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Estimation of urban temperature and humidity using a lumped parameter model coupled with an EnergyPlus model

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ABSTRACT

In this paper, we describe a lumped thermal parameter model coupled with an EnergyPlus model used for estimating temperature and specific humidity in the near-surface urban environment. Estimations made by the model are compared to measurements obtained from data loggers installed in an urban canyon of Masdar Institute (Abu Dhabi). Based on these comparisons, we first evaluate the most likely ratios of heat released into the urban canyon by a building air handling unit and the wind tower that produces adiabatically cooled air. Next, we analyze three specific case studies to obtain a local estimate of the accuracy that is reached by the coupled scheme. To estimate its global precision, we perform a sensitivity and Monte-Carlo analysis over the most likely ratios of heat emitted by the air handling unit and the wind tower. Although validation in a dense downtown is still lacking and will be undertaken in the future, this study suggests that urban temperature and humidity can be estimated with an acceptable accuracy under moderate waste heat releases and anthropogenic heat gains.

1. Introduction

The Middle-East is well-known for its hot and humid climate. While a number of studies report interesting analyses of temperature and humidity measured within the urban canopy layer of European cities [1,2], Middle Eastern cities have seldom been investigated. For instance, the experiment by Charabi and Bakhit [3] highlights certain properties of the Urban Heat Island (UHI) effect measured in Muscat (Oman). The UHI phenomenon was also analyzed in Kuwait City (Kuwait) by Nasrallah et al. [4]. Comparing the UHI effect reported in several arid North American locations to the one measured in Kuwait City, they discovered that the position of the city, the absence of dense vegetation, and the height of buildings could enable us to mitigate the UHI effect in hot and arid environment.

Past studies have often focus on the experimental analysis of urban temperature, rarely giving in-depth consideration of humidity. Among the few studies providing equal attention to humidity, the research led by Jáuregui and Tejeda [5] showed the average diurnal cycle of specific humidity for rural, suburban, and urban areas of Mexico City. Nevertheless, their analysis is purely based on measurements and does not provide explicit guidance that can be used for including an estimation of humidity in an urban canopy model.

Urban canopy models were developed to improve the representation of urban areas in meteorological models. Several urban canopy models now in widespread use include a building energy model to more accurately represent the impact of building thermal processes on the ambient environment in the Urban Canopy Layer (UCL), the lowest layer of the Urban Boundary Layer (UBL) [6–8]. Urban canopy models can be run as stand-alone programs or, alternatively, driven by a meteorological simulation. In either mode, they are used mainly by the urban climate research community, which largely focuses on the characteristics of the urban environment and not the performance of buildings.

Building energy models allow us to approximate the indoor energy consumption in response to outdoor conditions. Building energy models are widely employed in isolated mode by consulting engineers working with architects and building owners. After defining a suitable basic design, analysts try to evaluate the efficiency of different design options or retrofitting strategies [9,10]. The main drawback in using building energy models in a stand-alone mode is that the UHI phenomenon is neglected.

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α_x	albedo of surface x, –
δ_{ex}	air handling unit exhaust heat ratio, – or %
δ_{wt}	wind tower heat ratio, – or %
ε	emissivity, –
η_q	latent heat recovery effectiveness, – or %
η_T	sensible heat recovery effectiveness, – or %
ρ_x	density of x, kg/m^3
ϕ_x	relative humidity of x, – or %
ω_x	water content of x, m^3/m^3
A_x	area of x, m^2
C_x	sensible heat capacitance of x, J/K
$\widetilde{C}_x$	latent heat capacitance of x, J
c_x	specific heat of x, J/(kg K)
d_x	depth of x, m
H_x	scheduled dependent value of x- or %
I_x	water provided by irrigation on x, kg/(m^2 s)
k	U-value, W/(m^2 K)
L_x	latent heat of vaporization of x, J/kg
l_x	length of x, m
$\dot{m}_x$	mass flow rate of x, kg/s
$n(.)$	cardinality, –
Q_x	sensible heat of x, W
$\widetilde{Q}_x$	latent heat of x, W
P_x	precipitation on x, kg/(m^2 s)
p_x	pressure on x, Pa
q_x	specific humidity of x, kg/kg
q_{sat}	specific humidity at saturation, kg/kg
$R_{x,y}$	sensible heat resistance between x and y, (m^2 K)/W
$\widetilde{R}_{x,y}$	latent heat resistance between x and y, m^2/W
$r_{x,y}$	aerodynamic resistance between x and y, s/m
T_x	temperature of x, $^\circ C$ or K
$\bar{T}_x$	average temperature of x, $^\circ C$ or K
t	time, s
V_x	volume of x, m^3
w_x	width of x, m
z_x	height of x, m
Subscripts	
b	building
ex	exhaust air from the air handling unit
f	facade
g	ground (soil)
HL	HOBO logger
I	irrigation system
s	street
sky	sky
r	road
ubl	urban boundary layer
urb	urban canyon
veg	vegetation
wa	wall
wi	window
wt	wind tower

