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A study of the "wall effect" caused by proliferation of high-rise buildings using GIS techniques

Man Sing Wong[a], Janet Nichol[a,*], Edward Ng[b]

[a] Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong
[b] Department of Architecture, The Chinese University of Hong Kong, Hong Kong

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ABSTRACT

This paper describes a novel method using Geographic Information Systems (GIS) to investigate the "wall effect" caused by proliferation of high-rise buildings along the coast in Kowloon Peninsula of Hong Kong. The research utilises the concept of building frontal area index which is calculated based on three dimensional buildings in 100 m grid cells. The main ventilation pathways across the urban area are located using Least Cost Path analysis in a raster GIS and validated by field measurements. Field measurements were also taken in front of windward and leeward buildings. Results show that winds are forced by high frontal area values, to deviate around coastlines with blocks of "wall effect" buildings parallel to the coast. Average wind speeds of 10.5 m s^{-1} were observed on the windward side of "wall effect" buildings defined according to a southeasterly wind direction, while average wind speeds immediately to the lee side of "wall effect" buildings as well as further inland, were approximately 2.5 m s^{-1} (four times lower). To confirm the "wall effect" hypothesis, scenario analysis was performed by removing these buildings from the model and re-running it. This revealed a 5% increase of air ventilation to urban areas inland, since more fresh onshore air is able to penetrate from the coast. This improvement is significant since only 0.05% of buildings in the study area were removed. Overlay of the ventilation pathways over a thermal satellite image representing Heat Island Intensity (HII) indicated significantly lower HII values, and reduced extent of the core HII areas, around the ventilation paths.

1. Introduction

In affluent coastal cities with high land prices, unrestricted commercial exploitation of land commonly gives rise to a distinctive pattern of building development, known in Hong Kong as the "wall effect". This term aptly describes a coastline with high-rise buildings oriented parallel to the coast in order to maximise sea views and developers' profits. At the same time, adjacent buildings and those farther inland suffer from blocked views, lower sunshine and light levels, and well as the build-up of pollution and an urban heat island effect due to lack of ventilation. The term "wall effect" thus has negative connotations, and has become a controversial issue in Hong Kong, where the lack of flat land has given rise to extremely high built densities, which in turn generate an urban heat island of up to 12 °C in the urban core (Nichol, 2005; Nichol, Fung, Lam, & Wong, 2009). The general characteristics of "wall effect" have been defined as (i) less than 15 m between the frontal (blocking) buildings and those behind, (ii) frontal buildings are taller than those behind, (iii) frontal buildings have more than 35 floors and (iv) frontal buildings face the prevailing wind (Yim, Fung, Lau, & Kot, 2009).

As urban populations increase, many modern cities in both temperate (Baker et al., 2003; Hawkins, Brazel, Stefanov, Bigler, & Saffell, 2004; Oke, 1982) and tropical regions (Fung, Lam, Nichol, & Wong, 2009; González, Luvall, Rickman, Comarazamy, & Picón, 2007; Jusuf, Wong, Hagen, Anggoro, & Hong, 2007; Nichol, 1996, 2005; Nichol et al., 2009) are reporting significant heat island effects resulting from high building densities. Air flow between rural and urban areas is one of the parameters governing urban heat island formation and the build-up of pollution (Haeger-Eugensson & Holmer, 1999; Oke, 1982). The core of Hong Kong's urban heat island is the mixed commercial and residential district of Mongkok (Fung et al., 2009; Nichol et al., 2009), the world's most densely populated urban district, which is situated in the middle of the urbanised Kowloon Peninsula, approximately 2 km from the coast. Mongkok and other inner districts also suffer from air pollution levels several times higher than air quality standards for the basic pollutants (Louie et al., 2005), e.g. the annual U.S. Environmental Protection Agency standard for $PM_{2.5}$ (particulate matter with diameter of 2.5 μm or less) is 15 μg m^{-3}, and all five of Hong Kong's

* Corresponding author. Tel.: +852 27665952; fax: +852 23302994.
E-mail addresses: m.wong06@fulbrightmail.org (M.S. Wong), lsjanet@inet.polyu.edu.hk, lsjanet@polyu.edu.hk (J. Nichol), edwardng@cuhk.edu.hk (E. Ng).

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$PM_{2.5}$ monitoring stations recorded more than double this amount for every year from 2003 to 2007 (EPD, 2009). The controversy surrounding the "wall effect" has led to the need to evaluate its impacts on urban temperature and air quality due to the blocking of sea breezes and reduced ventilation to inner areas. Yim et al. (2009) conducted the only previous study of the ventilation impacts of "wall effect" buildings on the adjacent street environment using a Computational Fluid Dynamics (CFD) model. In their study, the modelling results were validated by a wind tunnel simulation. The results predicted that the air velocity at 2 m above the ground in a street canyon would decrease by approximately 30% and 40%, if wall buildings upwind are 2 times or 4 times the height of the street canyon respectively and the retention time of pollutants would increase by 45% and 80%.

