Urban Climate 9 (2014) 35–53

Contents lists available at ScienceDirect

Urban Climate

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

Computationally efficient prediction of canopy level urban air temperature at the neighbourhood scale

Bruno Bueno [a,*], Matthias Roth [b,1], Leslie Norford [a,2], Reuben Li [c,3]

[a] Massachusetts Institute of Technology, Massachusetts Avenue 77, Cambridge, MA 02139, USA
[b] National University of Singapore, 1 Arts Link, Kent Ridge, Singapore 117570, Singapore
[c] University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo, Japan

ARTICLE INFO

Article history:
Received 18 December 2013
Revised 21 May 2014
Accepted 29 May 2014

Keywords:
Urban Heat Island
Urban climate
Urban canopy model
Urban boundary layer
Weather prediction
Neighbourhood scale

ABSTRACT

The Urban Weather Generator (UWG) is a simple and computationally efficient model that predicts canopy level urban air temperature using meteorological information measured at a reference weather station. An evaluation of an improved version of the model, which accounts for different urban morphologies and building usage distributions within a city, is presented in this paper. Calculated urban air temperatures are compared with measurements from a network of weather stations in Singapore, representing a range of land uses, morphological parameters and building usages. The comparison shows a satisfactorily performance of the model for all weather conditions and for different reference weather stations. Singapore is located in a hot and humid climate where vegetation plays a critical role in climate regulation, the urban morphology is very heterogeneous and air-conditioning systems are generally used throughout the year. This makes Singapore an interesting case study in order to analyse the potential and limitations of the model. The study shows that the model can be applied to different climates and urban configurations to obtain an estimation of the Urban Heat Island (UHI) effect. However, the

* Corresponding author. Present address: Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstrasse 2, 79110 Freiburg, Germany. Tel.: +49 761 4588 5377.
E-mail address: bruno.bueno@ise.fraunhofer.de (B. Bueno).
[1] Tel.: +65 6516 6103.
[2] Tel.: +1 617 253 8797.
[3] Tel.: +81 3 3812 2111.

http://dx.doi.org/10.1016/j.uclim.2014.05.005

simplifications and assumptions of the model prevent it from capturing very site-specific microclimate effects.

1. Introduction

Urban areas are characterized by an increase in air temperature relative to the surrounding undeveloped, rural areas, a phenomenon known as the Urban Heat Island (UHI) effect. The UHI effect has been quantified from meteorological observations carried out in many cities around the world. Recent examples include studies by Roth (2007), Hicks et al. (2010), Lee and Baik (2010), Zhou and Shepherd (2010), and Houet and Pigeon (2011). The study and prediction of the UHI effect is important in order to integrate climate-sensitive considerations into the decision-making process of urban design and operation (Coutts et al., 2010).

The UHI effect arises mainly from differences in morphology and surface materials of the urban relative to the surrounding rural terrain. The city reduces the diurnal cycle of air temperature due to the presence of more surfaces with large heat capacities, increasing the effective thermal inertia (Erell and Williamson, 2007). Furthermore, urban surface roughness decreases the mean wind velocity and reduces the heat removal through convection. Added to this is the heat gain due to anthropogenic sources (Sailor, 2011) and lower evaporation due to the reduction of vegetated areas.

Grimmond et al. (2010) review the existing modelling approaches to predict the UHI effect, which include statistical and numerical models. Of the latter, microscale computational fluid dynamics (CFD) models are capable of accurately predicting information about the canopy-microscale UHI distribution at a particular location (Santiago and Martilli, 2010). However, due to their high computational cost, their scope is spatially and temporally limited; thus, typically, these models are not applied to annual calculations or analyses at a scale larger than a few blocks, for example. Furthermore, the accuracy of CFD simulations strongly depends on the boundary conditions, for which detailed information in most cases is not available, and on the treatment of the turbulence closure and radiation. Although CFD simulations can be very useful for specific studies, especially involving distribution of wind speed, a very high computational cost is paid for a gain in accuracy that is not guaranteed.

Mesoscale models are considered state-of-the-art in atmospheric weather prediction and are used as operational and research tools. These models represent the urban canopy as an aerodynamic roughness for which analytical expressions act as a bridge between the surface and the first atmospheric layer. The latest generation of mesoscale models is coupled with urban canopy models (Masson, 2000; Kusaka et al., 2001; Martilli et al., 2002), improving the representation of the thermal and roughness effects of urban areas on the atmosphere. However, the application of mesoscale models to urban climate predictions, for which the temporal scale of interest ranges from a few days to one year or even a century, is affected by the same limitations as for microscale CFD models.

As an alternative to computationally expensive mesoscale models, Bueno et al. (2012b) proposed an Urban Weather Generator (UWG) to estimate the UHI effect in the urban canopy layer using meteorological information measured at an operational weather station located in an open area outside the city. The UWG is based on energy conservation principles applied to control volumes in the urban canopy layer and the urban boundary layer for which boundary conditions can be imposed (Fig. 1). The model is also a bottom-up building stock model (Kavgic et al., 2010) that can be used to estimate building energy consumption at the city scale, specifically accounting for the interactions between buildings and the urban environment.

The present study describes an extension of the UWG's capabilities after first reviewing its most important aspects. While the previous version allowed the user to define only one representative urban configuration and building use for a given city, the new version is able to differentiate various neighbourhood characteristics within a city and different building uses within an urban area. As a result, the UWG can now be used to estimate the UHI effect and building energy consumption at neighbourhood resolution. Other changes include the addition of longwave radiation effects of water