Urban Weather Generator: Physics-Based Microclimate Simulation for Performance-Oriented Urban Planning

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Abstract

Deciphering the urban microclimate is a long-standing research topic which has been lately consolidated as a major interest in the built energy and environment community. Research investigates at a fast pace the physical laws and simulation techniques to better understand the urban built environment and the ways of improving it. The snap increase in the amount and breadth has come at a price of little systematization and appreciation of knowledge. With that in mind, this chapter provides a gentle overview of the Urban Weather Generator (UWG), a physics-based microclimate simulation paradigm developed and maintained over the past decade to quantify the energy interactions between buildings and the urban climate. This chapter favours a consistent and progressive introduction of the main concepts and architectural treatments in the UWG over an exposition of the most related literature. Knowledge of changes in the urban environment and their effect on building energy performances can potentially support a better decision-making framework for civil engineering systems, particularly at the planning and design stage. We present the initial motivations, theoretical models, case studies, and practical achievements of the UWG that have thus far been made as well as the many challenges that await us in this nascent field. This chapter aims to give an insight into the importance of considering the urban microclimate as well as to stimulate further research.

Keywords: Urban Weather Generator · Urban microclimate · Physics-based simulation · Outdoor thermal environment · Urban heat island

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Nomenclature

A	area, m^2
A_f	lateral heat exchange area, m^2
C	capacitance / conductance, W s K^{-1} / W m^{-2} K^{-1}
C_k	model parameter related to the diffusion coefficient
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
c_v	specific heat at constant volume, J kg^{-1} K^{-1}
d	thickness, m
E	turbulent kinetic energy, m^2 s^{-2}
g	gravity acceleration, m s^{-2}
h	heat transfer coefficient, W m^{-2} K^{-1}
H_{rur}	rural sensible heat flux, W m^{-2}
H_{urb}	urban sensible heat flux, W m^{-2}
K_d	diffusion coefficient, m^2 s^{-1}
l_k	length scale, m
Q	heat flux, W m^{-2}
Q_{surf}	sum of net-radiation, sensible, and latent heat fluxes at the surface, W m^{-2}
R	resistance, K W^{-1}
t	time, s
T	temperature, K
T_{deep}	annually average ambient air temperature of the site, K
U	window U-factor, W m^{-2} K^{-1}
u_{circ}	circulation velocity, m s^{-1}
u_{ex}	exchange velocity, m s^{-1}
u_{ref}	reference air velocity, m s^{-1}
V	volume, m^3
$\dot{V}$	volume flowrate, m^3 s^{-1}
z	vertical space component, m
z_i	boundary layer height, m
z_r	blending height, m
z_{ref}	reference height, m
θ	potential temperature, K
θ_{ref}	reference potential temperature outside the control volume, K
ρ	density, kg m^{-3}
$(\rho c)_l$	volumetric heat capacity of layer l, J m^{-3} K^{-1}

Abbreviation

AEC	architecture, engineering, and construction
API	application programming interface
CHTC	convective heat transfer coefficient
DOE	Department of Energy
EPW	EnergyPlus Weather
HVAC	heating, ventilation, and air conditioning
MIT	Massachusetts Institute of Technology
RC	resistance-capacitance
RSM	Rural Station Model
TEB	Town Energy Balance
UBLM	Urban Boundary Layer Model
UCL/M	Urban Canopy Layer / Model
UC-BEM	Urban Canopy and Building Energy Model
UHI	Urban Heat Island
UWG	Urban Weather Generator
VCWG	Vertical City Weather Generator
VDM	Vertical Diffusion Model

1 Introduction: A dance between art and science

Climate change is now pervasive in scientific, social, and political communities. There is clearly a detectable global warming trend in the long-term climate records. Vast resources are being processed, transported, and consumed in order to accommodate humans in our modern life. As a consequence, exhaustion of raw materials and transformation of chemical substances have generated an increasing level of hazardous residues that may pollute air, water, and soil.

With over half of the global population residing in cities now and an arguably growing projection of urban settlements in the near future, the scale of this resource demand is profound and the subsequent problems are unprecedentedly intensified in every aspect. Motivated by these challenges, urban sustainability holds great attention to tackle energy and environmental issues. Buildings, which incorporate most human activities in the urban areas, are identified as having the highest economic mitigation potential of any other energy sector. Simulation models play an essential role in the decision-making process for performance-oriented building design and urban planning.

Mathematical models are central to high-level human endeavor to formally abstract, understand, and change the world. On the other hand, simulation models are low-level computer-aided specializations to numerically implement such mathematical rigor, with various applications in physical observations, engineering systems, social sciences, etc. As we delve into the literature, we have found a rich family of simulation paradigms for energy systems at the building and urban scale, ranging from physics-based computational approximation to data-driven black-box generalization. Thanks to a few ambitious initiatives, some software progress has been made to assist designers, planners, and engineers in improving the sustainability of their districts and cities. Recent networking efforts have also produced a roadmap toward a broad introduction of simulation-based domain, or may have just opened a Pandora's box in the AEC industry.

These developments are still in their infancy, as buildings and cities are extremely complex systems that require a need for interdisciplinary research in simulation studies. One particular issue is the Urban Heat Island (UHI) effect [Oke 1973], which states that the climate pattern in urban areas is different from that in rural areas due mainly to distinct built ecosystems. The UHI effect modifies the thermal response of buildings, especially naturally ventilated buildings, and may intensify the peak energy demand in summer. At the same time, the energy performance of buildings can also have an impact on the outdoor urban microclimate, mainly through waste heat emissions. Regardless of how successfully the UHI effect has been observed throughout the world, many people still fail to incorporate it into their simulation-based analyses of energy use or thermal comfort, since the weather data used in practice comes from the station measurements at an open site (e.g., airport) that do not accurately represent the local urban environment.

On-going developments in measurement and modeling of the UHI are adapting localized environmental data for simulation use. It is possible to adopt geospatially-aware regional models to generate site-specific weather sequences by driving them with the observations from nearby stations. In particular, mesoscale models are considered state-of-the-art in atmospheric weather prediction and are used for either research or practice [Grimmond et al. 2010]. Popular simulation tools include computational fluid dynamics (CFD), Weather Research and Forecasting (WRF), ENVI-met, etc. However, due to the high computational cost, their feasibility is usually limited considering the time-constrained nature of real engineering applications. In addition, the accuracy of these models in conjunction with a spatially fine mesh depends strongly on the boundary conditions, for which detailed information is not easily available in common practice. Despite some promising evidence in ad hoc studies, a painfully high computational cost is usually paid for a gain in accuracy that cannot be guaranteed.

Perhaps the most interesting irony we should point out is that, during a design or planning stage, whenever a performance verification uses simulation to approximate the real behavior of a system, one has to recognize that no system ever behaves as its model (which is de facto an idealization) predicts [Augenbroe 2012]. Seeking the "best" simulation might actually be counterproductive since it would often lead to over-engineered models with time-consuming computation runs. Surprisingly, the need for sophisticated simulation seems to be less than what is usually assumed, owing to the presence of system uncertainties, the lack of required information, or the preference of decision makers. A reasonably impressive principle of simulation in performance-oriented design for civil projects is, therefore, to promptly provide a variety of parametric calculations and rational feedback when an advanced simulation model cannot offer a more accurate answer.

