



Global sensitivity analysis of an urban microclimate system under uncertainty: Design and case study



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ABSTRACT

Over the last decade, significant efforts have been made to develop sophisticated physics-based urban simulators, given the undeniable need for sustainable-city initiatives to consider the potential impacts of climate change and massive urban growth. Nevertheless, even as a growing number of researchers have expanded their scope to the urban realm, there remain many problems resulting from the complexity of the urban microclimate, such as the Urban Heat Island (UHI) effect. This study is initiated with the intention to account for uncertainty in developing more coherent and integrated strategies concerning the energy and environmental issues in an urban system. The analysis builds upon the previously reported and updated Urban Weather Generator (UWG) to present a deep look into an existing urban microclimate system in Abu Dhabi (UAE). The case-specific baseline information is generated for the UWG and a global regression-based sensitivity analysis using the Monte Carlo technique is performed. Based on 30 candidate inputs covering the meteorological factors, urban characteristics, vegetation variables, and building systems, the uncertainty analysis indicates that the UWG is a fairly robust simulator to approximate the urban thermal behavior in downtown Abu Dhabi for different seasons. The identified significant factors will be the subject of future research to gain a higher resolution of critical urban simulation inputs, thereby providing more informed domain knowledge of the underlying mechanisms driving the microclimatic effect on the energy and environmental performances.

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1. Introduction

Global concern about depletion of non-renewable energy sources and anthropogenic climate change has become increasingly prevalent in recent years [1]. Over the next decade, the United Nations predicts that we need to plan and build new homes for billions of city-dwellers worldwide [2]. This unprecedentedly continuous urbanism, if shaped merely by informal or inadequate policy measures, can potentially lead to worrisome consequences for the built environment, the economy at national or international level, and the life quality of billions of people. In response to the urgency of acting to mitigate these challenges, many governmental administrations have prioritized, among other actions, decarbonizing the energy system and reducing GHG emissions at local and global scales in order to achieve a clean-energy economy [3]. While

the magnitude of GHG emissions varies among different cities, the building-related emission is always a key contributor [1]. Urban systems need to be better understood to effectively tackle these problems in existing or new neighborhoods, not only which current sectors may cause the environmental issues but also what future changes may best reduce the energy consumption.

As cities develop, the urban area is characterized by an increase in air temperature compared to the surrounding rural area, a phenomenon called the Urban Heat Island (UHI) effect [4]. Regardless of the inherent uncertainties in predicting future climate and weather patterns, the UHI has been measured and documented throughout the world, including in Washington, DC, New York [5], Vancouver, Marseille [6], London [7], Abu Dhabi [8], etc. In particular, Crawley [9] studied the UHI effect on an office building and suggested that the corresponding energy consumption could be modified between 5% (increase in summer) and 10% (decrease in winter). In order to meet the increasing peak demand in summer, more electricity generation by power plants will lead to higher emissions of VOCs, suspended particulates, and CO₂, as well as to aggravation of global warming and formation of harmful smog

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Nomenclature

A_f	lateral heat exchange area (m^2)
c_p	specific heat of air at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$)
c_v	specific heat of air at constant volume ($\text{J kg}^{-1} \text{K}^{-1}$)
h_{bld}	average building height (m)
H_u	sensible heat flux at the surface of the control volume (W)
$K_{r,dir}/K_{w,dir}$	fraction of the direct solar radiation received by the road/wall
$Q_{LW,down}$	down-welling infrared radiation specified in the EPW file (W)
$Q_{LW,road}/Q_{LW,roof}/Q_{LW,wall}$	long-wavelength heat exchange between the atmosphere and the road/roof/wall (W)
R^2	coefficient of determination
r_{aspect}	aspect ratio
r_{shade}	fraction of the road shaded by trees
$S_{hor,dir}$	direct solar radiation on a horizontal surface (W m^{-2})
$S_{norm,dir}$	direct normal solar radiation (W m^{-2})
$T_{road}/T_{roof}/T_{wall}$	surface temperature of the road/roof/wall (K)
u_{ref}	reference air velocity (m s^{-1})
V_{CV}	control volume (m^3)
VF_{i-j}	view factor from i to j
w_r	average road width (m)

