

1 **An Indoor-Outdoor Building Energy Simulator to**  
2 **Study Urban Modification Effects on Building Energy**  
3 **Use – Model Description and Validation**

4 Neda Yaghoobian

5 *Mechanical and Aerospace Engineering Department, University of California San Diego, 9500 Gilman*  
6 *Drive, La Jolla, CA 92093-0411*

7 Jan Kleissl

8 *Mechanical and Aerospace Engineering Department, University of California San Diego, 9500 Gilman*  
9 *Drive, EBU II-580, La Jolla, CA 92093-0411*

10 E-mail: [jkleissl@ucsd.edu](mailto:jkleissl@ucsd.edu); Phone: 858-534-8087; fax: (858) 534-7599

11

12 **Abstract**

13 While there have been significant advances in energy modeling of individual buildings and urban canopies, more  
14 sophisticated and at the same time more efficient models are needed to understand the thermal interaction  
15 between buildings and their surroundings. In particular to evaluate policy alternatives it is of interest how building  
16 makeup, canyon geometry, weather conditions, and their combination modify heat transfer in the urban area. The  
17 Temperature of Urban Facets Indoor-Outdoor Building Energy Simulator (TUF-IOBES) is a building-to-canopy model  
18 that simulates indoor and outdoor building surface temperatures and heat fluxes in an urban area to estimate  
19 cooling/heating loads and energy use in buildings. The indoor and outdoor energy balance processes are  
20 dynamically coupled taking into account real weather conditions, indoor heat sources, building and urban material  
21 properties, composition of the building envelope (e.g. windows, insulation), and HVAC equipment. TUF-IOBES is  
22 also capable of simulating effects of the waste heat from air-conditioning systems on urban canopy air  
23 temperature. TUF-IOBES transient heat conduction is validated against an analytical solution and multi-model  
24 intercomparisons for annual and daily cooling and heating loads are conducted. An application of TUF-IOBES to  
25 study the impact of different pavements (concrete and asphalt) on building energy use is also presented.

26

27 *Keywords: Building energy simulator; Dynamic online modeling; Urban heat island mitigation.*

# 1 Nomenclature

2	$A_0$	amplitude of the soil surface temperature ( $^{\circ}\text{C}$ )
3	$abs$	window absorptance as a function of incidence angle
4	$c$	effective volumetric heat capacity ( $\text{J kg}^{-1} \text{K}^{-1}$ )
5	$COP$	coefficient of performance of the air conditioning system
6	$C_{p_{air}}$	air specific heat capacity ( $\text{J kg}^{-1} \text{K}^{-1}$ )
7	$D$	thermal damping depth (m) due to temperature fluctuations
8	$H$	building height (m)
9	$h$	heat transfer coefficient
10	$k$	effective thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ )
11	$L$	building length (m)
12	$LW$	longwave radiation ( $\text{W m}^{-2}$ )
13	$P$	time period
14	$Q_A$	anthropogenic heat from air conditioning systems (W)
15	$Q_c$	sensible heat generated inside the building (W)
16	$Q_e$	latent heat from internal loads (W)
17	$Q_h$	turbulent sensible heat flux ( $\text{W m}^{-2}$ )
18	$q_{CE}$	convection from internal loads ( $\text{W m}^{-2}$ )
19	$q_{cond}$	conduction heat flux ( $\text{W m}^{-2}$ )
20	$q_{conv}$	convection heat flux from the zone surfaces ( $\text{W m}^{-2}$ )
21	$q_{IV}$	sensible load due to infiltration and ventilation ( $\text{W m}^{-2}$ )
22	$q_{LWS}$	longwave radiation flux from internal sources in a zone ( $\text{W m}^{-2}$ )
23	$q_{LWX}$	net longwave radiant exchange flux between zone surfaces ( $\text{W m}^{-2}$ )
24	$q_{sol}$	transmitted solar radiation flux absorbed on indoor surfaces ( $\text{W m}^{-2}$ )
25	$q_{SW}$	net shortwave radiation flux to the zone surface from interior light ( $\text{W m}^{-2}$ )
26	$q_{sys}$	heat transfer to/from the HVAC system ( $\text{W m}^{-2}$ )
27	$R_{aa}$	outdoor air-to-indoor air thermal resistances ( $\text{m}^2 \text{K W}^{-1}$ )
28	$R_{ai}$	outdoor air-to-indoor wall surface thermal resistances ( $\text{m}^2 \text{K W}^{-1}$ )
29	$SHGC$	solar heat gain coefficient of window

1	$SW$	shortwave radiation ( $W\ m^{-2}$ )
2	$SW_s$	shortwave radiation from internal sources ( $W\ m^{-2}$ )
3	$T_a$	average soil surface temperature ( $^{\circ}C$ )
4	$V_{can}$	air volume inside the urban canopy ( $m^3$ )
5	$W$	building width (m)
6		
7	<i>Greek letters</i>	
8	$\alpha$	thermal diffusivity ( $m^2s^{-1}$ )
9	$\rho$	air density ( $kg\ m^{-3}$ )
10	$\tau$	transmittance of window
11		
12	<i>Subscripts</i>	
13	down	downwelling radiation
14	dir	direct component of solar irradiation
15	diff	diffuse component of solar irradiation
16		

# 1. Introduction

Urbanization or replacing natural land cover with buildings and impervious surfaces has resulted from rapid population and economic growth. Built-up surfaces have different radiative and thermal properties and as a result a different surface energy balance than adjacent rural areas. In addition, the geometry of buildings and canopies changes flow patterns (e.g. [1, 2]) and traps radiation lowering effective albedos [3-6]. All of these effects are responsible for a different climate in urban areas with relatively higher surface and air temperatures (with a few exceptions, [7]) which is called the (surface or air temperature) urban heat island (UHI, [8]). Anthropogenic waste heat (e.g. from transportation, building air-conditioning) enhances UHI effects (e.g. [9-11]; for a review on anthropogenic heat flux modeling see Grimmond et al. [12, 13]; Sailor [14]).

Since land use change in urban areas modifies climate and weather [15, 16], physical processes in built areas and their causes and effects must be quantified effectively. Thermal and radiative properties of urban materials, building conditions (new versus old buildings), size, type, and location of windows, canyon geometry, anthropogenic heat fluxes, and most importantly the combination of these factors in different weather conditions affect urban heat transfer and building energy use. Several studies have been performed and different models have been developed to analyze these scenarios and improve mitigation measures in metropolitan areas (e.g. [17-21]). Most existing building energy models emerged from the engineering community such as, EnergyPlus [22], ASHRAE Toolkit [23], DOE-2 (U.S. National Renewable Energy Laboratory; NREL), the Building Loads Analysis and System Thermodynamics program (BLAST; U.S. Army Construction Engineering Research Laboratory), and Thermal Analysis Research Program (TARP; [24]). These models simulate the energy balance at the outside building wall/window surfaces, wall heat conduction, the energy balance at inside faces and the indoor air heat balance. However, these models do not model the outdoor canopy air including heating, ventilating and air-conditioning (HVAC) heat emissions, the ground surface energy

1 balance, and radiative effects of surrounding buildings. On the other hand, urban energy balance  
2 models in the meteorological community usually exclude dynamic modeling of the indoor  
3 building energy balance and anthropogenic heat fluxes released from HVAC systems. These  
4 components are usually included as prescribed values or offline models (see Grimmond et al.  
5 [12, 13, 25] for a review).