With that in mind, Bueno [2012] proposed the Urban Weather Generator (UWG), a physics-based simulation paradigm, to quantify the energy interactions between buildings and the urban climate. Since then, the UWG has been progressively developed and maintained at the Massachusetts Institute of Technology (MIT), along with a few intergovernmental and commercial collaborations. The UWG is now a standalone program to quickly generate localized microclimate sequences, which could be readily used as the urban weather data, based on rural meteorological information in public weather files and site-specific urban characteristics. At the same time, it has the potential to evaluate the building energy consumption at a neighborhood or city scale, specifically accounting for the UHI effect. A typical run of annual calculation with an acceptable performance can be currently finished in *minutes*, given normal computational power. The UWG enjoys the marriage of building physics and urban climatology to enable a fresh way to express and explore a wide range of energy and environmental studies in an urban context – a bridge between abstraction and specialization, a dialogue between designer and engineer, as well as a dance between art and science.

It is time to present what we have learned and achieved over the past decade. The purpose of this chapter is to explain some basic treatments that lead to the foundation of UWG, and specifically, to cover how the underlying models behave with customized variations. A second purpose is to direct the practitioners to some of the recent open-source code and software tools that have come out of the UWG, as well as some of the historically relevant case studies that were used to validate the UWG mechanism. We consider this chapter as a formal statement to illustrate what the UWG is capable of at present and to suggest some possible improvements in the future.

This chapter is intended to be accessible to a general audience; that is, it is intended for researchers, engineers, designers, and hopefully the people outside of our field. Therefore, while mathematical and physical arguments will be used, the goal is for the theoretical treatments to be intuitive and neat rather than technical and rigorous. Sometimes, specific details may be suppressed for general readability; interested reader may further look into the original documents and/or links that are referred. We expect the reader in both academia and industry can benefit from this chapter.

2 Scientific modeling: The UWG innovation

We begin by reviewing the core of the UWG mechanism. In general, a complex physical system consists of multiple functional components, whose evolution can be characterized by differential and/or discrete equations in time and space domains. Some linear and nonlinear treatments are then applied to different equations based on specific physical laws. In our case, modeling the urban microclimate is even more complicated due to the diverse time and space scales involved in meteorological study. The space scale, for example, can vary from a few meters (e.g., building)

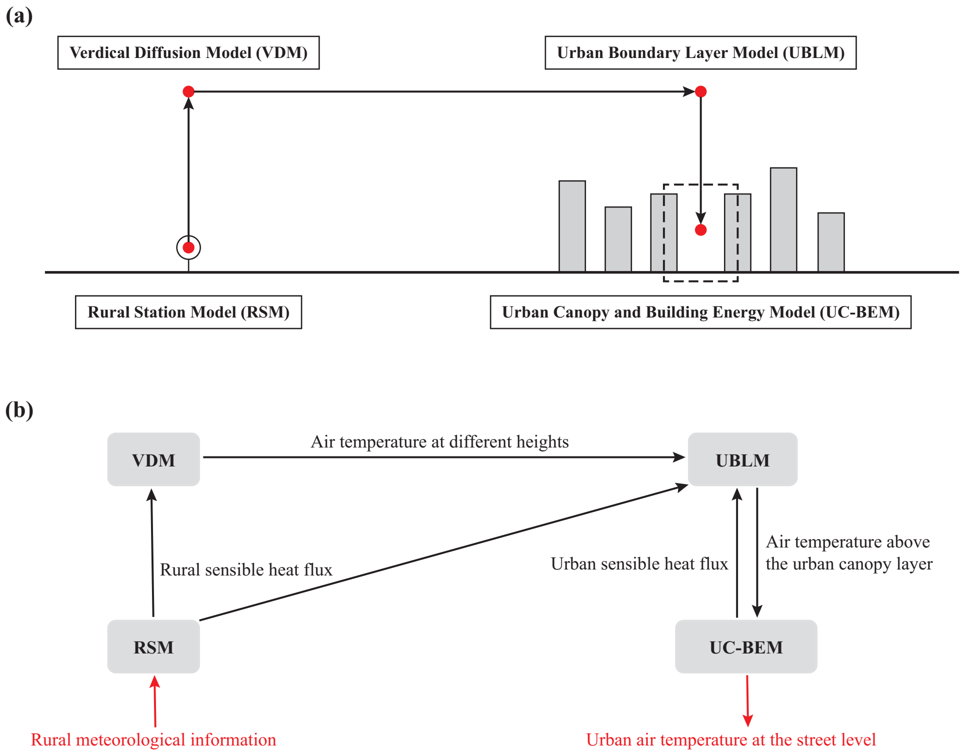

Figure 1: Diagram of the basic UWG scheme. **(a)** Four coupled models in the UWG; **(b)** Information exchanged among different models in the UWG.

to several kilometers (e.g., neighborhood). It is hardly possible to resolve all the scales online with one single model given the available computational resources in practice.

To make things efficient, one universal recipe is to introduce separate models with some synchronization between them to exchange boundary information. Accordingly, the system would no longer be differentiable as a whole, and a higher level of abstraction is needed to fully leverage such modularity. Inspired by this idea, the exchange of mass, momentum, and energy in an urban context could then be implicitly specified by embedding an urban canopy layer and building energy model within a mesoscale atmospheric model. The boundary conditions of the mesoscale model may be further provided by some other models at a larger scale. Given great care for each model and their connectivity, such a synthesized simulation is able to generate sufficiently good energy and environmental data with reasonable computation time.

Following this rationale, the program architecture of UWG is mainly composed of four modules: the Rural Station Model (RSM), the Vertical Diffusion Model (VDM), the Urban Boundary Layer Model (UBLM), as well as the Urban Canopy and Building Energy Model (UC-BEM). Loosely speaking, the UWG creates the UHI profile by processing necessary information from a rural station to an urban site via these four modules, as shown in **Figure 1(a)**. The function interrelations and information exchange between each module are illustrated in **Figure 1(b)**. Related physical phenomena in one model can be implicitly forced using the information from the other model(s), so that all the models are coupled online in a coherent direction. We will now detail the essential treatments of each model within the UWG scheme.

2.1 Rural Station Model

The RSM [Bueno 2012; Bueno, Norford, et al. 2013b] is a rural canopy model that reads hourly meteorological data measured at the rural site and calculates rural sensible heat flux, which will

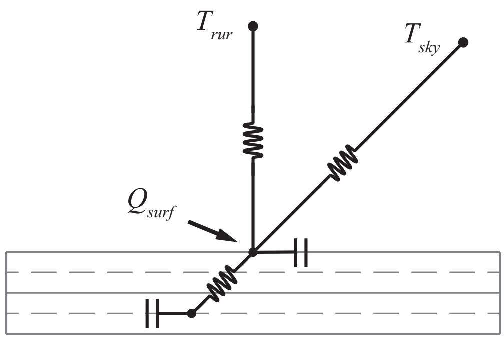

Figure 2: The heat transfer process as a thermal network of constant resistances and capacitances in the RSM (mainly from [Bueno, Norford, et al. 2013b]). A capacitance is associated with each temperature node. Nodes are connected via resistances. The surface heat flux is represented by an arrow.

then be used by the VDM and UBLM.

