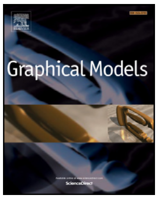
Graphical Models 000 (2017) 1–13

Contents lists available at ScienceDirect

Graphical Models

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



Large-eddy simulations of pedestrian-level ventilation for assessing a satellite-based approach to urban geometry generation

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ARTICLE INFO

Article history:
Received 20 January 2017
Revised 7 June 2017
Accepted 13 June 2017
Available online xxx

Keywords:
Large-eddy simulation
Pedestrian-level ventilation
Building height retrieval
Building footprint
Hong Kong

ABSTRACT

Realistic digital elevations of urban areas are required in urban studies but are not always available. There is a need to extract urban information from satellite images that can be used for, but not limited to, studies of the urban wind environment. This study evaluates urban geometries, including building heights and building footprints, extracted from various satellite images by large-eddy simulations for air ventilation assessment (AVA). The result shows that building heights extracted from TerraSAR-X synthetic aperture radar (SAR) images and the fused results of SAR and WorldView-2 optical (stereo) images are suitable for AVA. Better performance in representing tall buildings, rather than low buildings, is found to be more important for AVA purposes. Moreover, the performance of building geometries retrieved from fused satellite images with and without real building footprints is comparable, which suggests that building footprints extracted from stereo images are reliable.

1. Introduction

Wind comfort and wind safety for pedestrians are important requirements for city design and urban planning [1]. In subtropical high-density cities such as Hong Kong, urbanization causes a number of problems such as urban heat islands and air pollution [2]. Urban ventilation is found to be a way of mitigating these problems [3–5]. Good air ventilation is very important for high-quality healthy living and comfortable thermal sensations. Thermal comfort can be achieved by capturing natural wind. 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 [6]. 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 and turbulent transport at rooftop level, which provide dilution capacity for contaminants and remove contaminants from street canyons. When the purpose 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.

In the literature of urban air ventilation, various research methods have been used to describe the complex flows over urban environments. Computational fluid dynamics (CFD) techniques such as the Reynolds-averaged Navier–Stokes (RANS) model, large-eddy simulation (LES), and direct numerical simulation (DNS) are among the commonly used tools [7,8]. Urban ventilation is strongly influenced by wind speed and direction, which in turn are affected by three-dimensional urban morphology [9–11]. Unfortunately, realistic digital elevations of urban areas required in CFD studies are not always available for open access, especially in the less developed regions of the world where urban population growth is concentrated. There is a well-known problem of urban data quality and availability in these regions. Furthermore, surface geometries and urban morphologies are found to have a significant influence on urban heat islands [12], especially for regions with a hot and humid microclimate [13]. High-resolution digital elevations have been extensively used in studies of urban climate and outdoor thermal comfort [14]. Therefore, there is a need to develop methodologies of extracting urban geometries in urban areas that can be used for, but not limited to, studies of urban ventilation.

The term ‘urban geometry’ in this study reflects the physical characteristics of an urban form, simply referring to building footprints and building heights. Field measurement and satellite-based data are available methods for obtaining urban information. Classical field measurement is highly accurate for small study areas but is time-consuming. Satellite technology provides a fast

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http://dx.doi.org/10.1016/j.gmod.2017.06.003
1524-0703/

Please cite this article as: W. Wang et al., Large-eddy simulations of pedestrian-level ventilation for assessing a satellite-based approach to urban geometry generation, Graphical Models (2017), http://dx.doi.org/10.1016/j.gmod.2017.06.003

and economic way to obtain large-area morphological information. There are three kinds of remote sensing technologies that can extract building information: stereo photogrammetry technology with pairs of optical images (hereafter referred to as stereo images), synthetic aperture radar (SAR) technology, and light detection and ranging data (LiDAR) technology. However, there are limitations to these methods: (1) stereo images tend to underestimate the height of tall buildings, and taller buildings produce larger errors [15]; (2) the interferometry of SAR provides noisy and incomplete data, particularly for high-density urban areas where the mutual interference of surrounding buildings is significant [16,17]; and (3) LiDAR data are expensive and are limited by flight restrictions for applications in large urban areas [18]. Therefore, recent studies have also been devoted to the integrated use of different kinds of data for building data retrieval [17,18].

The objective of the present study is to assess the performance of building geometry extractions from different kinds of satellite images for potential use in urban ventilation studies with CFD techniques. Evaluation of building data extraction from satellite images from the perspective of a particular application, i.e., urban ventilation, has rarely been attempted to date as far as we know. What affects pedestrian comfort directly is the wind flow within cities, in particular, the local turbulence level [7]. We therefore use an LES model to produce CFD simulations in this study. LES overcomes the deficiencies of RANS by explicitly resolving large, energy-containing turbulent eddies and parameterizing only small (subgrid) scale turbulence [19,20]. The dimensionality, spatial resolution, and turbulence intensity that an LES model can handle are superior compared to most of the other methodologies, and sometimes also to other CFD models, i.e., RANS and DNS [21]. LES provides not only mean flow fields but also instantaneous turbulences, which are especially important for human comfort at the pedestrian level in the urban canopy layer [22].