6       There have been some advances in modeling the *interaction* between urban climates and  
7 building energy use. For example Kikegawa et al. [9] coupled a one dimensional urban canopy  
8 meteorological model with a simple sub-model for building energy analysis. Salamanca et al.  
9 [26] developed and implemented a Building Energy Model (BEM) in an urban canopy  
10 parameterization for mesoscale models. BEM was coupled with a multi-layer urban canopy  
11 model and implemented in WRF/urban [27] with a statistical multi-scale modeling ability  
12 ranging from continental, to city, and building scales. On the building scale, Bueno et al. [28]  
13 proposed an iterative scheme for coupling EnergyPlus and the Town Energy Balance (TEB) 2-  
14 dimensional urban canopy model. Iteratively, TEB outdoor surface temperatures serve as  
15 boundary conditions for EnergyPlus and window temperature and HVAC waste heat from  
16 EnergyPlus are passed back to TEB. Iterations continue until the canyon temperature converges.  
17 Through EnergyPlus Bueno et al. [28] were able to simulate complex HVAC systems  
18 considering latent heat exchange between indoor and outdoor, building demand response  
19 strategies, and daylighting. However, this iterative process and the TEB discrete numerical  
20 method for solving heat conduction [6] likely cause the model to be computationally too  
21 expensive for the long time periods required in building energy modeling (one year). Bouyer et  
22 al. [29] developed a CFD (Fluent [30]) – thermoradiative (from the Solene model) coupled  
23 simulation tool to estimate the microclimate influence on building energy consumption. Bouyer  
24 et al. [29] also admit that the computational cost of annual simulations is prohibitive.

1           The review of the literature highlights the need for computationally efficient models which  
2 employ physical process-based descriptions at fine spatial scales and capture microclimate and  
3 building energy effects of urban modifications and heat island mitigation measures. The  
4 Temperature of Urban Facets Indoor-Outdoor Building Energy Simulator (TUF-IOBES) model  
5 introduced in this paper is a building-to-canopy model that simulates indoor and outdoor  
6 building surface temperatures and associated heat fluxes in a high resolution, 3-dimensional  
7 urban domain to estimate urban microclimate, cooling/heating loads, and energy use in  
8 buildings. The indoor and outdoor energy balance processes are coupled online and dynamically  
9 take into account real weather conditions, urban microclimate, indoor heat sources, infiltration,  
10 building and urban material properties and composition of the building envelope (e.g. windows,  
11 insulation), and HVAC equipment. TUF-IOBES also simulates the effect of waste heat emissions  
12 from HVAC systems on urban canopy air temperature and in consequence on urban and building  
13 heat transfer.

14           The description of the outdoor and indoor energy balance models and their integration is  
15 presented in section 2. In section 3 TUF-IOBES simulations of transient heat conduction are  
16 validated against an analytical solution of the interior wall surface temperature response to a step  
17 change in outside air temperature. Also TUF-IOBES simulations of yearly and daily cooling and  
18 heating loads are validated against other building energy simulators. In section 4 an example of a  
19 TUF-IOBES application on simulating effects of urban material modifications on building  
20 energy use is presented. Conclusions are presented in Section 5. A detailed application of TUF-  
21 IOBES to study urban heat island mitigation measures is presented in [XX].

22

## 1 **2. Model description**

### 2 **2.1 Outdoor energy balance model**

3 Our urban energy modeling research builds upon a study with the Temperature of Urban  
4 Facets in 3-D (TUF3D, [31]) model in Yaghoobian et al. [32]. The TUF-IOBES outdoor energy  
5 balance model that determines outside surface and canopy air temperatures is still based on  
6 TUF3D. The geometry, view factor, and sunlit-shaded algorithms for simulating radiation  
7 distribution over a 3-dimensional (3D) domain are directly adopted from TUF3D. Generally, the  
8 geometry of TUF3D is composed of arrays of buildings with the ability of rotating the domain.  
9 Surfaces are sub-divided into patches of identical size. The surface energy balance consisting of  
10 net longwave  $LW_{net}$  and net shortwave  $SW_{net}$  radiation (accounting for multiple reflections of  
11 direct solar radiation and shading), conduction  $q_{cond}$ , and convection  $q_{conv}$  is solved and  
12 enforced for each patch surface (Eq. 1).

$$SW_{net} + LW_{net} = q_{cond} + q_{conv} \quad (1)$$

13 Direct and diffuse horizontal solar radiation is based on the TUF-IOBES forcing data file  
14 (explained later). Downwelling longwave radiation from the sky is based on Brown's sky model  
15 [33] as implemented in the ASHRAE Toolkit [23], where  $LW_{down}$  is a function of air and dew  
16 point temperatures, cloud cover and cloud height.

17

### 18 **Fenestration model**

19 Fenestrations (windows and skylights) are key components in building thermal design since  
20 they affect energy use through radiative transmission, conductive heat transfer (often lumped  
21 together as solar heat gain), infiltration air leakage, and daylighting which may affect the amount  
22 of artificial lighting. The size and position of windows, composition and thickness of glass  
23 panes, and shading devices strongly impact the cooling and heating loads in buildings.

1 The simple geometry of buildings with opaque walls in TUF3D was modified to  
2 accommodate windows, which are also resolved by one or several patches. The net shortwave  
3 radiation incident on each window patch ( $SW_{net}$ ) is simulated based on the method used in  
4 ASHRAE Toolkit

$$5 \quad SW_{net} = (abs_{dir} \times SW_{dir}) + (abs_{diff} \times SW_{diff}) - [(SHGC_{dir} - \tau_{dir}) \times SW_{dir} + (SHGC_{diff} - \\ 6 \quad \tau_{diff}) \times SW_{diff}] + (SHGC_{diff} - \tau_{diff}) \times SW_s, \quad (2)$$

7 where  $abs$ ,  $\tau$ , and  $SHGC$  are absorptance, transmittance, and solar heat gain coefficient of the  
8 window, respectively.  $SW_s$  is the total shortwave radiation from internal sources. Subscripts  $dir$   
9 and  $diff$  stand for direct and diffuse components of solar radiation. Direct absorptance,  
10 transmittance, and SHGC of the glazing depend on the incidence angle of solar radiation. TUF-  
11 IOBES is capable of simulating up to triple pane windows. The transmitted shortwave radiation  
12 is passed to the indoor heat balance (Eq. 4 later).