The RSM is based on an energy balance at the soil surface, where a transient heat diffusion equation is formulated using a thermal network of constant resistances and capacitances to represent the heat storage and release from the ground. As shown in **Figure 2**, by dividing the soil into discrete layers, the model solves a system of finite difference equations where:

for the first layer

$$d_1(\rho c)_1 \frac{\partial T_1}{\partial t} = C_{1,2}(T_2 - T_1) + Q_{surf} \,, \tag{1}$$

for each middle layer l

$$d_l(\rho c)_l \frac{\partial T_l}{\partial t} = C_{l,l+1}(T_{l+1} - T_l) + C_{l,l-1}(T_{l-1} - T_l) \,, \tag{2}$$

and for the deepest layer n

$$d_{n-1}(\rho c)_{n-1} \frac{\partial T_{n-1}}{\partial t} = C_{n-1,n}(T_{deep} - T_{n-1}) \,. \tag{3}$$

Surface sensible heat fluxes are calculated using a convective heat transfer coefficient (CHTC), which is a function of the air velocity above the canopy layer based on empirical correlation. Considering the accuracy requirement of UWG, latent heat fluxes due to the presence of vegetation (if any) are simply calculated as a prescribed fraction of the absorbed shortwave radiation.

2.2 Vertical Diffusion Model

The VDM [Bueno 2012; Bueno, Hidalgo, et al. 2013a] reads hourly meteorological data measured at the rural site and the rural sensible heat flux calculated by the RSM to derive vertical profiles of the air temperature above the rural area, which will then be used by the UBLM.

It is worth noting that the VDM and UBLM take the concept of potential temperature to evaluate the air temperatures at different heights without specifically including the pressure differences. The potential temperature (usually denoted as θ) of a parcel of fluid at a certain pressure is the temperature that the parcel would acquire if adiabatically brought to a standard reference pressure. As shown in **Figure 3**, the VDM calculates the vertical profiles of quasi-steady

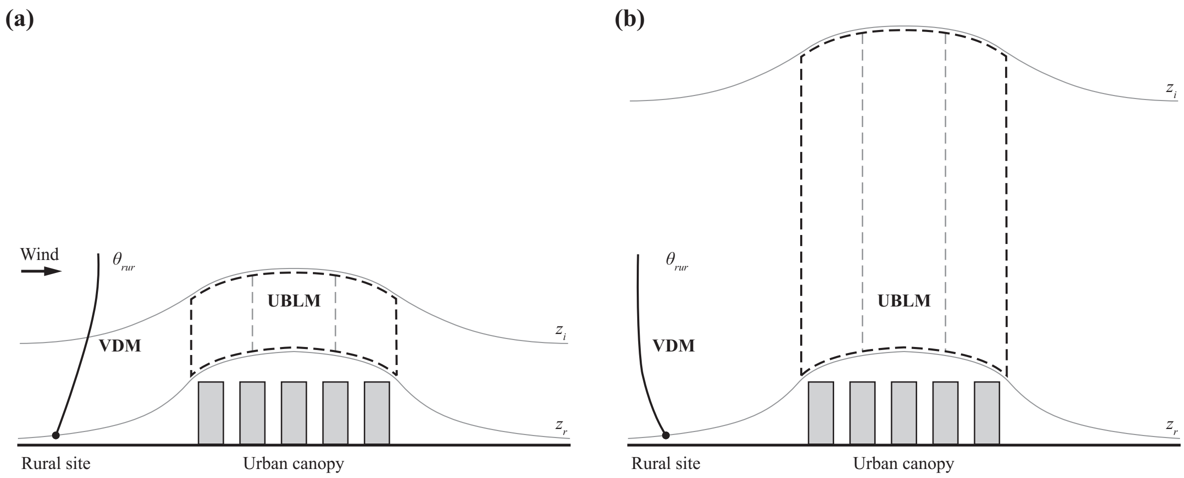

Figure 3: Representation of the physical domain of the VDM and UBLM (mainly from [Bueno, Hidalgo, et al. 2013a]). **(a)** Nighttime case with geostrophic wind; **(b)** Daytime case with urban breeze. Idealized vertical profiles of potential temperature are shown at rural sites (not at scale).

potential temperature based on a heat diffusion equation:

$$\frac{\partial \theta(z)}{\partial t} = -\frac{1}{\rho(z)}\frac{\partial}{\partial z}\left[\rho(z) K_d(z) \frac{\partial \theta(z)}{\partial z}\right], \tag{4}$$

where the lower bound is the temperature measured at the rural site $\theta(z_r)$, and the upper bound considers the fact that at a certain height (normally about 150–200 m) the profile of potential temperature is approximately uniform so that:

$$\left.\frac{\partial \theta}{\partial z}\right|_{z_{ref}} = 0\,. \tag{5}$$

The difficulty of implementing this diffusion equation in the VDM lies in the estimation of the diffusion coefficient (K_d), due mainly to the difficulty of predicting stable boundary layers. This coefficient is currently established as a function of the turbulent kinetic energy at each vertical level:

$$K_d = C_k l_k E^{1/2}\,, \tag{6}$$

where l_k and E are obtained by iteratively solving a set of coupled functions based on specific atmospheric conditions. A comprehensive description of the VDM is presented in the appendix of [Bueno 2012; Bueno, Hidalgo, et al. 2013a], and a new formulation for certain aerodynamic treatments has been updated in the appendix of [Bueno et al. 2014].

2.3 Urban Boundary Layer Model

The UBLM [Bueno 2012; Bueno, Hidalgo, et al. 2013a] calculates the air temperatures above the urban canopy layer using the meteorological information from the rural site, the vertical profiles of air temperature from the VDM, the rural sensible heat fluxes from the RSM, and the urban sensible heat fluxes from the UC-BEM.

The UBL is assumed as a region of well-mixed air and there is no significant heat exchange at the top of it. The model solves an energy balance for a control volume with imposed boundary conditions:

$$V_{ubl}\rho c_v \frac{d\theta_{ubl}}{dt} = H_{urb} + \int u_{ref}\rho c_p(\theta_{ref} - \theta_{ubl})dA_f \ , \tag{7}$$

where θ_{ref} is the potential temperature outside the city derived from the VDM. The term on the left-hand side stands for the thermal inertia of the control volume, and the second term on the right-hand side represents the advection effect. The control volume is bounded by the blending height (z_r), where the impacts of individual obstacles on the vertical domain become horizontally blended (e.g., at the rural site), and the boundary layer height (z_i). These heights are the inputs to be determined before simulation.

As one might expect from common atmospheric knowledge, the UBL is affected by changes in the urban surface and there is a diurnal variation at the mesoscale level [Stull 2012]. During nighttime, the longwave radiation exchange between the sky and the rural surface makes the boundary layer stratified and the nighttime UBL is mixed at a low height (usually 50–100 m). During daytime, on the other hand, the solar radiation heats the surface and the resulting atmospheric layer is well mixed up to a higher altitude (usually 700–1500 m). In trying to capture the diurnal pattern with a pragmatic concern of the computational cost, the UBLM differentiates between nighttime and daytime conditions,[1] as well as between the advection driven by geostrophic wind (forced effect) and by urban breeze circulation (buoyancy effect), as depicted by **Figure 3**.