To make the paper easier to follow, we clarify here the goals of each section and the main conclusions before going into detail: neighborhood-scale urban geometries are introduced in Section 2, including the actual (measured) data and those extracted from satellite images for assessment. In Section 3, we introduce the LES model used in this study, including the definition of the pedestrian-level ventilation indicator, velocity ratio, and basic model setups in Section 3.1, and LES model validation by CFD guidelines in Section 3.2. Details of the main results are presented in Sections 4 and 5. Section 4 evaluates building height extraction with actual building footprints. This section concludes that building heights extracted from SAR images and the fused results of SAR and stereo images are suitable for air ventilation assessment (AVA) studies, and better performance in representing tall buildings, rather than low buildings, is found to be more important for AVA purposes. Section 5 evaluates building footprints retrieved from stereo images and concludes that such a method is reliable. Sections 6 and 7 further discuss and summarize the study.

2. Neighborhood-scale urban geometries

Hong Kong is one of the most densely built cities in the world. It is located in the Pearl River Delta region of China, which is experiencing rapid urbanization. The Mong Kok area on the Kowloon Peninsula of Hong Kong has tall buildings and narrow streets that form deep street canyons. Irregular street orientations and building layouts make the urban morphology in the region more complex. Mong Kok is herein chosen as the case study for this paper.

In a recent study, we proposed an approach that jointly uses high-resolution WorldView-2 stereo images and multi-temporal TerraSAR-X SAR images to retrieve urban geometries in high-density urban areas, which has the advantage of both datasets [23]. Procedures of the proposed approach are shown in Fig. 1a. In the first step of the present study, actual (measured) urban geometries in a neighborhood of Mong Kok provided by the Hong Kong Planning Department are utilized as topography input for the LES model. The domain is 1.2 km × 1.2 km, as given in Fig. 2a. The data have a horizontal resolution of 2 m. The methodology proposed in Fig. 1a for retrieving building heights in urban areas using both stereo and SAR images assumes that the building footprints are known and involves two main stages: First, estimated initial building heights are retrieved from stereo and SAR images, respectively; second, according to an object-based fusion approach, the initial building heights are then combined. The bias of building heights between actual data and data extracted from stereo images, SAR images, and the fused result of the two kinds of images is given in Fig. 2b, c, and d, respectively. The four sets of data in Fig. 2 are topography inputs for simulation of ventilation in the first step of building data assessment.

However, in reality, building footprints are generally unknown if building heights are unknown. Therefore, urban geometries including both building footprints and building heights are extracted from satellite images, as shown in Fig. 1b. The method in Fig. 1b is similar to that in Fig. 1a except that the building footprints are extracted from stereo images rather than being provided by measurements. Building footprints are retrieved only from stereo images, as these are pairs of optical images and have small positioning error. The performance of these building data in terms of pedestrian-level ventilation in large-eddy simulations is evaluated in the second step of this study. In this step, we utilize a 2 km × 2 km neighborhood in Mong Kok, with a horizontal resolution of 2 m. Three sets of data will be involved: actual (measured) data, the fused result of both kinds of satellite images (stereo and SAR) with real building footprints, and the fused result with building footprints extracted from stereo images. These three sets of data will be shown together with the simulated velocity ratios in a later section.

3. The parallelized large-eddy simulation model

The LES model used in this study is the Parallelized LES Model (PALM), which was developed at the Institute of Meteorology and Climatology of the Leibniz Universität Hannover in 1997 [24]. PALM has been validated for simulating flows and turbulence characteristics at the street-canyon and neighborhood scale and has been widely used in studies of urban street-canyon flows in recent years [25–29], including high-density urban areas in Hong Kong [30] and Macau [22]. The code used in this study is the most updated PALM version 4.0 [31]. More details can be found on the PALM homepage (https://palm.muk.uni-hannover.de/trac).

3.1. Indicator and simulation setup

In AVA studies, we are especially interested in pedestrian-level wind velocity. The wind velocity ratio (VR) is used as an indicator, which is calculated by

$$VR = V_p / V_\infty, \qquad (1)$$

where V_P is the wind velocity at the pedestrian level (2 m above the ground), and V_∞ is the wind velocity at the top of the wind boundary layer and is not affected by ground roughness [4]. A top boundary layer of 500 m is commonly used in Hong Kong AVA studies [32].

Model domain and grid spacing: in the main runs of Section 4 (evaluation of building height extraction with actual building footprints), the model domain, i.e., the input building data size, is 1.2 km by 1.2 km. In Section 5 (evaluation of building footprints retrieved from stereo images), the model domain is 2 km by 2 km. In both Sections 4 and 5, horizontal grid spacing sizes are

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