International Journal of Applied Earth Observation and Geoinformation 13 (2011) 586–594

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

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

Quantitative urban climate mapping based on a geographical database: A simulation approach using Hong Kong as a case study

Liang Chen*, Edward Ng

School of Architecture, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China

ARTICLE INFO

Article history:
Received 11 October 2010
Accepted 15 March 2011

Keywords:
Urban climate mapping
Geographical information system
Urban simulation
Sky view factor
Frontal area density

ABSTRACT

The urban environment has been dramatically changed by artificial constructions. How the modified urban geometry affects the urban climate and therefore human thermal comfort has become a primary concern for urban planners. The present study takes a simulation approach to analyze the influence of urban geometry on the urban climate and maps this climatic understanding from a quantitative perspective. A geographical building database is used to characterize two widely discussed aspects: urban heat island effect (UHI) and wind dynamics. The parameters of the sky view factor (SVF) and the frontal area density (FAD) are simulated using ArcGIS-embedded computer programs to link urban geometry with the UHI and wind dynamic conditions. The simulated results are synergized and classified to evaluate different urban climatic conditions based on thermal comfort consideration. A climatic map is then generated implementing the classification. The climatic map shows reasonable agreement with thermal comfort understanding, as indicated by the biometeorological index of the physiological equivalent temperature (PET) obtained in an earlier study. The proposed climate mapping approach can provide both quantitative and visual evaluation of the urban environment for urban planners with climatic concerns. The map could be used as a decision support tool in planning and policy-making processes. An urban area in Hong Kong is used as a case study.

1. Introduction

Urbanization is inevitable. More than half of the world's population currently lives in cities (Population Reference Bureau, 2009), and this number is anticipated to reach 60% (or 4.9 billion) by the year 2030 (UNFPA, 2007). A direct consequence of this rapid and continuing urbanization process is that the environment has been severely changed by artificial development and construction. Natural vegetation has been removed and natural terrain has been altered and mounted densely with high-rise buildings. The result is a new type of geometry (i.e., the urban geometry) that has significant impacts on the microclimate in the urban environment. Differences in surface material and geometric form result in the widely observed and discussed urban heat island effect (UHI) (Arnfield, 2003), and building bulks dramatically modify the aerodynamic environment in cities (Oke, 1987). Consequently, human thermal comfort and urban living quality are greatly affected.

Climatic issues have been increasingly recognized in building design and urban planning (Oke, 1988; Givoni, 1998; Eliasson, 2000; Cleugh et al., 2009). Urban planners and decision makers, faced with the task of designing urban environments that promote high living quality, are always in great need of knowledge transfer and decision support tools. Hong Kong (22°15′N, 114°10′E) is one of the world's densest cities, with its more than 7 million inhabitants living in approximately 260 km^2 of land. With its hot and humid subtropical climate, it is faced with challenges in urban development that are not experienced by any other metropolises around the world. Under these circumstances, urban climatic considerations have been increasingly recognized in the development of planning standards and guidelines. A series of governmental and research projects have been conducted to study the impact of the urban environment on outdoor thermal comfort, with the objective of providing implications for planning and design (Planning Department, 2005, 2008; Ng, 2009).

The objective of the present study is to translate climatic understanding into analytical maps that provide quantitative information for decision making. Two main climatic impacts are considered: UHI and wind dynamics. A simulation approach using a geodatabase to characterize the urban geometry is conducted. A densely built-up area in Hong Kong, the Kowloon peninsula, is used as a case study. The study site is a 4 km × 5.6 km coastal area with

* Corresponding author at: Room 701, Wong Foo Yuan Building, School of Architecture, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China. Tel.: +852 26096597.
E-mail addresses: chenliang@cuhk.edu.hk, chenliangcl@gmail.com (L. Chen).

0303-2434/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jag.2011.03.003

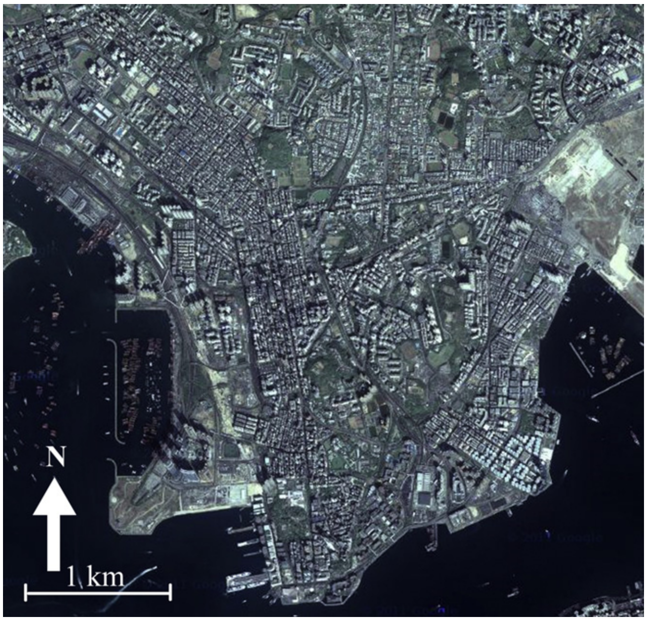

Fig. 1. Google™ map of the study site: the Kowloon peninsula.

flat terrain and little vegetation, as shown in Fig. 1. Building form is therefore the dominant factor in affecting the local urban climate.