We sketch some basic developments of the advection effect, for which the UBL is divided along the windward direction into various control volume sections. In presence of geostrophic wind, the reference velocity (u_{ref}) is set to the velocity outside the control volume, derived from a logarithmic vertical profile above the rural site via the VDM. The lateral area of heat exchange (A_f) considers the width of the urban area orthogonal to the wind direction. The temperature calculated for an upwind section in the UBL is used as the reference temperature for the subsequent downwind section. Under the circumstance of urban breeze, a characteristic circulation velocity is expressed as:

$$u_{circ} = \left[\frac{g(H_{urb} - H_{rur})z_i}{\rho c_p \theta_{ref}}\right]^{1/3} , \tag{8}$$

where H_{urb} and H_{rur} are obtained from calculations in the UC-BEM and RSM, respectively. The advection is assumed to be buoyancy-driven if the circulation velocity is greater than the wind velocity outside the city. Of course, the reference velocity will then become the circulation velocity in the energy balance equation, and the lateral area of heat exchange includes its entire city perimeter. The temperature of the UBL section at the periphery of the city is used as the reference temperature for the central area of the city. A clearer and more formal description on the UBLM can be followed via [Bueno 2012; Bueno, Hidalgo, et al. 2013a; Bueno et al. 2014].

Interestingly, there is a digression in the history of developing the UBLM that we should mention. After the original version [Bueno 2012; Bueno, Hidalgo, et al. 2013a] was built, Bueno et al. [2014] further included the radiation effects of water vapor and carbon dioxide in the energy balance of the UBL. However, this treatment was removed by Yang [2016] following an argument that the air is essentially transparent to the longwave radiation emitted from its boundary

[1] The eagle-eyed reader might note that, technically, solving only two different sets of equations for nighttime and daytime conditions would somewhat lead to discontinuities during the transition periods in the morning and evening, respectively. Although some small jumps in the temperature profile have been observed in our numerical trials, we treat this as a minor issue from the perspective of practical implementation. The discontinuities can be attenuated by the thermal inertia of the air body in the UBL and can be further reduced by adaptively shifting the transition times between day and night.

surfaces with a body size of around 1 km in altitude. This argument has been numerically validated using simulations, and hence, the UBLM returned back to its original version again. Given the available evidence, it is not very clear that the above discussion settles one way or another which version is better in terms of the accuracy requirement associated with the UWG. It might be practically reasonable to rely on the current UBLM, while further research is needed to refine such debate as we proceed in the future.

2.4 Urban Canopy and Building Energy Model

The UC-BEM [Bueno 2012; Bueno, Norford, et al. 2013b] calculates the urban weather information at the street level and estimates the building energy consumption at the neighborhood scale, using the meteorological data measured at the rural site, the air temperature above the urban canopy layer calculated by the UBLM, and the built characteristics of a specific urban site.

In order to be coupled with mesoscale atmospheric simulations online, the UC-BEM considers the well-established Town Energy Balance (TEB) scheme [Masson 2000] for modeling the urban canopy layer. The TEB maps the 3D urban geometry to a 2D canyon model consisting of a roof, a wall, and a road, with average site characteristics. It calculates the climate conditions within a neighborhood formed by identical urban configurations, where all the orientations are equally possible. Based on the energy balance, the urban canyon air is assumed as a well-mixed thermal zone that exchanges heat with the generic road, the generic wall, and the atmosphere above the urban canopy. The underlying goal is to robustly capture the basic physical machanisms that lead to the microclimate conditions in a specific urban site.

In decoding the physical machinery of the energy interactions within an urban environment, it would be remiss to not consider the anthropogenic heat fluxes, which generally include the heat released from building operation, traffic vehicles, and human metabolism [Sailor 2011]. The outdoor metabolic heat is disregarded in the current urban canopy model, as it is negligible compared to other heat sources. The traffic-generated heat, normally remains at 8–15 W/m^2 in many cities, is incorporated as a prescribed profile in the canyon energy balance [Yang 2016]. Finally, as the largest portion of the anthropogenic heat sources, the building operation is physically parameterized to allow a better representation by embedding a building energy model in the TEB scheme [Bueno, Pigeon, et al. 2012a]. This naturally justifies the foundation of the UC-BEM.

Abiding by this logic, it might be tempting to associate a detailed physics-based simulation (e.g., EnergyPlus) with the TEB scheme. However, this does not work well for our general purpose. The problem is that, for the many different building types in an urban site, it is computationally hard to include all the detailed simulations and to couple them with mesoscale atmospheric models online as one standalone program. Another reason lies in the fact that a sophisticated physics-based simulation requires more information than is usually available during a design or planning stage, and thus leads to an over-engineered method that exceeds the level of our expectation. In order to efficiently parameterize the essential energy nexus between buildings and the urban climate, the UC-BEM considers a thermal network of constant resistances and capacitances [Bueno, Norford, et al. 2012b], as shown in **Figure 4**.

The RC model retains major design parameters that are typically considered in building energy and urban climate studies. To simplify the estimation of various building types within a neighborhood, the commercial building reference data has been imported by Yang [2016] from the US DOE online database [Deru et al. 2011] into the UC-BEM. This allows us to express a rich family of abstract building types that make up the urban area, instead of modeling each individual building. Accordingly, the BEM simulates hourly load behaviors for every building type using either the default values provided by the database or the customized values provided by the user

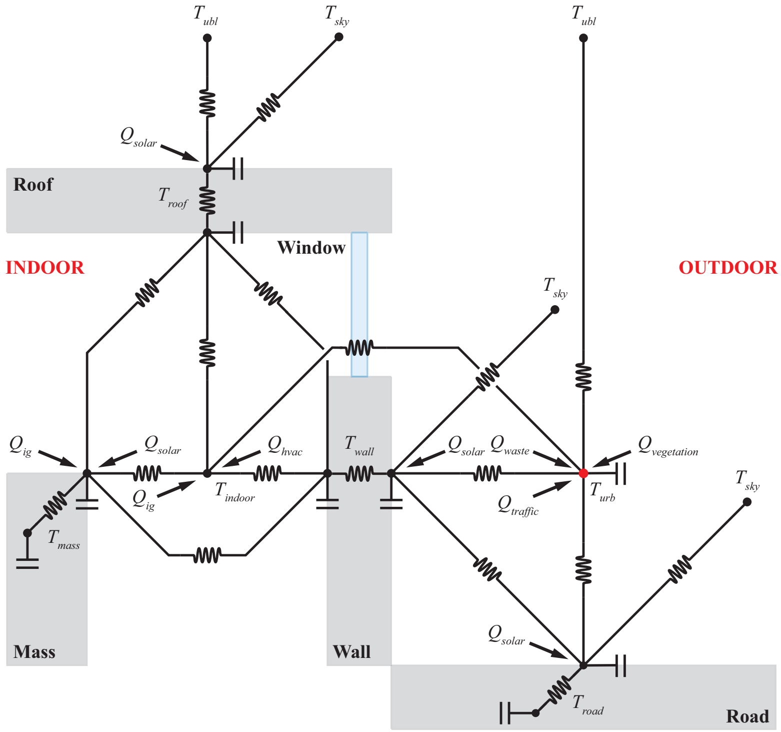

Figure 4: Representation of the UC-BEM based on a thermal network of constant resistances and capacitances (mainly from [Bueno, Norford, et al. 2012b] with revisions from [Yang 2016]). A capacitance is associated with each temperature node. Nodes are connected via resistances. The heat sources of each node are represented by arrows. The red node denotes the urban canyon air temperature. Subscript *ig* stands for internal heat gain.

