Building and Environment 45 (2010) 1880–1889

Contents lists available at ScienceDirect

Building and Environment

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

A simple method for designation of urban ventilation corridors and its application to urban heat island analysis

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A R T I C L E I N F O

Article history:
Received 7 December 2009
Received in revised form
22 February 2010
Accepted 24 February 2010

Keywords:
Frontal area index
Geographic information systems
Remote sensing
Urban heat island
Ventilation path

A B S T R A C T

This paper describes urban wind ventilation mapping, using the concept of "building frontal area index", and uses the Kowloon peninsula of Hong Kong as an example of a dense, sub-tropical urban environment where ventilation is critical for human health. The frontal area index is calculated for uniform 100 m grid cells, based on three dimensional buildings in each cell, for eight different wind directions. The frontal area index is then correlated with a land use map, and the results indicate that high density commercial and industrial areas with large building footprints had higher values than other urban land use types. Using the map of frontal area index, the main ventilation pathways across the urban area are located using least cost path analysis in a raster GIS. Field measurements of urban winds confirmed the significance and functionality of these modelled ventilation paths. Comparison of the pathways with a map of the urban heat island suggests that ventilation is a key parameter in mitigating heat island formation in the study area. Planning and environmental authorities may use the derived frontal area index and ventilation maps as objective measures of environmental quality within a city, especially when temperatures in the inner city are a major concern.

1. Introduction

The urban heat island (UHI) is defined as the temperature difference between urban and rural areas. As urban populations increase, many cities in both temperate [1–3] and tropical regions [4–9] 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 [3,10]. Low horizontal wind speeds are usually associated with high surface roughness, where energy is lost by vertical instability due to a high density of built structures [11]. The pressure differences along temperature gradients can also induce low-level breezes across the urban-rural boundary.

Most of the data included in wind and air quality studies are from ground level instruments. The gathering of data over large regions such as a city therefore, is a major challenge to these studies. Wind tunnel models provide another method for visualising the local wind direction and pollutant dispersion at large scales over a district. For example, Duijm [12] used the wind tunnel model in Lantau island, Hong Kong at a large scale (1:4000) over a small area, and Mfula et al. [13] tested a very large building model at 1:100 scale to identify pollution sources affecting buildings, based on wind and pollutant patterns at the surface. Although wind tunnel studies of urban ventilation can provide accurate wind models measured under constrained conditions, the small area coverage, high computer processing requirements and high operational cost often prohibit their usage. In recent years, a variety of numerical models have been developed for modelling air ventilation, such as the PSU/NCAR mesoscale model (known as MM5) and the computational fluid dynamics (CFD) model. The MM5 model works for mesoscale phenomena such as sea breezes and mountain–valley flows [14] with large area coverage at coarse resolution, while the CFD model simulates urban wind flows over smaller areas in greater detail. The CFD model is being widely used in engineering flow analysis, building and structural design, urban wind flow predictions [15], and air pollution dispersal modelling [16–18]. It comprises a set of physical models which attempt to closely match the real urban geometry and thus simulate the air flow around buildings and along streets. The CFD model is thus highly computer-intensive and generally inapplicable to large areas or whole cities. The only known exception to this is the use of a CFD model running on a supercomputer, which models temperature and air flow over a 5 × 5 km area of Tokyo [19]. Therefore, wind ventilation modelling at city scale, especially over densely urbanised regions with complex street and building structures is challenging.

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doi:10.1016/j.buildenv.2010.02.019

Now, geographic information systems (GIS) and remote sensing techniques can provide alternative solutions by adopting simplified assumptions and numerical approximations. Wind modelling for near surface conditions can be simplified mathematically by estimating roughness parameters from building structures. Several studies have modelled surface roughness using GIS and remote sensing techniques and several parameters have been suggested for calculation of surface roughness. These are zero-plane displacement height (z_d) and the roughness length (z_0) [20,21], plan area density (λ_p), frontal area index (λ_f) [22,23], average height weighted with frontal area (z_h), depth of the roughness sub-layer (z_r) [24,22] and the effective height (h_{eff}) [25] etc.

Among these urban morphological parameters, the "frontal area index" has been suggested as a good indicator of the roughness of the urban surface for mesoscale meteorological and urban dispersion models [22,23]. Frontal area index is the measurement of building walls facing the wind flow in a particular direction (frontal area per unit horizontal area) (Fig. 1). It has a strong relationship with surface roughness z_0, and is a function of the flow regime within urban street canyons [23]. Gál and Unger [26] calculated the frontal area index from lot area polygons in Szeged, Hungary for depicting the potential ventilation paths over the city. They suggested lot area polygons as the unit for frontal area calculation since the buildings in Hungary are individually separable and the density of built area in Szeged is far less (11%) than in the Kowloon peninsula of Hong Kong (71%). Although Gál and Unger [26] provided a thorough method for the depiction of ventilation paths using frontal area index and other parameters, the pathways were located mainly by visual inspection, and the results were not practically validated. More details of frontal area index will be given in Section 3.