13

#### 14 **Transient heat conduction model**

15 There are several methods for simulating transient heat conduction in building envelopes  
16 [34] such as Lumped parameter methods [35], frequency response methods [36], numerical  
17 models like finite difference method (FDM) and finite element method (FEM) [37-39], and Z-  
18 transform methods [40, 41]. Fully discrete numerical models (especially FDM) are the most  
19 popular schemes in building and urban energy analysis. However, FDM have several  
20 disadvantages such as computational cost (especially for thin layers such as windows), storage  
21 requirements, and numerical stability. In order to evaluate building-canopy energy interactions  
22 over time scales greater than a few days a more efficient heat conduction scheme is needed.

23 In TUF-IOBES we have implemented a Z-transform method utilizing Conduction Transfer  
24 Functions (CTFs), which is an analytical based scheme for calculating conduction in solid media



1 {40-42). CTFs are applied for example in EnergyPlus and the ASHRAE Toolkit. CTFs are  
 2 calculated based on the State Space Method which assumes a linear change in temperature  
 3 between two time steps. CTF reduce computational cost since the resulting conduction equation  
 4 is linearly relating surface heat flux only to the temperatures and fluxes at the inside and outside  
 5 faces of the medium (unlike in FDM and FEM, element temperatures within the medium are not  
 6 required). CTF coefficients only need to be determined once for each medium (wall, roof,  
 7 window, and ground patches). In TUF-IOBES over a domain of 5 by 5 buildings, CTF reduced  
 8 *overall* computational time by a factor of 15 compared to the FDM. This difference would be  
 9 even greater for larger and more complex domains.

10 Due to round-off and truncation errors, the CTF method has stability problems in thermally  
 11 massive construction [41, 22] including thermally thick soil layers. To find soil surface  
 12 temperature using CTF the soil layer has to be thermally thin. As a result, a constant “deep soil”  
 13 temperature at the bottom boundary of the simulation domain can no longer be assumed. In TUF-  
 14 IOBES to obtain the deep soil temperature over any time period  $P$ , following Hillel [43] we  
 15 solve the diffusion equation for a soil with constant thermal properties, a sinusoidal temperature  
 16 boundary condition at the surface and a constant temperature boundary condition at infinite  
 17 depth

$$T_{soil}(z, t) = T_a + A_0 e^{-z/D} \sin \left[ \frac{2\pi (t - t_0)}{P} - \frac{z}{D} - \frac{\pi}{2} \right]. \quad (3)$$

18 In this equation  $T_{soil}(z, t)$  is the boundary condition for deep soil temperature at time  $t$  and  
 19 depth  $z$  (m),  $T_a$  is the average surface temperature ( $^{\circ}\text{C}$ ) over  $P$ ,  $A_0$  is the amplitude of the surface  
 20 temperature ( $^{\circ}\text{C}$ ) over  $P$ .  $D = \sqrt{\alpha P / \pi}$  is the thermal damping depth (m) of temperature  
 21 fluctuations over  $P$ , and  $\alpha$  is the thermal diffusivity ( $\text{m}^2\text{s}^{-1}$ ).  $t_0$  is the time lag from an arbitrary  
 22 starting time to the occurrence of the minimum temperature in period  $P$ . To avoid stability  
 23 problems, the maximum allowed  $z$  is initialized as  $3D$  for  $P = 86400$  s where the soil

1 temperature amplitude is 5% of the diurnal surface temperature  $A_0$ . Instead of computing  $T_a$  and  
2  $A_0$  from soil temperatures (usually not available), hourly *air* temperature is used [44]. Since soil  
3 is composed of heterogeneous horizontal layers, the effective thermal conductivity ( $k$ ) is  
4 calculated as the harmonic average of thermal conductivities of the soil layers [45]. The effective  
5 volumetric heat capacity ( $c$ ) is derived from the weighted sum of the thermal capacities of each  
6 separate layer [46].  $k$  and  $c$  weighted by volume fraction of each layer are used to define an  
7 effective and constant thermal diffusivity  $\alpha = k/(\rho_{soil}c)$ , where  $\rho_{soil}$  is the soil density. CTF is  
8 then used to compute the soil surface temperature using the boundary condition obtained through  
9 Eq. 3.

10

#### 11 **Convection model**

12 In a simple representation of buoyancy-driven and wind-driven air flow over a surface, the  
13 turbulent sensible heat flux ( $Q_h$ ) in building energy balance models is typically expressed by the  
14 heat transfer coefficient ( $h$ ) multiplied by the driving force expressed by the temperature ( $T$ )  
15 difference between the surface and air ( $Q_h = h [T_{surface} - T_{Air}]$ ). There are several methods for  
16 calculating the heat transfer coefficient (e.g. [47-51, 24]). Models differ as to the degree of  
17 complexity of modeling free and forced convections on horizontal or vertical surfaces  
18 considering thermal stratification of the adjacent flow.

19 In TUF-IOBES, based on TUF3D, stability-corrected Monin–Obukhov similarity theory can  
20 be used for modeling heat transfer from horizontal surfaces. The transfer from vertical surfaces is  
21 based on a flat plate forced convection relationship considering patch surface roughness and  
22 effective wind speed [31]. Alternatively, the DOE-2 model [52] can be applied which is a  
23 combination of the MoWiTT [50] and BLAST [51] models. In the DOE-2 method, the sum of

1 the forced and natural convection components differs for windward and leeward surfaces and is a  
2 function of surface roughness.

3

#### 4 **Forcing data: Annual weather data file**

5 Building energy analyses should be forced with a full year of representative weather data  
6 such as the TMY3 (Typical Meteorological Year 3) files provided by the National Solar  
7 Radiation Data Base. TUF-IOBES inputs hourly global horizontal, direct normal, and diffuse  
8 horizontal irradiances, cloud cover and height, dry bulb and dew point temperatures, pressure,  
9 wind speed, and wind direction at reference height from the TMY3 file. TMY3 information is  
10 linearly interpolated within the hour. TMY3 wind speed, direction, and air temperature are  
11 applied at the reference height in the surface layer; wind speed and temperature profiles in the  
12 roughness sub-layer (logarithmic law) and inside the canopy (exponential profile for wind and  
13 constant canopy air temperature) are based on Krayenhoff and Voogt [31].