(e.g., by updating the database) according to specific case. The goal is a better estimation of the building energy pattern at the urban scale and the temporal heat fluxes associated with the surrounding environment. The BEM considers a single building zone with a generic thermal mass and uses weighted average thermal parameters in the energy balance calculations to avoid additional computations for a trivial gain in accuracy. Many other assumptions and treatments have also been made to keep the model as simple as possible while maintaining the key features that represent the general system dynamics (mostly for the HVAC systems). Based on the energy conservation principle, the energy flow of each node is related to all the heat fluxes that interact with it. This can be described, without loss of generality, as:

$$C_j \frac{dT_j}{dt} = \sum_k \frac{1}{R_k}(T_k - T_j) + \sum Q_j \,, \tag{9}$$

where C_j and T_j are the capacitance and temperature of node j, R_k and T_k are the resistance and temperature of node k associated with node j, and Q_j is the heat flux acting on node j. A few iterations of the RC model are needed to calculate specific values.

To give a concrete idea of how the RC model actually works, we consider the urban canyon air temperature (i.e., the red node in **Figure 4**) as an example. In the current version, the urban canyon energy balance accounts for the heat fluxes from the wall, window, and road, the heat exchange between the canyon air and the above atmosphere simulated by the UBLM, the heat fluxes due to exfiltration from buildings, the anthroponegic heat sources (i.e., waste heat emissions and traffic-generated heat), as well as the heat flux from vegetation; so we have:

$$
\begin{aligned}
V_{can}\rho c_v \frac{dT_{urb}}{dt} &= \sum_i A^i_{wall} h^i_{wall}(T^i_{wall} - T_{urb}) + \sum_i A^i_{window} U^i_{window}(T^i_{indoor} - T_{urb}) \\
&+ A_{road} h_{road}(T_{road} - T_{urb}) + u_{ex}\rho c_p A_{road}(T_{ubl} - T_{urb}) \\
&+ \sum_i \dot{V}^i_{inf/vent}\rho c_p (T^i_{indoor} - T_{urb}) + \sum_i Q^i_{waste} + Q_{traffic} + Q_{vegetation}\,, \qquad (10)
\end{aligned}
$$

where i denotes the building type i that is considered in the UC-BEM.

Likewise, an analogous energy balance is solved for each node in **Figure 4** based on the formulation of Equation (9). The external surface temperatures of the wall, roof, and road are also calculated by solving a set of heat diffusion equations as described in the RSM (Equations (1)-(3)). Similarly, CHTC is applied to evaluate the surface sensible heat fluxes. As required by the UBLM, the urban sensible heat fluxes are expressed as the sum of the heat exchange between the canyon air and the UBL and the convective heat fluxes from the roof, including the portion of waste heat emissions from the outdoor HVAC equipment located there. Once the quasi-steady state is obtained for both indoor and outdoor environments, the building energy consumption will be re-calculated to incorporate the UHI effect.

Each component in the energy balance of the UC-BEM has been carefully characterized and updated in terms of its treatment. In retrospect, we have found that the UWG is indeed becoming more physically sound and more capable to handle increasingly detailed information. While it is hardly possible for us to detail all the formal arguments here to justify the underlying physical laws, we hope interested reader could look into their manifests following the work of [Bueno, Pigeon, et al. 2012a; Bueno, Norford, et al. 2012b; Bueno 2012; Bueno, Norford, et al. 2013b; Bueno et al. 2014; Yang 2016; Mao 2018], especially some of the appendices.

In more recent independent work, Moradi et al. [2019] resolved a multi-layer vertical profiles of the urban environment and included an advanced tree model within the UC-BEM, which yields another simulation paradigm called Vertical City Weather Generator (VCWG). Given the boundary conditions from the rural area, an urban VDM calculates the quasi-steady thermal quantities within each control volume, which is obtained by splitting the urban computational domain into multiple layers. Essentially, the urban VDM could be approximated by a set of one-dimensional time-averaged momentum equations in the cross- and along-canyon components, which will be coupled with other models within the VCWG. As a result, the VCWG extends the UWG to initiate parametric investigation of design options for the urban environment at some spatiotemporal variations within the canyon.

3 Simulation tool: The UWG community

We now move from high-level semantics of the UWG to practical simulation programs and tools. Intuitively, boundary-coupled partial differential equations and discrete event equations are synchronized to form a thermal information network of constant resistances and capacitances within the UWG. Derivatives and integrals can be numerically solved using finite methods, while the RC model can be numerically addressed using a state-space formulation. Each component is specified in the computer program by (1) defining a class, (2) exposing its boundary conditions, and (3) encapsulating the constraints between the boundary conditions, state variables, and their derivatives. The ultimate synthesized program can be further integrated with other APIs to facilitate a more coherent workflow.

Currently, the UWG is built to process the hourly meteorological information in public EPW files mostly from rural stations. EPW files provide the default environmental boundary

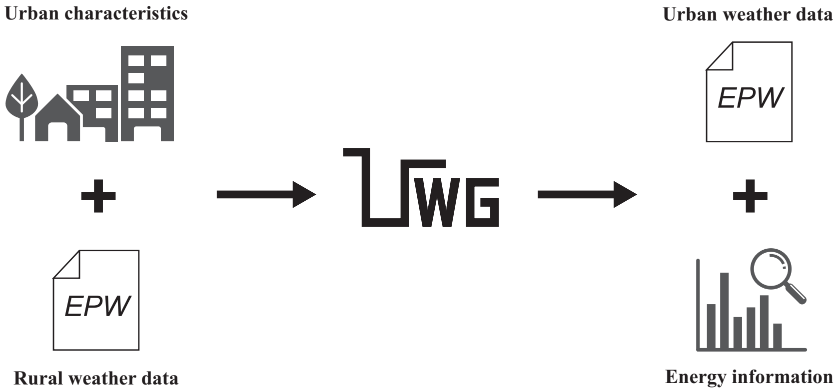

Figure 5: General workflow of the UWG. (As of 2019, the output of simulated energy information is only enabled in the Excel interface of the UWG MATLAB version and in the Dragonfly.)

conditions that drive energy performance simulations at the building and urban scale. As one might encounter in practice, selecting a suitable weather data source when no station is close to the project site under study is often a form of art. Although there is no generally accepted protocol, the UWG initiates a better decision-making paradigm to some extent. As shown in **Figure 5**, starting with the rural weather data provided in the EPW format and the specific urban characteristics, the UWG generates the simulated urban weather data (during either an entire calendar year or a subset thereof) that can be readily exported to the EPW format. In addition, the UWG outputs a fruitful set of energy information (e.g., surface temperature, heat flux, energy use, etc.) that can be further analyzed for various purposes.

The UWG program has been under development since 2008, and some public releases of the open-source code were announced. Moreover, several attempts have been actively made to introduce the UWG as a software tool in many research and commercial communities [Nakano 2015; Awino 2019]. While the UWG was nurtured at MIT, it is really the engagement of many people around the world that has made it a joy to use for urban design computing. It is also recognized as a specific purpose program, allowing it to be deployed not only as a prototype tool in many AEC companies, but also as a teaching tool in numerous educational institutions. A great example of this is the Dragonfly plugin for Grasshopper, which makes it possible for designers to efficiently perform large-scale climate and UHI modeling within the Rhino interface. These use cases take advantage of the UWG's capabilities not only for numerical simulations, but for building interactive APIs, database access, and much more. We present some popular resources here.