Before developing a building energy model for Town Energy Balance (TEB), Bueno et al. [11] coupled TEB to an EnergyPlus[1] model to exploit the advantages and overcome the drawbacks of both. To develop a simulation scheme of complexity appropriate for building professionals and engineers, Bueno proposed a Resistance and Capacitance (RC) representation of a building energy model and the coupled adjacent atmosphere [13]. In the Urban Weather Generator (UWG), he extended the lumped parameter approach to energy balances to include a rural reference weather station and the UBL above the UCL [14]. In this way, the UWG maps a reference weather file to estimated conditions at an urban neighborhood. While the UWG itself necessarily couples the building to the UCL, the use of the UWG is decoupled from the building energy model. This requires the user to provide to the UWG the same key building parameters to be used in the building energy model.

This paper proposes a new method that leverages the capabilities of detailed building performance simulations but retains the direct coupling of that simulation with a representation of the urban canopy model, for which the new scheme uses a lumped thermal parameter model. The fact of coupling an urban canopy model with an EnergyPlus model ordinarily adds complexity in terms of software programming. In order to solve this issue, we decided to use the Building Controls Virtual Test Bed (BCVTB) [15]. This technology allowed us to implement a Matlab thread that executes the lumped thermal parameter model and communicates with the EnergyPlus external interface. While building surface temperatures and convective heat transfer coefficients, waste heat emissions, and air handling unit exhausts approximated from the EnergyPlus model were iteratively employed by the lumped thermal parameter model, the latter was mainly in charge of computing dry-bulb temperature, wet-bulb temperature, and wind speed in the UCL to improve the accuracy of exterior surface conditions considered by the EnergyPlus model.

The coupled scheme can be used in several applications. First, a model of urban temperature is required to estimate the building cooling energy penalty due to the UHI effect. The model also allows us to develop and test different approaches to reducing the UHI effect. Finally, in order to optimize city-wide demand side management interventions, what-if retrofitting scenarios can easily be generated and evaluated by changing the parameters of the coupled scheme model. This could become an effective decision support tool for policy makers. Before being employed in all these applications, the reliability of the coupled scheme in terms of urban temperature and specific humidity estimations must be proved.

2. Coupled scheme

To estimate dry-bulb temperature and specific humidity in the UCL of Masdar Institute, we coupled a lumped thermal parameter model with an EnergyPlus model. First, the EnergyPlus model calculates sensible and latent heat fluxes coming from air handling unit exhausts, and waste heat releases. The building energy model also computes wall and window surface temperature. Next, all these values are employed by the lumped thermal parameter model to evaluate the urban canyon temperature, specific humidity, and pressure. The same parameters are also computed for road and soil surfaces. In addition to the information assessed from the EnergyPlus model, the lumped thermal parameter model requires values for meteorological parameters in the UBL: dry-bulb temperature, precipitation, pressure, relative humidity, and wind speed. For this purpose, an EnergyPlus weather file is created based on actual hourly measurements we obtained from the weather station located at the top of the Masdar wind tower. Finally, the dry-bulb temperature, wet-bulb temperature, and wind speed calculated from the lumped thermal parameter model are used by the EnergyPlus model as outdoor boundary conditions of walls and windows.

Fig. 1 shows the urban topography we considered for designing the coupled scheme. Like Bueno et al. [11], the building defined via the EnergyPlus model (also called the reference building) is assumed to be surrounded by buildings of equal height z_b, length

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[1] EnergyPlus is a detailed dynamic building energy simulation engine (cf. Crawley et al. [12]).