14

#### 15 **2.2 Indoor energy balance model**

16 Unlike the gridded outdoor energy model, the indoor model computes bulk heat exchange  
17 and temperature between surfaces. The indoor energy balance model is based on subroutines in  
18 the ASHRAE Toolkit. The inside surface heat balance shows that the heat transfer due to  
19 convection, longwave and shortwave radiation is balanced by conduction:

$$q_{LWX} + q_{SW} + q_{LWS} + q_{cond} + q_{sol} + q_{conv} = 0, \quad (4)$$

20 where  $q_{LWX}$  is the net longwave radiant exchange flux between zone surfaces modeled using  
21 Walton's mean radiant temperature with balance method [53],  $q_{SW}$  is the net shortwave radiation  
22 flux to the surface from interior light which is assumed to be distributed over the surfaces in the  
23 zone (walls, floor, and ceiling) through a user defined fraction,  $q_{LWS}$  is the longwave radiation

1 flux from equipment, people, and lights in a zone modeled using the method of  
2 radiative/convective split of heat,  $q_{cond}$  is conduction flux through the wall simulated using CTF  
3 method,  $q_{sol}$  is the transmitted solar radiation flux absorbed on indoor surfaces, and  $q_{conv}$  is the  
4 convective heat flux to zone air based on air and surface temperature difference. Eq. 4 yields the  
5 indoor surface temperatures. Since the unknown surface temperature in the net longwave radiant  
6 exchange flux between surfaces ( $q_{LWX}$ ) is fourth order (Stefan-Boltzmann law), Eq. 4 is a  
7 nonlinear equation which is solved by Newton's method (unlike the ASHRAE Toolkit which  
8 linearizes this equation).

9 The air in the thermal zone is considered to be well-mixed. The air heat balance consists of  
10 convection heat transfer from the zone surfaces ( $q_{conv}$ ) which is based on the indoor air and  
11 surface temperature difference, convective part of internal loads ( $q_{CE}$ ), the sensible load due to  
12 infiltration and ventilation ( $q_{IV}$ ), and the heat transfer to/from the HVAC system ( $q_{sys}$ ):

$$q_{conv} + q_{CE} + q_{IV} + q_{sys} = 0. \quad (5)$$

13 The air heat balance equation yields the room air temperature and the heating or sensible  
14 cooling load ( $q_{sys}$ ) at each timestep. TUF-IOBES simulates a single or dual-setpoint (deadband)  
15 system with no upper limit on air flow (unlimited capacity) such that the cooling and heating  
16 setpoints are immediately satisfied.

17

### 18 **2.3 Dynamic coupling of indoor and outdoor energy balance models**

19 First a real weather data file (TMY3) forces the outdoor energy balance to obtain canopy  
20 air and urban surface temperatures. Then through the indoor energy balance (Eqs. 4 and 5)  
21 surface temperatures, air temperature, and cooling/heating load inside the building are obtained.  
22 Finally the waste heat from the air-conditioning (AC) system increases the canopy air  
23 temperature.

1 Anthropogenic heat from AC systems is the combination of latent ( $Q_e$ ) heat from  
2 equipment and people, sensible ( $Q_c$ ) heat generated inside the building, and the work required for  
3 operating the thermodynamic cycle [9]. The total waste heat of the AC system ( $Q_A$  [W]) is

$$Q_A = (Q_c + Q_e) \left( \frac{1 + COP}{COP} \right), \quad (6)$$

4 where  $COP$  is the coefficient of performance of the AC system. Assuming that the AC systems  
5 are mounted on the walls (versus on rooftops) of the buildings and instant mixing into the  
6 canopy, the waste heat increases the canopy air temperature. Using air density ( $\rho_{air}$ ), specific  
7 heat capacity ( $C_{p_{air}}$ ), and volume of the air inside the canopy ( $V_{can}$ ), the temperature increase  
8 ( $\Delta T_{AC}$ ) from these anthropogenic heat fluxes becomes

$$\Delta T_{AC} = \frac{Q_A dt}{\rho_{air} C_{p_{air}} V_{can}}, \quad (7)$$

9 where  $dt$  is the simulation timestep. Since the air temperature above the canopy layer is imposed  
10 as the boundary condition, it is not affected by anthropogenic heat release and the canopy air  
11 temperature.

12 In TUF-IOBES the indoor and outdoor energy balance processes are dynamically coupled.  
13 At each timestep the outdoor energy balance model uses the simulated inside building surface  
14 temperatures at the previous timestep from the indoor energy model. On the other hand, the  
15 indoor energy balance model uses the outside building wall temperature simulated at the current  
16 timestep as its boundary condition. Also, the transmitted solar radiation in the interior surface  
17 heat balance  $q_{sol}$  is based on the radiation in the outdoor energy balance.

18

### 19 **3. Validation**

20 The complexity of building energy simulation programs and simplifications in describing  
21 the physical processes imply that careful validation is essential. Ideally, the performance of a

1 building energy simulator should be validated against measured data from a real building.  
2 However, such data are not available as the urban indoor and outdoor environment is too  
3 complex to be instrumented sufficiently. So as stated by Zmeureanu et al. [54], sufficient testing  
4 should be conducted to assure that the probability of failure is sufficiently low to be acceptable.  
5 In this section a transient heat conduction simulation in TUF-IOBES is validated against an  
6 analytical solution of interior wall surface temperature response to a step change in outside air  
7 temperature. In addition yearly and daily cooling and heating load simulations in TUF-IOBES  
8 are validated against other whole building energy simulators.

### 9 **3.1 Analytical validation for a step change in outdoor air temperature**

10 The variation of inside surface temperature ( $T_i$ ) of a cavity wall due to a step change in  
11 outdoor air temperature (OAT) in TUF-IOBES is compared against the analytical solution. The  
12 building is a rectangular zone ( $L \times W \times H = 6.0 \text{ m} \times 6.0 \text{ m} \times 3.6 \text{ m}$ ) with four exterior walls and  
13 no windows. Walls, outdoor air, and room air temperatures are assumed to be in steady state at  
14  $20^\circ\text{C}$  initially. At  $t = 0$ , the OAT drops to  $0^\circ\text{C}$  ( $\Delta T_0 = 20^\circ\text{C}$ ) while the room air temperature is  
15 kept constant at  $20^\circ\text{C}$ . The mean radiant temperature (used for calculating the radiant exchange  
16 between interior surfaces) is equal to the room air temperature and there is no air infiltration,  
17 internal mass and solar radiation. Walls, ceiling, and floor are composed of a 0.28 m brick cavity  
18 wall. The total U-value of the building walls is  $1.42 \text{ W m}^{-2} \text{ K}^{-1}$  (Table 1). More information can  
19 be found in Zmeureanu et al. [54] and Pratt [55].

20

21 TABLE 1 Building element thermal properties and thickness by layer. Given the thermal resistances of outside and  
22 inside air, the heat transfer coefficients on outdoor and indoor surfaces are  $34.0 \text{ W m}^{-2} \text{ K}^{-1}$  and  $8.0 \text{ W m}^{-2} \text{ K}^{-1}$ ,  
23 respectively. Thermal resistances of outdoor and indoor air are defined as the reciprocal of the heat transfer  
24 coefficient on outdoor and indoor surfaces. Air cavity thickness was calculated based on the thermal resistance  
25 given in Zmeureanu et al. [54].

