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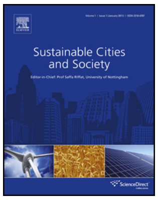

Engineering Advance

Recent challenges in modeling of urban heat island☆

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ABSTRACT

The elevated air temperature of a city, urban heat island (UHI), increases the heat and pollution-related mortality, reduces the habitats' comfort and elevates the mean and peak energy demand of buildings. To countermeasure this unwanted phenomenon, a series of strategies and policies have been proposed and adapted to the cities. Various types of models are developed to evaluate the effectiveness of such strategies in addition to predict the UHI. This paper explains the compatibility of each type of model suitable for various objectives and scales of UHI studies. The recent studies, mainly from 2013 to 2015, are further categorized and summarized in accordance with their context of study.

Contents

Abbreviations: UHI, urban heat island; PET, physiological equivalent temperature; ANN, artificial neural network; TEB, town energy budget; LST, land surface temperature; BEM, building energy model; UCM, urban canopy model; MCM, microclimate model; MM, meso-scale model; CFD, computational fluid dynamics; GIS, geographic information systems; MODISm, oderate-resolution imaging spectroradiometer; LIDARl, aser illuminated detection and ranging.

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1. Introduction

There has been a drastic increase in the world population in recent years, new megacities are born and existing megacities become more populated (Fig. 1) (UN, Department of Economic and Social Affairs, 2014). Besides new economical, managerial and social challenges associated with growing cities, a deformed energy budget pulls them toward a warmer climatic condition, known as urban heat island (UHI). Highly populated areas mandate cities to develop either vertically or horizontally, resulting in more released anthropogenic heat, a higher blockage effect against urban ventilation, a higher absorption of solar radiation due to the implementation of artificial materials, and eventually a reduced long-wave emission to sky due to the blockage effect of buildings (Ashtiani, Mirzaei, & Haghighat, 2014; Mirzaei & Haghighat, 2010a).

The elevated temperature triggers heat-related diseases and premature deaths in the cities (Basu & Samet, 2002; Doyon, Belanger, & Gosselin, 2008). Moreover, the elevated air and surface temperatures during UHI events increase the city-scale mean and peak cooling energy demand due to lower efficiency of HVAC systems in higher temperatures as well as a significant drop in the thermal comfort level (Moonen et al., 2012). Despite various efforts in mitigating the UHI effect, the effectiveness of the mitigation strategies cannot be evaluated with a high level of certainty due to weakness of current models in their design and prediction stages. This implies that the developed tools should precisely include a series of complex phenomena occurring in a city and avoid unrealistic assumptions as well as the intensive computational calculations.

This paper aims to summarize the recent efforts in modeling of the UHI effect. For this purpose, various studies in building, neighborhood and city scales are firstly identified. Then, these works are summarized in six major categorizes of research interest, including urban ventilation and surface material alteration, health and comfort, UHI spatial–temporal variation, model evaluation and enhancement, future temperature forecast, and building energy saving.

2. Modeling approaches – goal of the study

The goal of a UHI study delineates the type of an adapted model. Urban physics include a combination of complex and diverse phenomena, interacting in different scales from human body to city size. Therefore, it is very crucial as a first step of a UHI study to simplify physics and scale of the investigated subject. This implies that a suitable model can be only identified in compliance with the defined objective in order to minimize the complexities and computational costs of the study.

Mitigation strategies such as urban ventilation and surface material alteration (Santamouris, 2014; Takebayashi & Moriyama, 2012), improvement of occupant and pedestrian comfort/health (Mirzaei & Haghighat, 2010b, 2012; Mochida & Lun, 2008), and building energy demand (Sun & Augenbroe, 2014) are amongst widely investigated UHI topics. In general, the mentioned objectives are recognized to be in accordance with different perspectives from different communities including building scientists, architects, urban climatologist, meteorologists and geographers.

3. Scale of the study

The UHI models are diverse in terms of scale with respect to the aim of a study, changing from building-scale for investigation of the impact of the UHI on thermal comfort of a pedestrian to urban-scale for exploring the effect of synoptic wind on urban ventilation.

3.1. Building-scale models

These models, known as building energy models (BEM), are mainly limited to an isolated building envelope where the influence of neighboring buildings on its energy performance is neglected. This implies that BEMs are developed based on an energy balance applied to the building's control volume. Outdoor parameters such as temperature, solar radiation, long-wave radiation, and moisture are external inputs into such models. Various robust BEM tools (e.g. EnergyPlus, ESP-r, TRNSYS) are utilized to investigate the response of the building envelope against possible future scenario of climate change and exacerbated urban climate (Sailor, 2014). Obviously, these models are simplistic in representing the mutual impact of a building with its surrounding area and thus their integration with larger scale models is inevitable when the effect of UHI on building energy performance is investigated.

3.2. Micro-scale models

The interaction of a building with its surrounding environment in the surface layer is the basis of the development of microclimate models (MCM), which are widely employed by building scientists and architects. In principle, solar radiation and surface convection from the buildings' surfaces can be included in such models. In many MCMs, the airflow patterns around and within buildings are resolved using computational fluid dynamics (CFD) technique, dealing with the governing equations of the flow (Navier–Stokes equations). Another type of MCM, urban canopy model (UCM), has been broadly utilized to investigate the energy budget of an urban canopy layer (Masson, 2000). Unlike CFD based MCMs, the airflow model is decoupled from the energy budget equations in UCMs. In general, the impact of different parameters such as building orientation, street canyon aspect ratio, surface materials, vegetation and tree planting on the calculation of surface convection, pedestrian comfort, and urban ventilation can be investigated using CFD and UCM MCMs (Haghighat & Mirzaei, 2011; Mirzaei & Haghighat, 2010a; Tominaga et al., 2015).

The weakness of the microclimate CFD models is their limited domain size (few hundred meters) due to the extensive computational cost. UCMs are also weak in the detail presentation of airflow around the buildings for example in thermal comfort associated studies.

3.3. City-scale models

Investigation of the large-scale UHI variation of a city is broadly adopted in urban climatology and meteorology fields. The impact of urban-scale policies to mitigate the UHI, e.g. urban ventilation, pollution dispersion management, and greening, is mostly analyzed using meso-scale (MM) tools. The developed models are based on the governing equations of fluid dynamics whilst equally important models such as radiation, cloud cover and soil are integrated into the calculations. As the major limitation, the meso-scale models are applied on very coarse cells, implying a weak resolution on the surface layer to observe interactions between buildings and their environment.

City-scale observation and modeling of the UHI is one of the applications of the remote sensing. The thermal images taken by satellites (e.g. Terra and Aqua) and airborne measurement devices are processed to correlate surface temperatures and land-use/land-cover of a city. For this purpose, regression models are commonly developed to explain spatial–temporal land surface temperature (LST) variation associated with parameters such as topographic position, land-cover diversity, building volume per area, orientation, and anthropogenic heat release (Voogt & Oke, 2003). The regression models, however, have low spatial resolution. They are

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