3.1 Open-source code: Fantastic projects and where to find them

With the increasing demand in the day-to-day life of scientific modelers for both productivity and utility, the need for high performance computing has become pressing. UWG is fast because of careful system design and the right combination of suitably chosen models that work well with each other. For the practitioners and researchers to fully benefit from the UWG wisdom, we provide two projects written in MATLAB[2] and Python[3] that are available (as of 2019) under the MIT License for open-source program.

Each computational module is written following the theoretical developments summarized in **Section 2**. Users can depend on the existing numerical implementation or customize their own formulation within the computing ecosystem. Through adaptive code manipulations, the UWG

[2]UWG MATLAB version. https://github.com/Jiachen-Mao/UWG_Matlab.
[3]UWG Python version. https://github.com/ladybug-tools/uwg.

can even be extended to couple with other dynamic models and algorithmic solvers to enable more advanced simulation-based analysis, model predictive control, etc. We invite the reader to follow the basic instructions from the websites of these projects.

Although we have touched thus far on efficiently and intuitively modeling physical systems, equally as important is a convenient way to interpret and communicate the results obtained. For many use cases, the spreadsheet system creates a surprisingly versatile environment for scientific modeling. One reason for its impressive success is that it is trivial to interactively manipulate the inputs and visualize the results, mainly within the spreadsheet. In order to achieve such seamless interactivity, the MATLAB version[2] further incorporates a macro-enabled Excel interface along with the UWG scripts. On the other hand, the Python version[3] is ready to be coupled with many other standard computing libraries to customize interactive data analysis and visualization with the UWG engine.

Taking advantage of these interfaces, one can easily create modeling results that embed urban computing problems at scale. We believe that EPW formatting, spreadsheet operation, and object-oriented programming provide a quite satisfying solution in many scenarios to the long-standing challenge of managing data for simulation use.

3.2 Dragonfly and so much more: The zootopia of urban design computing

Capitalizing on the UWG code, Dragonfly[4] is a plugin for Rhino and Grasshopper that allows users to model and estimate urban-scale climate and energy phenomena, such as the UHI effect, district energy use, etc. This is accomplished with the help of several simulation engines, including the UWG Python version.[3] It also links to several public climate-related databases and satellite image datasets (e.g., the Landset from NASA) for climate projection. Dragonfly intends to make large-scale climate variables easily accessible to the visual scripting interface of Grasshopper as well as the 3D visualization interface of Rhino. The latest executable version, including the program code (written in Python) is actively maintained within the Ladybug Tools,[5] which is available (as of 2019) under the GNU General Public License for open-source software.

Since the third millennium, the World Wide Web has increasingly propagated the mantra of distributed, concurrent, and collaborative development. A characteristic of many successful computational projects is that they enable modularization that consists of small discrete components with standardized interfaces. Each component is usually good at one particular task, thus providing a core of functions that could be further featured by a community. Structuring the code into small components allows each subsystem to be developed individually and then integrated into a larger system that yields something greater than their value in isolation [Wetter 2012]. This modularization facilitates reusing code and distributing computation efforts. It also benefits from different experts on different tasks, which can often improve the quality of the whole computing platform.

In agreement with this philosophy, Dragonfly is further connected with other plugins having distinct functions (e.g., Ladybug, Honeybee, and Butterfly) to form the Ladybug Tools that supports energy and environmental design. Thanks to a joint effort of different validated simulation engines and a rich library of computing and visualizing functions, the Ladybug Tools makes it possible for practitioners to build sophisticated models within the Grasshopper ecosystem and to predict not only urban microclimate, but also energy use, thermal comfort, and much more even without expert knowledge of particular simulation functionalities. Such extensive connectivity and interactivity further promote the use of the UWG and Dragonfly in urban design computing. As of July 2019, over 232,000 downloads of the Ladybug Tools plugins

[4]Dragonfly. https://www.ladybug.tools/dragonfly.html.
[5]Ladybug Tools. https://www.ladybug.tools/.

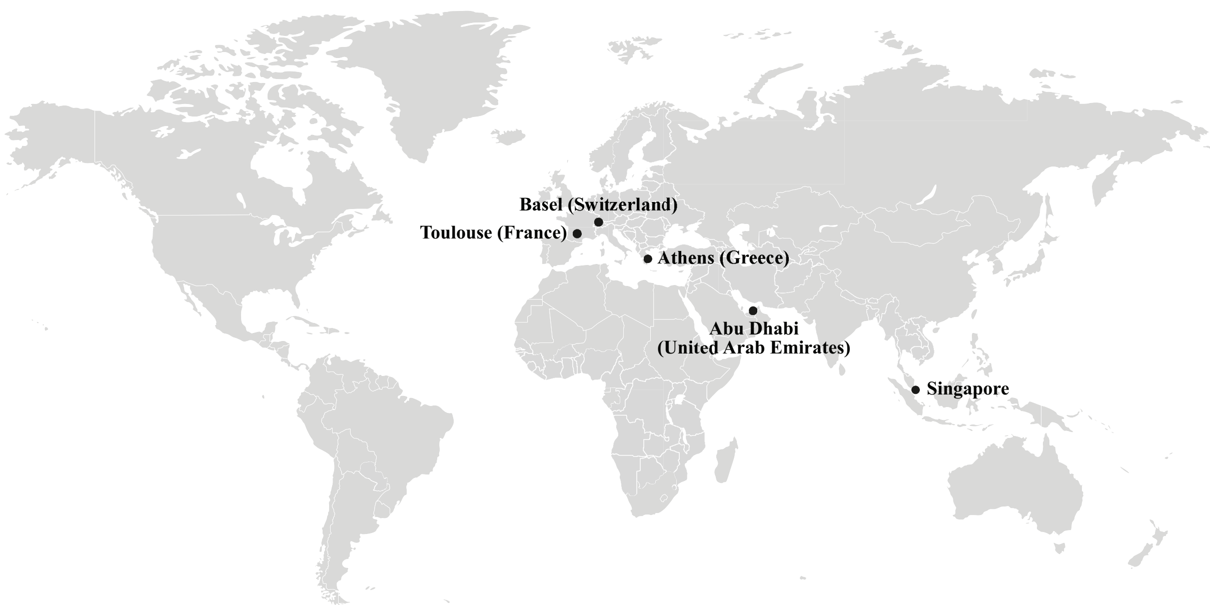

Figure 6: Plot of the case studies used to validate the UWG (as of 2019) on a world map.

have been made, and they have now been utilized as teaching tools in dozens of universities and graduate schools around the world.[5]

4 Case study: A tale of five cities

In what follows, we briefly describe some case studies that have been documented to validate the UWG mechanism during the course of its development. From a more pragmatic point of view, we intend to give an expectation of what the UWG is capable of compared with other atmospheric simulations. Please note that, given the stochastic and uncertain nature of real-world complex systems, some observations and conclusions might be case-specific and thus cannot be generalized. Of course, there is no single model that can work for all the scenarios. We present a few specific interesting lessons that we have learned and some plausible reasons for the observed phenomena. A summary of related case studies can be seen in **Table 1** and **Figure 6**.