26

1           Although in TUF-IOBES heat transfer coefficients can be calculated dynamically, to match  
2 the conditions in the analytical solution, heat transfer coefficients are fixed to the values  
3 provided by the reference.

4  
5 FIG. 1 Temporal variation of the inside surface temperature ( $T_i(t)$ ) of a 0.28 m brick cavity wall after a step change  
6 in outdoor air temperature of  $\Delta T_0$  at time zero. The y-axis scale is the relative change of the hourly interior surface  
7 temperature with respect to the drop in OAT at initial time based on Zmeureanu et al. [54]

8  
9           TUF-IOBES simulation results (Fig. 1) start at the same initial condition ( $T_i(t) = T_i(0) =$   
10  $20^\circ\text{C}$ ) and reach the same steady state value ( $T_i(t) = 16.4^\circ\text{C}$ ) at 45 h as the analytical solution.  
11 The analytical steady state solution is only a function of the room air temperature ( $T_{room}$ ) and the  
12 ratio of the outdoor air-to-indoor wall surface ( $R_{ai}$ ) and outdoor air-to-indoor air ( $R_{aa}$ ) thermal  
13 resistances of the cavity wall ( $T_i(45 \text{ h}) = T_{room} R_{ai}/R_{aa}$ ).  $R_{ai}$  and  $R_{aa}$  are the sum of the  
14 thermal resistances in Table 1. During the transient part, there is good agreement with a slight lag  
15 in TUF-IOBES. The difference is less than 2.3% (in terms of  $T_i(0)$  minus  $T_i(t)$ ) significantly  
16 improving over the 5% difference for CBS-MASS model [54].

## 17 18 **3.2 Inter-program validation**

### 19 *3.2.1 Annual cooling/heating load*

20           The performance of TUF-IOBES in estimating annual cooling and heating loads was  
21 compared to other building energy simulation programs using the International Energy Agency  
22 Building Energy Simulation Test (BESTEST) and Diagnostic Method [56]. BESTEST is a  
23 standard test for “systematically testing whole-building energy simulation models and  
24 diagnosing the sources of predictive disagreement” [56]. The base case of a Low Mass Building  
25 (Case 600) is used for annual load validation.

1 Case 600 consists of a rectangular single zone building (8 m north and south exposures  $\times$  6  
2 m east and west exposures  $\times$  2.7 m high) with lightweight construction, no interior partitions,  
3 and 12 m<sup>2</sup> of double glazing windows on the south exposure. The mechanical system is 100%  
4 efficient with no duct losses and no capacity limitation, no latent heat extraction, and a dual  
5 setpoint thermostat with deadband between 20°C and 27°C. The weather data file is in the typical  
6 meteorological year (TMY) format for Denver, Colorado (39.8° north latitude, 104.9° west  
7 longitude, 1609 m altitude) with an annual minimum of -24.4°C and a maximum of 35.0°C. The  
8 ground surface temperature is 10°C. Detailed information on building construction  
9 characteristics and all input data including weather can be found in Judkoff and Neymark [56].

10

11

12 FIG. 2 a) Annual heating, b) annual cooling, c) peak heating, and d) peak cooling loads ( $q_{sys}$ ) comparisons between  
13 TUF-IOBES and other building energy balance models provided in BESTEST

14

15 A comparison of annual and peak heating and cooling loads of TUF-IOBES and other  
16 building energy models from BESTEST is presented in Fig. 2. Since neither reference model  
17 results necessarily represent the ‘truth’ [56], the objective is to observe if the predicted thermal  
18 loads in TUF-IOBES fall within or close to the range of results from other programs. TUF-  
19 IOBES annual (5.36 MWh) and peak heating load (3.49 kWh) are in the range of loads (4.29 –  
20 5.7 MWh for annual and 3.43 – 4.35 kWh for peak heating load) of the other programs. The  
21 annual cooling load from TUF-IOBES (5.52 MWh) is 10% below the lowest prediction (range  
22 6.13 – 8.44 MWh). Likewise the peak cooling load (4.99 kWh) is under-predicted by TUF-  
23 IOBES compared to the other programs (5.96 – 7.18 kWh). Given that no sub-annual data are  
24 available for the other programs (with the exception of one day reported in the next section), it is  
25 difficult to assess the reason for the lower cooling load in TUF-IOBES.



1

### 2 *3.2.2 BESTEST Daily cooling/heating load*

3 TUF-IOBES hourly variation of cooling and heating loads over one day (January 4<sup>th</sup> -  
4 proposed in BESTEST for the TMY of Denver, CO) is compared to the other models for  
5 BESTEST case 600 (see section 3.2.1). Fig. 3 shows that TUF-IOBES cooling and heating loads  
6 are in good agreement with other models. The cooling load is underpredicted consistent with the  
7 observations for the entire year in Fig. 2.

8

9

10 FIG. 3 Comparison of hourly variation of thermal loads ( $q_{sys}$ ) on January 4<sup>th</sup> for BESTEST case 600 in Denver, CO.  
11 Positive thermal loads are heating loads and negative loads are cooling loads

12

13 Radiation is an important component of the indoor energy balance. The TUF-IOBES sunlit-  
14 shaded and view factor models which were adopted from TUF3D were validated separately by  
15 comparing downwelling shortwave radiation incident on south and west walls on March 5<sup>th</sup> and  
16 July 27<sup>th</sup> for case 600. Good agreement between TUF-IOBES and BESTEST was observed (not  
17 shown).

18

### 19 *3.2.3. Design day heating / cooling loads for an office building in Montreal*

20 A second test is performed to compare TUF-IOBES daily variation of thermal load in an  
21 office space to other building energy models. We simulated the conditions provided in  
22 Zmeureanu et al. [54] which consist of an intermediate-floor office with dimension  $L \times W \times H =$   
23  $30 \text{ m} \times 30 \text{ m} \times 3.6 \text{ m}$ , with four exterior walls and windows. The air temperature of the under

1 and overlying floor is equal to the air temperature of the analyzed space making vertical heat  
2 transfer in floor and ceiling slabs negligible. In TUF-IOBES the setup is approximated by a  
3 single story office building with thermally thick roof and floor constructions such that the effects  
4 of the roof surface temperature (affected by OAT and solar radiation) on the ceiling temperature  
5 and effects of the deep soil temperature on the floor temperature are negligible. Since thermal  
6 and radiative properties of the materials are not provided in Zmeureanu et al. [54], typical  
7 properties for the windows and building construction materials are assumed (see Table A1 in the  
8 appendix for details). The glazing-to-wall-ratio is 0.5 and windows are double glazing with  $U =$   
9  $2.8 \text{ W m}^{-2} \text{ K}^{-1}$ .

