia, and Australia (IPCC, 2013). Meanwhile, according to the World Health Organization, the urban population in 2014 accounted for 54% of the total global population, up from 34% in 1960, and it continues to grow. The urban heat island effect further intensifies large-scale high temperatures in high-density cities and threatens the inhabitants' health (Wang et al., 2016). In high-density Hong Kong, for example, the rate of warming increased by 0.37 °C per decade between 1989 and 2005, based on the observed temperature (Lam, 2006). The temperature is also projected to rise by 4.4 °C in 2090–2099 for the case of urbanization frozen at its 2006 level, and to rise by 5.2 °C for the case of a constant rate of urbanization (Leung et al., 2007). Mean mortality associated with heat stroke would experience a twofold per unit rise in net effective temperature beyond 26 °C (Leung et al., 2008).

Rapid urbanization in the tropical and subtropical regions means that a better understanding of how to design and plan a city with good ventilation performance is needed. To achieve neutral thermal sensation in an urban environment, a wind speed of 0.9–1.3 m/s is needed for a person wearing light clothing under shaded conditions (Ng and Cheng, 2012). Hence, thermal comfort can be achieved by capturing the natural wind. Meanwhile, good air ventilation is also important for pollutant dispersion in street canyons (Lo and Ngan, 2015; Mirzaei and Haghighat, 2010; Yuan et al., 2014). Outdoor air quality can further affect indoor air quality via natural as well as artificial ventilation, as indoor air will be replaced by outdoor air eventually (Chen, 2009). Therefore, providing good urban air ventilation is very important for quality and healthy living in high-density cities in tropical and subtropical regions (Ng et al., 2011; Yuan and Ng, 2014). However, a distinction should be made between ventilation for air quality and ventilation for thermal comfort. When the purpose is to study ventilation for air quality, the main parameters are flow rate, which provides dilution capacity for contaminants, and turbulent transport at rooftop level, which removes contaminants from street canyons. When the aim is to study ventilation for thermal comfort, the main parameter is wind velocity at the pedestrian level. This study focuses on ventilation for thermal comfort, so the main parameter to be investigated is the wind velocity ratio at the pedestrian level.

Urban ventilation is strongly influenced by wind speed and direction, which in turn are affected by three-dimensional urban morphology (Skote et al., 2005; Yang et al., 2013). As a combination of the individual shapes and dimensions of buildings and their arrangement in the city, urban density can be described by geometric parameters in planning like ground coverage ratio (λ_p), frontal area density (λ_f), and plot ratio (P). So-called parametric studies, which simplify complex actual urban geometries into simple morphological models, are widely applied in urban ventilation studies for their advantages of linking specific geometric parameters to air ventilation performance. Using a κ–ω shear stress transport turbulence model, Yuan and Ng (2012) carried out a parametric study with a focus on building porosity for better urban ventilation and evaluated the effects of wind speed on outdoor thermal comfort. Using a standard κ–ε turbulence model, Buccolieri et al. (2015) investigated the breathability in dense building arrays with λ_p values similar to those of typical European cities. Yang and Li (2011) modeled turbulence effects in two simple Hong Kong city models with relatively complex terrain under different atmospheric conditions, and the importance of thermal stratification was highlighted under a weak wind background. Hang et al. (2013) investigated neutral ventilation assessment in two idealized urban models with various approaching wind directions, while Lin et al. (2014) investigated urban canopy layer ventilation under neutral atmospheric conditions with the same λ_p (0.25) and λ_f (0.25) but with various urban sizes, building height variations, overall urban forms, and wind directions. Ramponi et al. (2015) provided a review of the literature for computational fluid dynamics (CFD) studies of outdoor ventilation for generic urban configurations and indicated that there is a lack of studies of urban configurations where not all parallel streets have equal widths. This initiated their CFD simulation of ventilation in generic urban configurations with different urban densities and equal and unequal street widths. Ho et al. (2015) examined flows over idealized two-dimensional street canyons of different building aspect ratios and urban boundary layer depths and utilized the friction factor and the air-exchange rate to parameterize aerodynamic resistance and street-level urban ventilation. Using large-eddy simulation (LES), Nazarian and Kleissl (2016) studied realistic solar heating in a three-dimensional idealized urban environment and investigated mean flow and turbulence statistics as determinants for urban canyon ventilation.