Energy and Buildings 114 (2016) 80–86

Contents lists available at ScienceDirect

Energy and Buildings

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

Numerical modelling of mean radiant temperature in high-density sub-tropical urban environment

Kevin Ka-Lun Lau[a,*], Chao Ren[a,b], Justin Ho[b], Edward Ng[a,b]

[a] School of Architecture, The Chinese University of Hong Kong, Hong Kong
[b] Institute of Energy, Environment and Sustainability, The Chinese University of Hong Kong, Hong Kong

ARTICLE INFO

Article history:
Received 25 February 2015
Received in revised form 9 June 2015
Accepted 11 June 2015
Available online 14 June 2015

Keywords:
High-density
Mean radiant temperature
Sub-tropical
SOLWEIG
Radiant heat load

ABSTRACT

Outdoor thermal comfort has been a widely concerned issue in tropical and subtropical cities. In order to assess the conditions of outdoor thermal comfort, quantitative information on different spatial and temporal scales is required. This paper employs a numerical model (SOLWEIG – SOlar and LongWave Environmental Irradiance Geometry) to examine the spatial and temporal variations of mean radiant temperature (T_{mrt}), as an indicator of radiant heat load and outdoor heat stress in high-density sub-tropical urban environment in summer. The SOLWEIG model is found to simulate the six-directional shortwave and longwave radiation fluxes as well as T_{mrt} very well. Simulation results show that urban geometry plays an important role in intra-urban differences in summer daytime T_{mrt}. Open areas are generally warmer than surrounding narrow street canyons. Street canyons are sheltered from incoming direct solar radiation by shading of buildings while open areas are exposed to intense solar radiation, especially along the sunlit walls where high T_{mrt} is observed due to reflected short-wave radiation and long-wave radiation emitted from the sunlit building walls. The present study confirms that there are great potential in using urban geometry to mitigate high radiant heat load and daytime heat stress in the compacted urban environment. In high-density subtropical cities where high daytime T_{mrt} causes severe thermal discomfort in summer, dense urban structures are able to mitigate the extremely high T_{mrt} and improve outdoor thermal comfort. However, the shading strategy has to be cautious about air ventilation in such a dense urban environment.

1. Introduction

Urbanization was at its fastest rate in the last few decades in sub-tropical cities which the hot and humid summer resembles climatic conditions in tropical regions. The high-density urban environment results in urban heat island phenomenon characterized by higher urban air temperature than rural surroundings [1,2]. During daytime, particularly from noon to early afternoon, heat stress is common due to high air temperature and intense solar radiation [2–4]. It does not only affect the people's behaviour and activities in outdoor environment but also results in heat-related health risks and mortality [5–8].

Shading from buildings or vegetation is able to improve outdoor thermal comfort in tropical cities. Measures including increasing height-to-width ratio of street canyons, providing shading devices and vegetation were found to be effective in mitigating heat stress in urban environment [2,9,10]. However, in high-density cities, there is often a lack of vegetation in the dense inner urban areas due to the limited land availability. It makes shading by buildings becomes particularly important in relieving heat stress in the urban environment.

Urban geometry is widely considered to play an important role in the provision of shading in the urban environment [11–14]. Previous studies on the effect of urban geometry on outdoor thermal environment are conducted in low- to mid-density urban environment [4,9,15–17]. The understanding of how urban geometry affects outdoor thermal environment in high-density cities is rather limited. It leads to ineffective urban design which may exacerbate thermal discomfort in the dense urban areas.

Mean radiant temperature (T_{mrt}) is one of the most important meteorological parameters, which governs human energy balance and outdoor thermal comfort [3,18]. It is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure' [19]. In outdoor thermal comfort studies, T_{mrt} is a more suitable parameter than conventional parameters like air temperature (T_a) since it shows large spatial variations within short distances, which is particularly important

* Corresponding author. Tel.: +852 39438101.
E-mail address: kevinlau@cuhk.edu.hk (K.K.-L. Lau).