10 Winter (December 21) and summer (July 22) design days in Montreal are forced using  
11 OAT, global horizontal and direct normal radiation provided in Zmeureanu et al. [54]. Since no  
12 information about ground surface temperature is available and most building energy models do  
13 not simulate it, ground surface temperature is set equal to OAT. Air infiltration is 1 air change  
14 per hour (ach). Internal heat gains from people and lights are  $10 \text{ W m}^{-2}$  and  $20 \text{ W m}^{-2}$   
15 respectively. Continuous operation of the HVAC system keeps the room air temperature equal to  
16  $20^\circ\text{C}$  during building occupancy from 9:00 to 17:00. Fig. 4 shows the comparison of the space  
17 thermal loads between TUF-IOBES, BLAST, CBS-MASS, TARP, and BEM [26].

18

19

20 FIG. 4 Heating (a) and cooling (b) load comparison between TUF-IOBES, BLAST, CBS-MASS, TARP, and BEM (a only)  
21 for an office space on a winter (a) and summer (b) design day in Montreal. The total load from BEM was digitized  
22 from Fig. 5b in Salamanca et al. [26]

23 The comparisons show that the TUF-IOBES cooling and heating load is in close agreement  
24 with CBS-MASS, BLAST, TARP and BEM. TUF-IOBES relatively too warm underestimating  
25 the total daily heating load and overestimating the total daily cooling load on the design days.

1 Despite an 8.7% difference in daily cooling load and a 12.5% difference in daily heating load  
2 between TUF-IOBES and TARP, the TUF-IOBES peak load is closer to TARP with a peak  
3 heating load difference of 3.69 kW (6.6%) and a peak cooling load difference of 1.52 kW  
4 (2.2%). On the other hand the difference in TARP and BLAST peak heating load is 4.96 kW  
5 (7.9%) and the difference in their peak cooling load is 5.84 kW (9.3%).

6 The differences between TUF-IOBES and other programs could stem from uncertainty in  
7 the material thermal and radiative properties which were not specified in the original reference.  
8 Also it is not clear that shortwave and longwave interaction between the building and  
9 surroundings are taken into account by Zmeureanu et al. [54].

10

### 11 **3.3. Discussion**

12 Overall the validation results indicate that TUF-IOBES performs well. TUF-IOBES  
13 accurately simulates an analytical case that demonstrates the performance of the conduction and  
14 interior heat balance components. Analytical testing of all components of the TUF-IOBES  
15 simulation is not possible due to the complexity of urban heat transfer. Instead, for heating loads  
16 TUF-IOBES is comparable to other standard building energy models. For cooling loads the  
17 inconsistent results between the model intercomparison for BESTEST (TUF-IOBES smaller than  
18 other building energy models) and Zmeureanu et al. [54] (TUF-IOBES larger than other building  
19 energy models) indicate that TUF-IOBES does not have a fundamental bias; rather unknown  
20 parameter settings could explain the variable results. For example for BESTEST, window diffuse  
21 optical properties were unknown and set to 0.6 for diffuse transmittance, and 0.086 and 0.06 for  
22 diffuse absorptance of outer and inner panes, respectively. Diffuse optical properties have a  
23 greater effect on (summer) cooling loads than (winter) heating loads, since beam irradiance is the

1 dominant radiative source term during the winter. So if the diffuse absorptance and/or  
2 transmittance were specified too small this could explain the reduction in cooling load.

3

## 4 **4. TUF-IOBES application: effects of ground surface** 5 **materials on building energy use**

6 While this paper focuses on the description of TUF-IOBES, we briefly demonstrate an  
7 application of TUF-IOBES to study the effect of ground surface materials on building energy  
8 use. A detailed application of the model is presented in Yaghoobian and Kleissl [57].

### 9 **4.1 Simulation setup**

10 The effect of urban materials on building energy use and air quality in urban areas has  
11 received much attention (e.g. [58-60, 19]). Air temperature over urban surfaces with low albedo  
12 is higher than the air temperature over reflective materials, which indirectly (through convective  
13 fluxes) affects urban building energy use. While this relationship holds for reflective roofs [20],  
14 reflective pavements have more complex effects due to their radiative interaction with  
15 surrounding building walls. The main objective of this initial study is to holistically evaluate  
16 local thermal and radiative effects of asphalt (representative of highly absorptive materials) and  
17 concrete (representative of more reflective materials) ground surfaces on building thermal loads.  
18 For this simulation a  $5 \times 5$  identical building array is resolved by  $99 \times 99$  identical patches of  
19 3.05 m length (Fig. 5). Buildings have a square footprint of 21.33 m (7 patches) on each side and  
20 a height of 18.28 m (6 patches; 4 floors). The buildings in the domain are separated by 16  
21 patches in both  $x$  and  $y$  directions (canyon aspect ratio of 0.38). The outputs are computed over  
22 the central building in the domain while the surrounding buildings provide appropriate radiative  
23 boundary conditions.

24

1 Fig. 5 Surface temperatures in the TUF-IOBES simulation domain with canopy aspect ratio of 0.38 at 1200 LST of  
2 January 1st in San Diego, CA. The length of each patch is 3.05 m. The center 4 × 5 patches of each façade are  
3 windows.

4

5 Building and system characteristics and the amounts of internal loads are chosen similar to  
6 the characteristics of prototypical post-1980 office buildings provided in Akbari et al. [20]. Each  
7 wall of the building has a double glazing window with dimensions 12.19 m (4 patches) height ×  
8 15.24 m (5 patches) width resulting in a window fraction of 0.47. Every day from 0600 to 1900  
9 LST each floor is occupied by 25 persons. Internal load from lighting is  $15.07 \text{ W m}^{-2}$  and from  
10 equipments is  $16.14 \text{ W m}^{-2}$  of floor area. The HCAV system operates continuously. Coefficient  
11 of performance (COP) of the HVAC system is 2.9 with cooling setpoint of  $25.55^\circ\text{C}$  and heating  
12 setpoint of  $21.11^\circ\text{C}$ . Infiltration is neglected. TMY3 weather data file for Miramar station  
13 (KNKX at  $32.87^\circ$  north latitude,  $117.13^\circ$  west longitude and 140 m altitude) in San Diego,  
14 California is used as forcing data at reference height. Properties of the building envelope and  
15 ground surface and sub-surface materials are presented in Tables 2 and 3. Deep soil temperature  
16 is the same in both asphalt and concrete cases and it is simulated based on TMY air temperature  
17 (Eq. 3).

18 TABLE 2 Building and ground material thickness and thermal and radiative properties by layer. Material properties  
19 are chosen based on Incropera and DeWitt [61] and examples in the ASHRAE toolkit and.

