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Urban heat island effect on energy application studies of office buildings

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ABSTRACT

Because of the urban heat island (UHI) effect a metropolitan area is typically warmer than its surrounding rural area. This has led to a growing concern that the use of standard (mostly rural) weather data leads to inadequate decision-making with regard to the energy efficiency of buildings in metropolitan areas. This paper conducts a series of computational studies that explore the UHI effect on two routine applications of building energy simulation: (1) predicting the magnitude of energy use and (2) predicting energy savings. We present the results based on case studies of office buildings in 15 representative cities across different climate zones in the U.S. The results show that the UHI considerably modifies the urban climate measured by cooling and heating degree days. As a consequence, ignorance of the UHI effect remarkably underestimates building total energy use in hot climate zones where cooling energy use is dominant, yet causes overestimation in cold climate zones where heating energy use is prevalent. In mild climate zones, the UHI effect only has a moderate effect because the effects on cooling and heating mostly average out. When building simulation is used to assess energy savings that is measured as the ratio to the corresponding baseline such as in a comparative analysis of retrofit measures, the UHI effect is less of a factor.

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1. Introduction

By the year 2010, 50% of the population of the world and 79% of that of the United States were living in urban areas, and this percentage is projected to grow in the future [1]. Because built-up areas have distinctly different characteristics compared to natural surfaces, urban climates could be distinctly different from the original natural environment. One of the most well-studied urban climate modifications caused by anthropogenic activities is the urban heat island (UHI). Many literature sources have confirmed that the UHI is strongly correlated with urban land use [2] and that the magnitude of the UHI increases during the urbanization process [3,4]. Arnfield [5] provided a review on the studies of the UHI effect with a broad geographic scope.

Computer models have been advocated to understand and quantify the UHI in various weather and land-use conditions [6]. Among these models, the Town Energy Budget (TEB) model and the Interaction Soil–Biosphere–Atmosphere (ISBA) model are well-established and validated against measurements by many studies [6–11]. Hence the TEB and ISBA model (TEB–ISBA) are used as part of our computational study, with the objective to simulate the UHI under different combinations of built-up surfaces and vegetation covers. We describe the models in more detail in Section 2.

As a consequence of the UHI, many studies worldwide indicate that buildings in urban areas consume more energy for cooling but less energy for heating than the rural counterparts [12–15]. In London, one study [12] showed that buildings in rural environments demanded 16% less cooling energy than similar buildings in urban environments during a typical hot week. Another study [15] showed that compared with rural buildings urban ones consumed 25% more energy for cooling while they used 22% less energy for heating. In Tokyo, a study [14] indicated that mitigating the UHI magnitude by merely 0.2 to 1.2 °C in the summer would reduce cooling energy consumption by 4% to 40%. Thus, it has been noticed that using standardized (mostly rural) weather data for the design of a building and its building systems is not adequate if it is situated in a dense urban environment.

Building energy simulation is extensively used with two major purposes: (1) predicting the magnitude of operational energy use and corresponding greenhouse gas emissions, and (2) predicting the savings from novel architectural design or energy-efficiency technologies over a given baseline. In either case appropriate weather data is crucial to the accuracy of the computational outcomes. Typical meteorological years (TMY) are widely used, which

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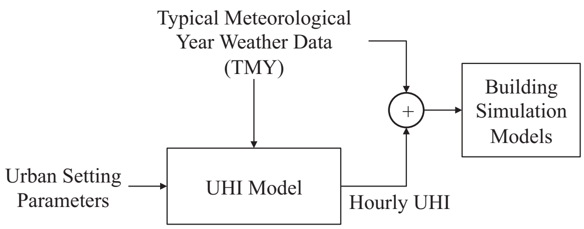

Fig. 1. Modification of TMY data by modeled hourly UHI magnitudes.

is derived from weather data collected in meteorological stations. Because the data collection station is usually located in rural environments, simulation results of urban buildings based on the TMYs can considerably deviate from the actual ones. There are many reasons why this performance gap occurs, but in this paper we aim to single out the cause of the UHI effect, all other things being equal. Building simulation studies [16] have revealed that energy predictions using TMY data without taking the UHI into account remarkably underestimate both energy consumption and peak power for cooling. To overcome this, one study [17] proposed to modify the TMY weather file to account for the UHI effect. They found that using the modified TMY weather increased overall energy consumption of air-conditioning by over 10% in both office buildings and residential apartments.