4.1 Europe

The case of Europe, in collaboration with the Centre National de Recherches Météorologiques (CNRM-GAME) in France, played an essential role during the initial development of the UWG cores and provided many perspectives on the urban climate situations in European cities [Bueno 2012]. Major explorations were conducted for Toulouse (France), Athens (Greece), and Basel (Switzerland).

In summary, the measured data from Toulouse and Athens along with a calibrated EnergyPlus model were used to validate the UC-BEM scheme on the simulation of indoor air temperature and energy demand [Bueno, Pigeon, et al. 2012a; Bueno, Norford, et al. 2012b]; while the field observations from Toulouse and Basel together with an advanced mesoscale atmospheric simulation were further compared to evaluate the performances of the VDM-UBLM scheme and UWG program on predicting the above-canopy and in-canopy outdoor air temperatures, respectively [Bueno, Hidalgo, et al. 2013a; Bueno, Norford, et al. 2013b]. These pilots have shown a reasonably good agreement, considering the many uncertainties associated with state-of-the-art urban climate and energy predictions. Therefore, the UWG makes it possible to carry out a

Table 1: Summary of the case studies used to validate the UWG (as of 2019).

Case study	**Europe**			**Singapore**	**Abu Dhabi, UAE**
	Toulouse, France	**Athens, Greece**	**Basel, Switzerland**		
Location					
Latitude	43.48°	37.98°	47.33°	1.37°	24.49°
Longitude	1.30°	23.68°	7.35°	103.98°	54.37°
Climate zone	Humid subtropical	Mediterranean	Temperate oceanic	Tropical rainforest	Hot desert
Köppen climate classification	*Cfa/Cfb*	*Csa*	*Cfb*	*Af*	*BWh*
Measurement					
Time	Feb 2004 – Mar 2005	May – Sep 2009	June – July 2002	Feb and July 2010	Oct 2016 – Aug 2017
Urban canyon air temperature	✓	✓	✓	✓	✓
Above-canopy air temperature	✓		✓		
Building energy use	✓			✓	✓
Anthropogenic heat flux	✓			✓	✓
Surface heat flux	✓		✓		
Reference	Bueno, Pigeon, et al. [2012a] Bueno, Hidalgo, et al. [2013a] Bueno, Norford, et al. [2013b]	Bueno, Pigeon, et al. [2012a]	Bueno, Hidalgo, et al. [2013a] Bueno, Norford, et al. [2013b]	Bueno et al. [2014]	Mao [2018] Santos et al. [2018]

Note: This table only presents the details of the measurements that have been used to validate the UWG scheme. There should be more energy and environmental information in each original case study than what we have included in the table.

long-term analysis of climate scenarios and design policies without having to run computationally expensive simulations.

Among the many achievements during the early developments and tests, the most important thing that we have learned is arguably how buildings and the urban climate essentially interact with each other. A general, if slightly nonrigorous, statement for such interaction is that the main mechanism by which the UHI effect influences the indoor environment and energy use is the outdoor air entering the building, which is usually caused by infiltration but also by natural or mechanical ventilation; on the other hand, the waste heat emissions from HVAC systems and (sometimes) exfiltration heat fluxes are the main force by which the building energy performance can affect outdoor thermal conditions. These observations highlight the significance of incorporating the UHI effect in the analysis of building and urban energy systems, which the reader should keep in mind.

4.2 Singapore

The case of Singapore, supported by the Singapore National Research Foundation, gave a test of the UWG model in a humid tropical climate [Bueno et al. 2014]. Unlike European-type cities, Singapore includes a wide range of different urban configurations and entails a more sophisticated evaluation process.

The field data was measured in urban areas of Singapore in which the use of HVAC systems is extensive. Despite the heterogeneous sites in Singapore, the refined UWG is able to produce good estimates of urban air temperatures and anthroponegic heat fluxes at a neighborhood resolution when compared with the data from observation and literature, respectively. In addition, the simplifications and assumptions in the UWG model prevent it from capturing some very site-specific microclimate phenomena, but make it sufficient to explore various urban morphology. If one is particularly interested in highly detailed microclimate effects or spatial UHI distributions within a neighborhood, more advanced computational simulations would be needed.

Perhaps the most interesting and also surprising discovery from the Singapore case is that the location of the rural weather station has a minimal impact on the simulation results and the dependence of the UHI magnitude on city size is quite small. Bueno et al. [2014] suggested an explanation that the energy balances of the urban canopy layer and urban boundary layer are weakly influenced by the advection effect. This argument, if proven to be true in a general context, would make the UWG fairly robust so that the choice of nearby rural weather station is, well, not that crucial for the analysis. Since this is the only time in all the tests that such discussion occurred, statistically speaking, we should revisit this issue in any future cases if sufficient resources are available.

4.3 Abu Dhabi

The case of Abu Dhabi (UAE), in partnership with the Masdar Institute of Science and Technology, extended the validation to tropical desert climate zone with highly heterogeneous urban sites [Mao 2018]. It was also used to test some more advanced simulation-based techniques [Mao, Yang, et al. 2017; Santos et al. 2018; Mao, Fu, et al. 2018].

The comparison between the measurements and predictions indicates that the newest UWG (as of 2019) can roughly capture the UHI pattern and can robustly approximate the thermal behavior of the urban microclimate system in Abu Dhabi for different seasons. Again, due to simplified parameterizations, the model is not able to significantly improve beyond the spatially- and functionally-averaged results when applied to a particular urban site. A numerical solution of the momentum equation would be required if the decision is associated with very detailed spatiotemporal microclimate effects. Nevertheless, the climate-mapping capability of the UWG is still useful since it helps to define the morphological parameters of the distinct neighborhoods within a city and allows physics-based analysis of the building energy performance distribution in spatially heterogeneous cities. Together with previous studies in Europe and Singapore, the UWG can be applied to different climate zones and urban configurations to yield an estimation of the UHI effect for design purpose.

Given the promise of UWG's satisfactory performance with exceptionally low computational requirement, perhaps for the first time, we attempted to enjoy some sophisticated simulation-based techniques in the urban microclimate realm. Specifically, the Monte-Carlo-based sensitivity analysis [Mao, Yang, et al. 2017] and heuristic-optimization-based model calibration [Santos et al. 2018; Mao, Fu, et al. 2018] have been empirically demonstrated to automate the UHI modeling procedure in the Abu Dhabi case. Preliminary results show that the UWG has a catalytic effect in obtaining good solutions even without parallel computing, and hence, opens up a potentially broad spectrum of new engineering applications. We hope to witness the power of UWG in simulation-based analysis among interested communities in the near future.

Finally, one appealing takeaway arises from the sensitivity analysis is that the most critical parameters that impact the urban microclimate behaviors in Abu Dhabi are the reference height of the VDM, the UCL-UBL exchange coefficient, the fraction of waste heat into canyon, and the nighttime urban boundary layer height. Ironically, these parameters remain the most uncertain among all the input parameters of UWG. Their values in specific urban site are often obtained from mesoscale atmospheric simulations, existing literature, and/or well-educated guesses since exact observations are hardly available. To see this as a trade-off, the accuracy of the UWG is sacrificed to some extent by simplified parameterizations, which are usually detailed in numerical simulations, with a goal to significantly improve computational efficiency. In order to reduce the uncertainty in modeling the UHI effect with UWG, some particular attention should be paid on these parameters.