Greek symbol

$\epsilon_{road}/\epsilon_{roof}/\epsilon_{wall}$	emissivity of the road/roof/wall
θ_o	critical canyon orientation
θ_{ref}	reference potential temperature outside the control volume (K)
θ_u	average potential temperature of the control volume (K)

λ	solar zenith angle
ρ	air density (kg m^{-3})
σ	Stefan-Boltzmann constant ($\text{W m}^{-2} \text{K}^{-4}$)

Abbreviation

AM	averaged model
BTEX	Benzene, Toluene, Ethylbenzene, and m-, p-, o-Xylenes
CFD	computational fluid dynamics
CO ₂	carbon dioxide
COP	coefficient of performance
DM	detailed model
DOE	Department of Energy
EPW	EnergyPlus Weather
GHG	greenhouse gas
HVAC	heating, ventilation, and air conditioning
IR	infrared radiation
LW	long-wavelength
RMSE	root-mean-square error
RSM	rural station model
SA	sensitivity analysis
SHGC	solar heat gain coefficient
SRC	standardized regression coefficient
SRRC	standardized rank regression coefficient
TEB	Town Energy Balance
UBL	urban boundary layer
UCL	urban canopy layer
UCM	urban canopy model
UHI	Urban Heat Island
UWG	Urban Weather Generator
VDM	vertical diffusion model
VOC	volatile organic compound

[10]. There is thus a pressing need for simulation tools to quantify the actual risks caused by the interactions between building thermal behaviors and urban climate changes, as well as to help building designers, facility managers, and policy makers produce informed decisions for the future.

Currently, there have been great efforts to incorporate the UHI effect into energy and environmental simulations, including mesoscale computational fluid dynamics (CFD) models [11,12], analytical and empirical algorithms [9], and physics-based urban canopy models [13–15]. As different models are developed for different uses, different spatial scales need to be clearly defined and different urban models need to be elaborated in terms of their capabilities to predict corresponding energy and environmental conditions. Although the mesoscale models are regarded as state-of-the-art in atmospheric weather predictions [16], their applications still remain limited due to high computational cost and lack of boundary condition data.

As an alternative, Bueno et al. [17] developed the Urban Weather Generator (UWG) to quickly estimate the UHI effect in the urban canopy layer and produce neighborhood-specific weather files, using the meteorological data measured at weather stations located in an open area outside the city. The UWG can also be considered as an off-line bottom-up model to evaluate the building energy consumption at the neighborhood-to-city scale. It has been validated in Toulouse (France), Basel (Switzerland) [17], Singapore [18], and Boston (USA) [19]. With continuous improvements and updates [20], the UWG has the potential to be a promising urban

microclimate simulation engine that shows satisfactory performance with acceptable computational cost.

However, despite these positive developments, urban simulation practice has been applied only to a fraction of new construction and urban morphologies. One recognized obstacle is the discrepancies, sometimes significant, between simulation-predicted and actual measured values [21]. The reason may lie in the fact that a single simulation only evaluates a single point in the parameter space without taking uncertainties into account. Consequently, building designers or city planners often perform manual parametric simulations varying one factor at a time, which is referred to as the local analysis. This is why some cynics would say that “models can be made to conclude anything provided that suitable assumptions are fed into them” [22]. As many inputs in the model are associated with some degree of uncertainty, due to changeable conditions or lack of knowledge about the exact value, sensitivity analysis of model parameters plays an important role in the simulation process in order to achieve valuable information and increase model confidence.

Sensitivity analysis (SA), presented by Saltelli et al. [23], is a measure of the effect of an input on the output. In general, given the input uncertainties, one is able to assess the uncertainty in the model response (uncertainty analysis), and eventually to identify the inputs that contribute most to that uncertainty (sensitivity analysis). Thus, SA can be of tremendous help in subsequent model analysis, including simulation-based optimization [24], meta-model analysis [25], automatic model calibration [26], etc. The SA

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