20

21 Table 3 Angular and diffuse Solar Heat Gain Coefficient (SHGC), absorptance and transmittance of window glass.  
22 Glass properties are chosen based on examples in the ASHRAE toolkit.

23

## 24 4.2 Results and Discussion

25 Fig. 6 shows a comparison of temperatures of ground surface, canopy air, outside building  
26 wall, inside building surfaces with the transmitted shortwave radiation into the building and  
27 hourly thermal loads for July 10<sup>th</sup> (a clear day with average wind speed of  $3 \text{ m s}^{-1}$ ) between the

1 simulations using asphalt and concrete ground surfaces. Roof surface temperature is not shown  
2 since in TUF-IOBES it is independent of the ground surface material.

3

4 FIG. 6 Comparison of a) ground surface, b) canopy air, c) outside building wall and d) inside building surface  
5 temperatures, e) transmitted shortwave radiation into the building, and f) hourly thermal loads for asphalt and  
6 concrete ground surface material for a summer day (July 10<sup>th</sup>) in San Diego, California. Outside building wall  
7 temperature is averaged over all four outside walls excluding windows. Inside building surface temperature is the  
8 average temperature of all surface temperatures inside the building excluding windows

9

10 The difference in albedo and (less so) other material thermal properties causes a higher  
11 ground surface temperature on asphalt than concrete with the maximum difference of 9.9°C.  
12 Since TUF-IOBES assumes perfect advection from inside the canopy to the atmospheric surface  
13 layer, the air temperature above the asphalt is only up to 0.25°C higher than that over concrete  
14 surface. Ground surface materials affect building surfaces directly (through radiation) and  
15 indirectly (through convection). Fig. 6c shows that despite the higher ground surface temperature  
16 and canopy air temperature over asphalt, building walls are cooler (with maximum difference of  
17 1.24°C) than over concrete. With the simpler TUF3D model, Yaghoobian et al. [32] similarly  
18 demonstrated that the thermal exchange between ground surfaces and walls is dominated by the  
19 effects of net shortwave radiation. Consequently, the larger building wall temperature over  
20 concrete is directly related to the higher albedo of concrete (0.35) than asphalt (0.18). Higher  
21 reflection from concrete also results in a 19.8% increase in total transmitted shortwave radiation  
22 into the building (Fig. 6e). Together, the larger transmitted shortwave radiation and larger heat  
23 conduction through the building envelope result in larger inside building wall (Fig. 6d) and  
24 indoor air temperatures. The contribution of transmitted shortwave radiation through windows on  
25 indoor temperatures is larger than the effects of conductive heat transfer through the building

1 envelope (Fig.6c, 6e). Consequently, the daily AC energy use to keep the indoor air temperature  
2 at the cooling setpoint increases 10.2% for the concrete ground surface (Fig. 6f).

3        During the winter the same processes cause a reduction in heating load over concrete. The  
4 total yearly cooling energy use for concrete is 7.5% (31 MWh) larger and total yearly heating  
5 energy use is 4.1% (0.9 MWh) smaller than over an asphalt surface. While the relative increases  
6 are similar the absolute magnitude of cooling energy use increase trumps the heating load  
7 savings resulting in an overall increase in building energy use near more reflective ground  
8 materials. These results differ from previous research. Other researchers focused on the increase  
9 in *air* temperature over dark surfaces compared to reflective surfaces ignoring the effect of  
10 reflected solar radiation on nearby buildings. This approach is justified for cool roofs, but  
11 inappropriate for cool pavement studies. Ground surface materials affect buildings both directly  
12 and indirectly and TUF-IOBES results show that in above scenario direct radiative effects are  
13 locally dominant.

14

## 15 **5. Conclusion**

16        An indoor-outdoor dynamically coupled urban model has been presented. The Temperature  
17 of Urban Facets Indoor-Outdoor Building Energy Simulator (TUF-IOBES) provides scientific  
18 and engineering results with policy relevance, for example by studying the holistic impact of  
19 heat island mitigation measures. TUF-IOBES was validated against analytical heat transfer  
20 results and against previously validated and well-known building energy models. Results of  
21 these carefully conducted tests indicate that TUF-IOBES can accurately simulate the thermal  
22 behavior of a building. Simulations of annual thermal loads on about two days of a single  
23 processor are possible in this two-way coupled model. The effect of a large number of  
24 parameters such as building conditions (e.g. infiltration rate, construction materials, window size

1 and type), canopy aspect ratio, and weather type (very hot and cold cities) on building thermal  
2 loads can be investigated [57].

3 TUF-IOBES is one of the first three-dimensional fully-coupled indoor-outdoor building  
4 energy simulators. Given the complexity of solar irradiance fields in the urban canopy the  
5 surface temperature fields and energy use can be simulated more faithfully. TUF-IOBES  
6 provides unprecedented insight into urban canopy and building energy heat transfer processes. It  
7 can improve our understanding of how urban geometry and material modifications and the  
8 interaction between buildings and their surroundings and dynamic combination of all of these  
9 effects in three dimensions modify urban energy use. Additional capabilities need to be  
10 developed such as more flexible model geometry to accommodate any possible building and  
11 canyon shape, more sophisticated HVAC system models, more sophisticated models for  
12 simulating vegetated surfaces (other than using Bowen ratio in Yaghoobian et al. [32]) and the  
13 water balance in urban areas. The TUF-IOBES outdoor convection model is simplistic albeit no  
14 ,more so than in other building energy models. Also, the feedback of changes in the urban  
15 canopy and anthropogenic heat release onto the atmospheric surface layer cannot be simulated,  
16 since the boundary conditions are imposed in the surface layer. In this case, models that can  
17 simulate the full boundary layer and mesoscale effects are more applicable (e.g. WRF-Urban  
18 [27]; Krayenhoff and Voogt [62]).

19

20

## 21 **Acknowledgements**

22 We thank (i) Scott Krayenhoff (University of British Columbia) for providing the TUF3D  
23 model, (ii) Chunsong Kwon (University of California, San Diego) for his contribution in  
24 importing TMY file into TUF-IOBES, (iii) Ron Judkoff and Joel Neymark in National



1 Renewable Energy Laboratory for providing BESTEST weather data. (iv) Funding from a

2 National Science Foundation CAREER award.

3

1 **6. Appendix**

2 TABLE. A1 Building element thermal properties and thickness by layer for cooling and heating load validations  
3 against an intermediate floor office in Zmeureanu et al. [54]. For simplicity floor construction is chosen to be the  
4 same as roof.