5 Conclusion and beyond: Maybe we are wrong

During the past decade, *homo sapiens* has evolved into *homo urbanus*. The vast bulk of resources that drive modern life is consumed within the buildings constructed in dense urban settlements. As decision makers associate with performance-oriented building design and urban planning, a complex energy interaction between buildings and the urban climate needs to be considered carefully given the growing concern of urbanization. One common problem in practice is that there is no weather station near the project site. In order to address this, a compelling case for the use of computer simulations is devised toward comprehensible design strategies.

Bridging the cultures that are often distant, the Urban Weather Generator (UWG) combines expertise from the diverse fields of building physics and urban climatology to create a new physics-based paradigm for energy and environmental computing in an urban context. UWG is configured to be effective and efficient, and questions the notions generally held to be the "physical laws" by design policy practitioners. On a personal note, this has reminded us of the importance of seeking out and appreciating work in other disciplines, even if it seems to lie outside our normal purview. It turns out that many others wanted exactly the same thing and picked up the UWG to pool their own collective knowledge.

Built on four physics-based models with simplified parameterizations, the UWG is able to quickly estimate the microclimate conditions at the urban street level by processing the meteorological information from public rural weather files. It can also be used as a bottom-up model to evaluate the major energy consumption within the specific urban site by aggregating the building stocks. With continuous refinements on the underlying mechanism and validations among different cities, the UWG shows that one can achieve acceptable simulation performance without incurring expensive machine computation. Some recent development of simulation tools further improve the user convenience and interactivity for scientific modeling.

Of course, UWG is still under development. Perhaps one potential direction would be to understand the latent heat exchange within the UWG mechanism. The humidity calculation requires a full consideration of the moisture from vegetation, soil, nearby bodies of water, etc., and these latent components have not been precisely characterized in the current UWG. Thus, in the UWG simulation (as of 2019), Yang [2016] assumed that the absolute humidity in the urban area is the same as in the rural site. It is also worth noting that the latent heat balance has never been empirically validated in our tests. In the current treatment, only a prescribed latent-energy fraction for specific component is considered. We believe that formalizing a holistic latent heat network within the four models is an important open question.

In addition, the performance of building and urban systems, which is central to the built environment, is a critical issue in which the UWG actually reinforces a lack of appreciation of complexity. That is, it decodes complexity through simplification, rather than interpretation. To see this, the current UWG assumes that the urban weather interacts with the rural weather via the VDM-UBLM scheme, while the air in the UBL is simplified to be well-mixed within the control volume. Furthermore, the energy exchange between the UBL and UCL is also simplified to be essentially adiabatic but joined with an exchange velocity (or exchange coefficient). Such simplified parameterization is indeed useful during an early design stage if one is not too finicky, but certainly will not be enough for advanced analysis to deeply comprehend the system. Given the trade-off between interpretation and computation, a hierarchical or parallel model synthesis might be entertained in the UWG architecture for different purposes in the future.

Finally, just because one has found a compelling mechanism to capture the UHI effect does not mean that there are not other, maybe better, paradigms. For example, the VCWG [Moradi et al. 2019] revises the original VDM-UBLM-UCM scheme and couples two VDMs to simulate the interactions between rural and urban weather. This treatment makes more physical sense and allows some more spatiotemporal estimations within the urban canyon. Given the close relationship between these two simulation paradigms, it is not clear at this moment which one is better; it might be that in seemingly similar situations slightly different perspectives prevail. In practice, it seems reasonable to use whatever makes it easier to obtain results, but this runs the risk of being physically inaccurate. Nevertheless, the UWG offers a hypothesis of simulating the urban microclimate. Some treatment might be inaccurate and, well, even wrong. Interested reader is welcomed to examine the mechanism and maybe create a new prototype.

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References

Augenbroe, G (2012). “The role of simulation in performance-based building”. In: *Building Performance Simulation for Design and Operation*, pp. 15–36.

Awino, HRA (2019). “Design-integrated Urban Heat Island analysis tool and workflow: Development and application”. Master’s thesis. Massachusetts Institute of Technology.

Bueno, B (2012). “Study and prediction of the energy interactions between buildings and the urban climate”. PhD thesis. Massachusetts Institute of Technology.

Bueno, B et al. (2014). “Computationally efficient prediction of canopy level urban air temperature at the neighbourhood scale”. In: *Urban Climate* 9, pp. 35–53.

Bueno, B, Hidalgo, J, et al. (2013a). “Calculation of air temperatures above the urban canopy layer from measurements at a rural operational weather station”. In: *Journal of Applied Meteorology and Climatology* 52.2, pp. 472–483.

Bueno, B, Norford, LK, et al. (2012b). “A resistance-capacitance network model for the analysis of the interactions between the energy performance of buildings and the urban climate”. In: *Building and Environment* 54, pp. 116–125.

Bueno, B, Norford, LK, et al. (2013b). “The urban weather generator”. In: *Journal of Building Performance Simulation* 6.4, pp. 269–281.

Bueno, B, Pigeon, G, et al. (2012a). “Development and evaluation of a building energy model integrated in the TEB scheme”. In: *Geoscientific Model Development* 5.2, pp. 433–448.

Deru, M et al. (2011). “US Department of Energy commercial reference building models of the national building stock”. Technical report. National Renewable Energy Laboratory.

Grimmond, CSB, Roth, M, Oke, TR, et al. (2010). “Climate and more sustainable cities: climate information for improved planning and management of cities (producers/capabilities perspective)”. In: *Procedia Environmental Sciences* 1, pp. 247–274.

Mao, J (2018). “Automatic calibration of an urban microclimate model under uncertainty”. Master’s thesis. Massachusetts Institute of Technology.

Mao, J, Fu, Y, et al. (2018). “Optimization-aided calibration of an urban microclimate model under uncertainty”. In: *Building and Environment* 143, pp. 390–403.

Mao, J, Yang, JH, et al. (2017). “Global sensitivity analysis of an urban microclimate system under uncertainty: Design and case study”. In: *Building and Environment* 124, pp. 153–170.

Masson, V (2000). “A physically-based scheme for the urban energy budget in atmospheric models”. In: *Boundary-Layer Meteorology* 94.3, pp. 357–397.

Moradi, M et al. (2019). “The Vertical City Weather Generator (VCWG v1.0.0)”. In: *Geoscientific Model Development Discussions* (in review). `https://doi.org/10.5194/gmd-2019-176`.

Nakano, A (2015). “Urban weather generator user interface development: Towards a usable tool for integrating urban heat island effect within urban design process”. Master’s thesis. Massachusetts Institute of Technology.

Oke, TR (1973). “City size and the urban heat island”. In: *Atmospheric Environment (1967)* 7.8, pp. 769–779.

Sailor, DJ (2011). “A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment”. In: *International Journal of Climatology* 31.2, pp. 189–199.

Santos, LGR et al. (2018). “Evaluating approaches for district-wide energy model calibration considering the Urban Heat Island effect”. In: *Applied Energy* 215, pp. 31–40.

Stull, RB (2012). *An introduction to boundary layer meteorology.* Vol. 13. Springer Science & Business Media.

Wetter, M (2012). “A view on future building system modeling and simulation”. In: *Building Performance Simulation for Design and Operation*, pp. 481–504.

Yang, JH (2016). “The curious case of urban heat island: A systems analysis”. Master’s thesis. Massachusetts Institute of Technology.