http://dx.doi.org/10.1016/j.enbuild.2015.06.035
0378-7788/

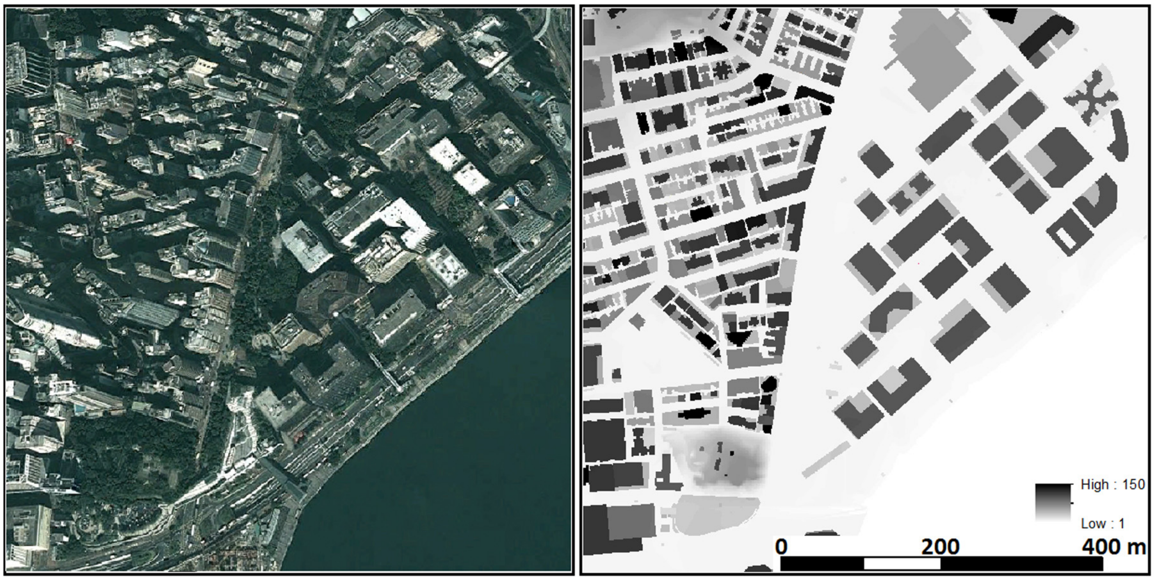

Fig. 1. Satellite image (left) and digital surface model (right) of the study area.

in the complex urban environment. Mayer and Höppe [18] showed that the difference in T_{mrt} between sun-exposed and shaded locations can reach up to 25 °C at noon while the difference in T_a is only less than 2 °C. It suggests that T_{mrt} is able to capture the intra-urban difference in outdoor thermal comfort conditions.

The objective of the present paper is to investigate the effect of urban geometry on the spatial variation of T_{mrt}, as an indicator of radiant heat load and outdoor heat stress, in high-density sub-tropical cities using Hong Kong as a case study. The study is conducted in a central urban area characterized by high-rise buildings and narrow street canyons. The Solar and LongWave Environmental Irradiance Geometry (SOLWEIG) model was employed to simulate T_{mrt} within the study area. Different urban settings, in terms of sky view factor (SVF) and street orientations, are compared and its implications on the design of urban geometry are also discussed.

2. Methodology

2.1. Study area

Hong Kong is located at the southeastern coast of China with latitude of 22.3° N. It has a sub-tropical climate, tending towards temperate during winter months [20]. Annual mean air temperature is 23.2 °C with summer average of about 28 °C. There is over 50% of possible sunshine from July to December with daily mean global solar radiation peaked at near 200 W m^{-2} in July.

The study area is located in the central part of Hong Kong. It is divided into western and eastern halves by a main road (Fig. 1). The western side is dominated by high-rise and densely built commercial buildings and retail activities while the eastern side is mainly composed of less dense high-rise hotels and commercial buildings with a large open square close to the harbourfront which is located in the southeastern part of the study area. Despite of the vegetation present along the main road, at the open square and in the park located in the southwestern part of the study area, there is little or no vegetation within the street canyons.

2.2. SOLWEIG model and input data

SOLWEIG (version 2014a) is a numerical model which simulates spatial variations of 3D radiation fluxes and T_{mrt} in complex urban settings [21]. The T_{mrt} is derived from the modelling of six-directional (upward, downward and from the four cardinal points) shortwave and longwave radiation fluxes. Shadow patterns and sky view factors (SVF) can also be generated by the model. The model is proven to provide accurate estimation of the radiation fluxes in different urban settings and weather conditions as well as in different regional contexts [22]. The advantage of the SOLWEIG model is the low computational requirement which allows larger area and longer period of interest [21,22]. Therefore, a more general or long-term climate or specific conditions can be simulated. Packages with detailed inputs normally require intensive computational power which limits the use in various situations. As the present study focuses on the radiant heat load of the urban environment, the SOLWEIG model offers a computationally efficient option to obtain information about the spatial variation of radiant heat load and potential heat stress area using T_{mrt} as an indicator.

Terrain and meteorological data are two major inputs for the SOLWEIG model. Terrain data is in the form of a digital surface model (DSM) which includes both ground topography and building structures within the study area. The DSM, with a spatial resolution of 1 m, is derived from the digital elevation model of Hong Kong as well as building and podium data obtained from the Planning Department. Podium are common building structures in Hong Kong that occupy the lower levels of high-rise buildings and generally cover larger building footprint than the building towers, serving as commercial or institutional purposes. As such, building tower and podium data in Hong Kong are separately documented. Meteorological inputs include air temperature, relative humidity, global solar radiation recorded at two ground-level meteorological stations operated by the Hong Kong Observatory (HKO). Hourly data of the above meteorological variables were collected in 2008. The diffuse and direct components of solar radiation were calculated according to Lam and Li [23]. Field measurements were conducted on a clear late-summer day (9 September 2008) for assessing the performance of the SOLWEIG model (Fig. 1b). Standard values of absorption coefficients for shortwave and longwave radiation are 0.7 and 0.97 [24]. According to Crawford and Duchon [25], surface albedo of building and ground surface is designated to 0.2 since the current version model assumes a uniform albedo value over the entire study area. Wind fields and materials of ground and building surfaces are not considered in the current version of the model. The emissivity of building walls is set to be 0.9 since the majority of