Previous studies worldwide indicated that the UHI was a significant factor to both building cooling and heating energy consumption and the magnitude of its impact depended on a variety of factors from both climate conditions and building characteristics. Most of the results were reported through cases at the individual building scale in a given climate location. Thus, there is limited work that explores the UHI effect across broader geographical areas that cover different climates such as the United States nationwide. Although it is well known that the UHI leads to an increase in cooling cost and a decrease in heating cost, it needs more work to understand when the effect is most significant if the total energy cost is of one's primary interest. Additionally, the magnitude of the UHI has a certain spatial variation in metropolitan areas so it is worthy to explore the UHI effect in locations of different urban densities. More importantly, we have seen few studies that scrutinized the impact of the UHI on the second use of building simulation, i.e., to predict energy savings as the result of an intervention, such as the planned deployment of energy efficiency technologies. For example, ASHRAE's new building energy code 90.1-2010 targets a decrease in energy consumption by 30% in comparison with the baseline as defined by ASHRAE, 90.1-2004. The question arises then whether proof of obtaining this saving percentage requires the inclusion of UHI in the simulation. Another instance is in comparing energy improvements from retrofit alternatives. This type of application may not need accurate predictions of the magnitudes of absolute energy consumption, but needs to accurately identify the relative change in energy use after improvements to the building.

The objective of this paper is to quantify the UHI effect on two types of energy application studies across 15 climate zones in the United States. The rest of this paper is organized as follows. Section 2 presents the methodology. Section 3 presents the results. Finally, we summarize and conclude in Section 4.

2. Methodology

Fig. 1 shows the procedure of this study. We use the TEB–ISBA model to generate hourly UHI magnitudes in various urban environments, which are characterized by urban setting parameters. The results lead to a modification of the rural TMY weather data used in the building simulation model, in our study EnergyPlus, to derive building cooling and heating energy consumption.

Table 1
Climate zones and representative cities in the U.S.

Climate zones	Representative cities
1A: very hot, humid	Miami, Florida
2A: hot, humid	Houston, Texas
2B: hot, dry	Phoenix, Arizona
3A: warm, humid	Memphis, Tennessee
3B: warm, dry	El Paso, Texas
3C: warm, marine	San Francisco, California
4A: mixed, humid	Baltimore, Maryland
4B: mixed, dry	Albuquerque, New Mexico
4C: mixed, marine	Salem, Oregon
5A: cool, humid	Chicago, Illinois
5B: cool, dry	Boise, Idaho
6A: cold, humid	Burlington, Vermont
6B: cold, dry	Helena, Montana
7: very cold	Duluth, Minnesota
8: subarctic	Fairbanks, Alaska

2.1. Modeled weather files

This study models the UHI in various urban settings, with the aim to generate modified TMY weather files that reflect the UHI effect in any urban setting.

2.1.1. Climate zones

The entire United States is divided into eight temperature-oriented climate zones based on heating degree days (HDDs) and cooling degree days (CDDs) used by the International Energy Conservation Code and ASHRAE. Each zone can also be further divided into three moisture-oriented regions. 15 specific cities in the U.S. listed in Table 1 are selected as representatives of different climate zones based on ASHRAE Standard 90.1.

2.1.2. Urban parameter settings

Another issue of UHI modeling pertains to a representation of urban density. To that end we use an urban parameterization by which complex three-dimensional urban surroundings are approximated by parameterized regular urban layouts. Fig. 2 shows the urban parameterization schema in which all buildings are identical and homogeneously distributed over a regular grid with varying urban density. This parameterization enables a three-dimensional urban layout to be characterized by a two-dimensional urban canyon with four geometric parameters: (1) canyon height H, (2) canyon aspect ratio H/W, (3) coverage of vegetation α_{veg}, and (4) coverage of buildings α_{bld}. Even though this urban parameterization largely decreases the complexity of urban form, it can still capture the three-dimensional characteristics necessary for the UHI effect [18]. In fact, the urban canyon is the mostly used representation for urban-scale climate modeling, which can yield a spatial resolution of a few hundred meters [7,19]. For the urban parameter settings, we utilize a dataset [20] that includes urban topologies and building physical characteristics across 33 regions in the world and subdivides urban areas into four categories according to urban density as follows: tall-building districts, and high-, medium-, and low-density cities. In total, this dataset consists of 125 instances.

In ASHRAE fundamentals [21], inland built environments are categorized into three terrain types (i.e., large city centers, urban and suburban areas, open country) to initially account for the variations of wind speed in different sites. Since the building simulation community is familiar with this categorization, this paper intends to analyze whether this categorization is significant to account for the UHI effect within metropolitan regions. Compared with the four categorizations in the dataset, we find that the tall building

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