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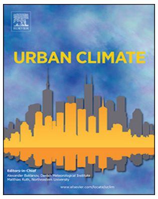

Shaping buildings to promote street ventilation: A large-eddy simulation study

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ABSTRACT

Proper ventilation of urban streets is important for safeguarding the health and comfort of urban inhabitants. To compare the influence of different street canyon building geometries on urban ventilation, large-eddy simulations (LES) have been performed under neutral stability conditions. Five different street canyon building geometries have been tested: the i) flat roof, ii) pitched roof, iii) round roof, iv) terraced building and v) building with balconies. The geometries were configured as seven building arrays, with six street canyons in between them aligned in the spanwise direction. The Air Exchange Rate (ACH) between the street canyons and the free atmosphere has been computed for the different cases. The results show that the ACH is very sensitive to the building geometry; therefore, it appears reasonable to suggest that buildings can be shaped to promote urban ventilation. The paper also proposes an alternative ACH estimation method based on the folded-normal distribution that is shown to produce very good estimates of the LES-computed ACH. The new method uses vertical mean velocity and turbulence statistics that can be obtained from less intensive Computational Fluid Dynamic (CFD) models. A simplified two-reservoir Pollutant Concentration (PC) estimation methodology based on the ACH results is also proposed.

1. Introduction

The World Health Organization reported that in 2012, around 7 million people died prematurely – one in eight of the total global deaths – as a result of air pollution. This finding more than doubles previous estimates and confirms that air pollution is now the world's largest single environmental health risk (WHO, 2014). Since adverse air quality tends to be primarily an urban problem, and given the very rapid pace of urbanization in this century (UNFPA, 2014), maintaining good air quality in built areas is of paramount importance to safeguard the health and comfort of urban inhabitants.

Air quality in cities is affected by ambient wind speed and direction, atmospheric stability, solar radiation and anthropogenic pollutant emissions (Britter and Hanna, 2003). Thermal pollution and chemical pollutant concentrations peak in cities, as opposed to the countryside, due to the high and localized anthropogenic emissions, as well as to the topographical and surface material properties of the urban fabric (Landsberg, 1981; Oke, 1987). Luke Howard, a British chemist and meteorologist, was one of the first scientists to address this evidence through observational work in the 1830s (Howard, 1838); and since then, research on urban air pollution has been on-going. In the second half of the 20th century, the first comprehensive air quality policy was established in the UK - the Clean Air Act of 1956 - which was followed by the US clean air act in 1963. Of specific relevance to urban pollution, an effort

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to move polluting plants and manufacturing outside of cities has been underway for decades. Vehicle circulation restrictions are also being implemented in various cities. That is the case for Madrid, for example, with the newly approved anticontamination protocol, or London, with the Low Emissions Zone (LEZ) regulation established in 2008 (Transport of London, 2015). Similar policies are concomitantly being implemented in other cities around Europe such as Paris, Milan or Budapest.

Nevertheless, since emissions are not the only factor contributing to pollution risk, regulations that pertain to urban planning and architectural design considerations are also starting to be implemented. The Hong Kong Air Ventilation Assessment (AVA) is one such regulation formulated to assess the impact of architectural designs on the pedestrian wind environment (Ng, 2009; Ng, 2012). Such building design guidelines that promote urban ventilation by accelerating pedestrian-level air flow and pollutant dispersion are becoming increasingly more important. This is especially true for dense urban environments where urban ventilation is most compromised (Oke, 1988b). However, despite Hong Kong's example, urban policies that incorporate guidelines to promote urban ventilation are still scarce. The reasons for this are numerous; one of the most important being the barrier posed by the technical expertise and effort required for modelling of air flow and pollutant dispersion that many local administrations do not possess to tailor regulations for their cities. This is why architectural and urban planning processes often fail to incorporate design strategies to enhance urban ventilation (Oke, 1988a). Therefore, the definition of broad design guidelines and urban ventilation estimation strategies that are of wide applicability across many cities would be most useful for an easier implementation of urban ventilation criteria within planning and architectural design processes.

While urban structures differ among different cities as well as between different neighbourhoods within the same city, arguably one of the most characteristic world-wide urban typology is the urban street canyon. The urban street canyon, is a typological urban configuration in which the dominant sources of pollution, vehicle emissions, concentrate in close proximity to the pedestrians (Britter and Hanna, 2003). Therefore, the urban street canyon has been often studied as an archetypal model in the context of urban air quality, urban ventilation, and urban heat island investigations, with the aim of developing a universal understanding of these problems that is of wide applicability.