Such CFD models are widely used for flow analysis around fixed structures in engineering and urban planning (Baik & Kim, 1999), and prediction of air pollution dispersal (Blocken, Carmeliet, & Stathopoulos, 2007; Huber et al., 2004; Kondo, Asahi, Tomizuka, & Suzuki, 2006). They depend on reconstructing the real urban geometry of a particular city to simulate air flow at building and street level. The computer-intensive nature of CFD models precludes their application to large areas or whole cities, but they can represent highly detailed flow patterns for small areas. An alternative approach for reconstruction of wind flow patterns and pollution dispersal at large scales over a district is the wind tunnel model. For example, Duijm (1996) used an atmospheric boundary layer wind tunnel in Lantau island, Hong Kong at the large scale of 1:4000 over a small rural study area, and Mfula, Kukadia, Griffiths, and Hall (2005) used a wind tunnel at a nominal building scale of 1:100 to determine the pollution source regions for buildings. Although the wind tunnel model can accurately represent urban ventilation under constrained conditions, like the CFD model, the small area covered, as well as high computer demands and operating costs discourage their use. Recently, several numerical models have been developed for modelling air flow over larger areas but at coarser resolution, including the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model (the Fifth-Generation Mesoscale Model, known as MM5). The MM5 model operates at mesoscale, to simulate phenomena such as mountain-valley and land-sea breezes (Dudhia, Gill, Manning, Wang, & Bruyere, 2003). Although Yim et al.'s (2009) study provides a method for the detailed depiction of the "wall effect" on a street canyon in Hong Kong, the model is limited to small areas, whereas the blocking of sea breezes as well as prevailing winds by tall buildings is likely to have wider impacts at district and city level. Thus application of wind ventilation models derived at detailed (street) level to whole city (city-scale), especially in dense urban regions with complex street and building structures is challenging.

The now ready availability of three dimensional digital data of modern cities on a Geographic Information Systems (GIS) platform enables the estimation of roughness parameters for wind ventilation modelling. The roughness parameters are zero-plane displacement height (z_d) and roughness length (z_0) (Counihan, 1975; Lettau, 1969), plan area density (λ_p), frontal area index (λ_f) (Burian, Brown, & Linger, 2002; Grimmond & Oke, 1999), average height weighted with frontal area (z_h), depth of the roughness sub-layer (z_r) (Bottema, 1997; Grimmond & Oke, 1999) and the effective height (h_{eff}) (Matzarakis & Mayer, 1992). The concept of frontal area index (λ_f) was introduced by Grimmond and Oke (1999) to represent the aerodynamic properties or roughness of the urban surface in mesoscale modelling of the urban climate. The λ_f is obtained from the surface area of all vertical building walls facing wind flow in a particular direction (frontal area per unit horizontal area) (Fig. 1). The frontal area index has a strong relationship with the roughness of the urban surface, and it influences the flow regime within urban street canyons (Burian et al., 2002).

For wind ventilation depiction, Gál and Unger (2009) proposed to inspect visually the ventilation paths depicted by frontal area index data. Although this method is feasible for a small study area, it cannot work across a whole city and the results cannot be validated quantitatively. Therefore, for transforming the frontal area index (pixel-base) to air corridor (path-base), least cost path analysis can be conducted on a GIS platform. This simulates the fresh air corridors based on the least resistance of λ_f across a city, e.g. high connectivity along the least cost path represents corridors of strong wind ventilation.

The aims of this paper are (i) to investigate the "wall effect" created by buildings along the coastline in Hong Kong using frontal area index values and least cost path analysis and (ii) to quantify the impacts of the "wall effect" on air flow across the city.

2. Study area

The study area is the highly urbanised 160 km^2 Kowloon Peninsula of Hong Kong, which has a mean population density of 43,000 persons/km^2, and the highest population density in the world (130,000 persons/km^2) in Mongkok district. The topography is mainly flat, but rises to 300 m at the northern edge, and one large park (Kowloon park) and a few small urban parks of less than 1 ha each, separate the generally built-up landscape. The climate is sub-tropical, with hot humid summers, and there is a marked urban heat island due to the high density and high rise urban form (Wong, Nichol, & Lee, 2010). Since Kowloon is a peninsula with few locations over 3 km from the coast, there is a strong belief by residents that the main cause of the urban heat island is the "wall effect", which prevents cool sea breezes from penetrating to the inner city. The environmental group Green Sense surveyed 155 housing estates in Kowloon and found that 104 of these have a "wall-like" design (Green Sense, 2009).

3. Frontal area index

The frontal area index (λ_f) is calculated as the total area of building facets projected to plane normal facing the particular wind direction, divided by the plane area (Burian et al., 2002; Grimmond & Oke, 1999; Wong, Nichol, To, & Wang, 2010) (Eq. (1), Fig. 1).

$$\mathrm{FAI} = \frac{\mathrm{Area}_{\mathrm{facets}} \cdot Z_{\mathrm{mean\ plane}}}{\mathrm{Area}_{\mathrm{plane}}} \tag{1}$$

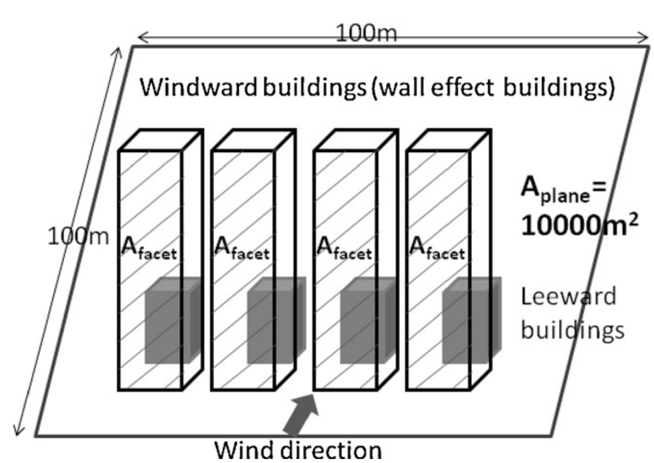

Fig. 1. Example of frontal area calculation.