The aims of this paper are (i) to demonstrate a simple automated method for deriving the frontal area index from three dimensional GIS building data, (ii) to demonstrate the use of the frontal area index map in least cost path (LCP) analysis to derive the frequency of occurrence of ventilation paths over the study area, and (iii) to identify the locations of major ventilation corridors and their relationships to urban heat island formation in the study area.

2. Study area

Hong Kong, a sub-tropical city with hot humid summers, suffers from the urban heat island effect caused by a high-rise, high density urban form, with population densities in the Kowloon peninsula exceeding 52,000 km^2 in some areas [9]. With temperature differences up to 9–10 °C between rural areas and the urban core [6,9], the Hong Kong population has recently shown great concern about the heat island effect. This is exacerbated by planning policies which allow building developers to maximise profits by blocking sea views resulting in the so-called "wall effect" around the coastline, and depriving inner areas of ventilation. The study area is the Kowloon peninsula in Hong Kong, which is 160 km^2 in extent and has a population over 2 million. It comprises mainly high density residential and commercial districts, with one large park (Kowloon Park) and a few small urban parks of less than 1 ha each. The topography is mainly flat, but at the northern edge, elevation rises to 300 m. Media reports suggest a strong belief by residents that the wall effect is a major cause of the urban heat island, by preventing cool sea breezes from reaching the inner city, and since Kowloon is a peninsula, this is a reasonable assumption. In planning for future urban renewal, data are needed to confirm and analyse the influence of ventilation on urban temperatures.

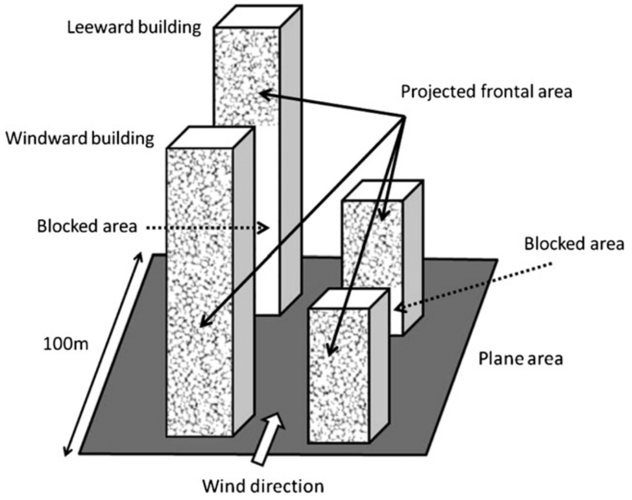

Fig. 1. Example of frontal area calculation.

3. Methods

3.1. Calculation of 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 (and independent of the angle of the building facets), divided by the plane area (equation (1)) [22,23].

$$\lambda_f = A_{facets}/A_{plane} \quad (1)$$

where λ_f is the frontal area index, A_{facets} is the total area of building facets facing the wind direction, and A_{plane} is the plane area. Therefore, a λ_f of ≥ 1.0 means that wind is mostly blocked by buildings within a selected plane region (e.g. $A_{facets} \geq A_{plane}$), and a λ_f of ca. 0.5 means that wind is half blocked (e.g. $2 \times A_{factors} \approx A_{plane}$).

Burian et al. [23] used a similar approach for estimating the λ_f in Los Angeles. Digital data of building polygons at 1:5000 scale were obtained from the Hong Kong Lands Department. A program was written in ESRI® ArcGIS™ 9.2 software to estimate the total frontal area in the projected plane normal to the specific wind direction. In this study we modified Grimmond and Oke and Burian et al.'s [22,23] algorithm by eliminating the areas blocked by buildings upwind, from the blocked area on leeward buildings (Fig. 1). This program is first set up for a particular wind direction and it generates projected lines in the wind direction with a 5 m horizontal increment. If the projected lines hit the first facet and do not reach the second facet, only the frontal area of the first facet is calculated. This modification of the original method is important for irregular building groups, and can reduce the number of facets being calculated in computer memory. The calculated frontal areas are then re-grouped based on horizontal plane polygons (e.g. grid cell of 100 m × 100 m, which is the resolution of the study).

We used grid cells of 100 m × 100 m size to calculate the λ_f because the Hong Kong Planning Department [27] in Hong Kong found that a grid resolution of 100 m was compatible with all variables used for determining dynamic potential and thermal load contributions in an urban climatic study. Also, since Nichol and Wong [28] show that a resolution of 200 m corresponds to intra-urban differences in air temperature between different land cover types, then a resolution of 100 m is more than adequate. Thus, our study calculated λ_f at 100 m grid resolution over the Kowloon peninsula (approx. 11 km by 7 km) for eight different wind directions (north, northeast, east, southeast, south, southwest, west, and northwest).