Within an urban street canyon, the presence of dominant circulation patterns and the turbulent momentum and scalar exchanges between the inside and the outside region of the canyon are very important aspects to take into account for dispersion calculations. For high building height (H) to street width (W) ratios, a particularly adverse flow regime could occur where the flow above the canyon skims across with minimal exchanges with the air inside the canyon (skimming flow regime, (Oke, 1988b)). That is, for street canyons with a wind angle nearly perpendicular to the main axis of the canyon, when the building spacing is reduced beyond a certain threshold, a decoupling of the flows above and below the canyon occurs. One way to quantify these exchanges is via a street canyon transfer velocity U_e, induced by mean (including dispersive) and turbulent fluxes; this transfer velocity has been extensively studied both experimentally and numerically (Vardoulakis et al., 2003). For air quality applications (or urban heat), the exchange velocity is best defined through the average rate of mass (or heat) transfer in or out of the urban canopy layer at a horizontal plane of interface between the in-canopy and above-canopy flows. Britter and Hanna (2003) introduced the concept of exchange velocity for the first time and studied the spatial temperature distribution and scalar exchanges at the plane of interface, to conclude that U_e was approximately 1% of the characteristic wind velocity U_{ref} above the street canyon. U_e is also frequently used in numerical simulations (e.g. Hamlyn and Britter, 2005; Solazzo and Britter, 2007). Di Sabatino et al. (2007) and Di Sabatino et al. (2008) used the exchange velocity to compare the performance of the k-ε turbulence closure model and the advection-diffusion method. Hamlyn and Britter (2005) estimated U_e as a fraction of U_{ref} and found that it ranges from 0.3% to 1% for regular cube arrays with variable packing densities. Solazzo and Britter (2007), through numerical studies, applied the concept of U_e to a street canyon with weak buoyancy effect, and concluded that the temperature inside the street canyon is nearly uniform and that U_e is about 1% of the free-stream wind speed.

Estimations of exchange velocities were also performed through experimental work. Barlow and Belcher (2002) and Barlow et al. (2004) developed wind tunnel experiments using the Naphthalene sublimation technique. In their analysis, they used the concept of a transfer velocity to relate the flux out of the canyon to the concentration within it and reported that the transfer velocity to wind speed aloft ratio varies with the building aspect ratio, reaching a maximum in the wake interference regime. This regime occurs in street canyons with $0.3 < H/W < 0.65$ (i.e. more widely spaced than the skimming regime) and is characterized by stronger vertical exchanges and interactions of the wakes of distinct buildings. Salizzoni et al. (2009) estimated the exchange velocity between the canyon and the external flow by measuring the cavity wash-out time, that is, the time it takes for the whole air cavity volume of the street canyon to be removed from the street canyon, and addressed the influence of the external turbulence on the transfer process. Salizzoni et al. (2011) developed wind tunnel experiments using the PIV technique and concluded that turbulent transfer is due to the coupling between the instabilities generated in the shear layer above the canyons and the advected turbulent structures in the outer boundary layer (the air above the urban boundary layer), and proposed to estimate the mass exchange between a two-dimensional cavity and the overlying boundary layer by looking at the pollutant wash-out from the cavity.

The exchange velocity has also been used for the so called “city breathability” concept that was introduced by Neophytou and Britter (2005) to express the potential of a city to remove pollutant and heat entrapment from urban environments. The same urban breathability ventilation indicator was used, among others, by (Buccolieri et al., 2010; Panagiotou et al., 2013; Tominaga, 2012). Panagiotou et al. (2013) quantified city breathability using U_e and conducted Reynolds-Averaged Navier Stokes (RANS) simulations for an inhomogeneous urban area to conclude that urban morphologies determine the shape and size of vortical structures that are present in the flow field, and thereby the exchange processes with the flow above. However the studies developed did not systematically study the effect of building morphology. Buccolieri et al. (2015), also through RANS simulation, studied city breathability by combining two ventilation concepts: mean flow rate and age of air. They developed studies of aligned arrays of cubes with variable areal building densities and concluded that the local mean age of air increases substantially by increasing the density. A similar