2. Background

2.1. Urban climatic map

Mapping urban climatic information for planning purposes is not a novel idea. Its basic landscape was developed in the 1990s in the institutional guidelines of Germany (VDI, 1997). In the last decade, climatic mapping has been applied to a number of governmental and research projects across the world, including the Urban Climate 21 program in Stuttgart, Germany (Office for Environmental Protection, N/A); the Climatological Air Temperature Map in Poland (Ustrnul and Czekierda, 2005); the Urban Environmental Climate Map in Japan (Tanaka et al., 2009); the Bioclimatic Map in Portugal (Alcoforado et al., 2009); the Local Climate Zone Map in Canada (Stewart and Oke, 2009), and the Urban Climatic Map in Hong Kong (Planning Department, 2008). Despite their different specialties and implementation methods, these projects all aim to provide visual and also analytical information for planners. Svensson et al. (2003) have introduced a GIS-based approach to implement urban climatic mapping systems. The practical GIS application makes the climatic information useful for urban planning easily accessible to planners.

Among many examples, the Hong Kong Climatic Map takes a bioclimatic approach by classifying the urban territory into different classes, corresponding to different human thermal comfort conditions, as described by the biometeorological index of the physiological equivalent temperature (PET) (Mayer and Höppe, 1987). Climatic factors considered include building density, topography, ground roughness and greenery. Thermal load and wind dynamics are used as bases for evaluating the urban microclimatic condition (Ng, in press). Because the project is an initial investigation along this line of research, the modeling and classification of the urban microclimate are mainly based on preliminary findings obtained in empirical studies and uses simple parameters such as building volume and site coverage. Other studies have suggested the usefulness of morphometric indicators, such as the sky view factor and the roughness length of building form, in describing the thermal and aerodynamic characteristics of urban environment (Oke, 1987; Grimmond and Oke, 1999). However, these indicators cannot be easily derived from the aforementioned parameters. Under such circumstances, a systematic and quantitative methodology to facilitate the development of urban climate mapping systems of this kind with more effective descriptions of the urban form is needed.

2.2. The simulation approach in urban climatology

The simulation approach has been increasingly adapted in urban climatology studies (Arnfield, 1990; Ratti et al., 2002; Gal and Sumeghy, 2007; Lindberg, 2007; Gal and Unger, 2008; Unger, 2009). In contrast to conventional remote-sensing methods (Nichol, 2005; Hung et al., 2006), the simulation approach reconstructs the physical urban environment in a silicon surrogate, and characterizes the spatial variation of quantities and relationships of the urban environment. Its integration with GIS platforms is particularly suitable for spatially related investigations. Geo-databases are normally used, including vector or raster data (Gal et al., 2009). In particular, the digital elevation model (DEM) is a raster format containing 3-D information on 2-D digital support. It is considered "not as a simple store of information, but as a tool for supporting many forms of analysis." (Falcidieno, 1994) Indeed, because of its direct connection with GIS systems, DEM has found its most common applications in geographical studies (Lin and Oguchi, 2006; Ruiz-Arias et al., 2009; Tarekegn et al., 2010). However, although the usefulness of DEM in modeling urban geometry in climatology studies has been confirmed (Ratti and Richens, 2004; Lindberg, 2007), related analyses and applications in the urban context remain sparse. In the present study, a DEM database with building height information is used to model the urban morphology.

3. Simulation methodology

The present study employs two well-developed parameters to quantify the UHI and wind dynamic environment of Hong Kong's urban environment: the sky view factor (SVF) (Watson and Johnson, 1987) and the frontal area density (FAD) (Burian et al., 2002). Computer programs are developed for this purpose, and high-resolution DEM database in 2 m resolution is used as input, as shown in Fig. 2.

3.1. Sky view factor simulation

The sky view factor (SVF), commonly denoted by ψ_{sky}, indicates the ratio between the radiation received by a planar surface from the sky to the radiation emitted to the entire hemispheric radiating environment (Watson and Johnson, 1987). It is a dimensionless value ranging from 0 to 1, where $\psi_{sky} = 0$ means that the sky is completely obstructed and the outgoing long-wave radiation is trapped in the urban canyons, and $\psi_{sky} = 1$ means that the sky is completely open and the radiation is freely emitted outside the urban canopy layer. Because of its important role in energy balance schemes, SVF has been commonly adapted to relate the urban geometry with UHI in urban climatology studies (Unger, 2004). In short, lower SVF indicates stronger UHI, and vice versa.

In the present study, an ArcGIS-embedded computer program is developed for calculating SVF. The algorithm is introduced in (Chen et al., in press) and has been proven to provide accurate estimation of SVF compared with fish-eye lens photos. Fig. 3 shows an illustration of the algorithm. Briefly, the method divides the hemispheric radiating environment with radius R into equal slices by a rotation angle α, and searches for a building with the largest elevation angle β along a particular direction. The elevation angle is calculated by the building height, which is read from the DEM database. If such a building is found, then the surface, S, it obstructs is considered as