5

## 1 7. References

- 2 [1] R.E. Britter, S.R. Hanna, Flow and dispersion in urban areas, *Annual Review of Fluid Mechanics* 35 (2003) 469–  
3 496.
- 4 [2] M.O. Letzel, M. Krane, S. Raasch, High resolution urban large-eddy simulation studies from street canyon to  
5 neighbourhood scale, *Atmospheric Environment* 42 (2008) 8770–8784.
- 6 [3] G.T. Johnson, T.R. Oke, T.J. Lyons, D.G. Steyn, I.D. Watson, J.A. Voogt, Simulation of Surface Urban Heat Islands  
7 under ‘Ideal’ Conditions at Night. Part I: Theory and Tests Against Field Data, *Boundary Layer Meteorology* 56  
8 (1991) 275–294.
- 9 [4] G.M. Mills, Simulation of the Energy Budget of an Urban Canyon-I. Model Structure and Sensitivity Test,  
10 *Atmospheric Environment* 27(1993) 157–170.
- 11 [5] J. Arnfield, J.M. Herbert, G.T. Johnson, A Numerical Simulation investigation of Urban Canyon Energy Budget  
12 Variations, in *Proceedings of 2nd AMS Urban environment Symposium (1998)*.
- 13 [6] V. Masson, A physically based scheme for the urban energy budget in atmospheric models, *Boundary Layer*  
14 *Meteorology* 94 (2000) 357-397.
- 15 [7] C.S.B. Grimmond, T.R. Oke, H.A. Cleugh, The role of ‘rural’ in comparisons of observed suburban–rural flux  
16 differences. Exchange processes at the land surface for a range of space and time scales, *International Association*  
17 *of Hydrological Sciences Publication* 212 (1993) 165–74.
- 18 [8] T.R. Oke, The surface energy budget on urban areas. *Modeling the Urban Boundary Layer*, American  
19 *Meteorological Society*, 1987, pp. 1-52
- 20 [9] Y. Kikegawa, Y. Genchi, H. Yoshikado, H. Kondo, Development of a numerical simulation system toward  
21 comprehensive assessments of urban warming countermeasures including their impact upon the urban buildings’  
22 energy-demands, *Applied Energy* 76 (2003) 449–466.
- 23 [10] Y. Kikegawa, Y. Genchi, H. Kondo, K. Hanaki, Impacts of city-block-scale countermeasures against urban heat  
24 island phenomena upon a building’s energy-consumption for air conditioning, *Applied Energy* 83 (2006) 649–668.
- 25 [11] A. Krpo, F. Salamanca, A. Martilli, A. Clappier, On the impact of anthropogenic heat fluxes on the urban  
26 boundary layer: a two-dimensional numerical study, *Boundary Layer Meteorology* 136 (2010) 105-127.
- 27 [12] C.S.B. Grimmond, M. Best, J. Barlow, A.J. Arnfield, J.J. Baik, S. Belcher, M. Bruse, I. Calmet, F. Chen, P. Clark, A.  
28 Dandou, E. Erell, K. Fortuniak, R. Hamdi, M. Kanda, T. Kawai, H. Kondo, S. Krayenhoff, S.H. Lee, S.B. Limor, A.  
29 Martilli, V. Masson, S. Miao, G. Mills, R. Moriwaki, K. Oleson, A. Porson, U. Sievers, M. Tombrou, J. Voogt, T.  
30 Williamson, *Urban surface energy balance models: model characteristics and methodology for a comparison study*.  
31 *Meteorological and Air Quality Models for Urban Areas*, A.Baklanov et al., Eds., Springer-Verlag, 2009, 97-124.
- 32 [13] C.S.B. Grimmond, M. Blackett, M.J. Best, J. Barlow, J.J. Baik, S.E. Belcher, S.I. Bohnenstengel, I. Calmet, F. Chen,  
33 A. Dandou, K. Fortuniak, M.L. Gouvea, R. Hamdi, M. Hendry, T. Kawai, Y. Kawamoto, H. Kondo, E.S. Krayenhoff, S.H.  
34 Lee, T. Loridan, A. Martilli, V. Masson, S. Miao, K. Oleson, G. Pigeon, A. Porson, Y.H. Ryu, F. Salamanca, L. Shashua-  
35 Bar, G.J. Steeneveld, M. Tombrou, J. Voogt, D. Young, N. Zhang, *The International Urban Energy Balance Models*  
36 *Comparison Project: First results from Phase 1*, *Journal of Applied Meteorology and Climatology* 49 (2010) 1268–  
37 1292.
- 38 [14] D.J. Sailor, A review of methods for estimating anthropogenic heat and moisture emissions in the urban  
39 environment, *International Journal of Climatology* 31 (2011) 189–199.

- 1 [15] M.J. Best, Progress towards better weather forecasts for city dwellers: from short range to climate change,  
2 Theoretical and applied climatology 84 (2006) 47-55.
- 3 [16] M.P. McCarthy, M.J. Best, R.A. Betts, Climate change in cities due to global warming and urban effects,  
4 Geophysical Research Letters, 37, L09705 (2010) 1-5.
- 5 [17] H. Taha, D. Sailor, H. Akbari, High-albedo materials for reducing building cooling energy use, Rep. LBL-3172L  
6 Lawrence Berkeley Laboratory, Berkeley, CA, 1992.
- 7 [18] H. Taha, Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat, Energy and  
8 Buildings 25 (1997) 99-103.
- 9 [19] H. Akbari, M. Pomerantz, H. Taha, Cool surfaces and shade trees to reduce energy use and improve air quality  
10 in urban areas, Solar Energy 70 (2001) 295–310.
- 11 [20] H. Akbari, S. Konopacki, Calculating energy-saving potentials of heat-island reduction strategies, Energy Policy  
12 33 (2005) 721–756.
- 13 [21] H. Shen, H.W. Tan, T. Athanasios, The effect of reflective coatings on building surface temperatures, indoor  
14 environment and energy consumption—An experimental study, Energy and Buildings 43 (2011) 573-580.
- 15 [22] U.S. DOE. EnergyPlus - Engineering reference.  
16 <http://apps1.eere.energy.gov/buildings/energyplus/pdfs/engineeringreference.pdf> last accessed on April 26, 2011.
- 17 [23] C.O. Pedersen, R.J. Liesen, R.K. Strand, D.E. Fisher, L. Dong, P.G. Ellis, A toolkit for building load calculations;  
18 Exterior heat balance (CD-ROM), American Society of Heating, Refrigerating and Air Conditioning Engineers  
19 (ASHRAE), Building Systems Laboratory, 2001.
- 20 [24] G.N. Walton, Thermal Analysis Research Program Reference Manual. NBSSIR 83- 2655. National Bureau of  
21 Standards, Washington, DC, 1983.
- 22 [25] C.S.B. Grimmond, M. Blackett, M.J. Best, J.J. Baik, S.E. Belcher, J. Beringer, S.I. Bohnenstengel, I. Calmet, F.  
23 Chen, A. Coutts, A. Dandou, K. Fortuniak, M.L. Gouvea, R. Hamdi, M. Hendry, M. Kanda, T. Kawai, Y. Kawamoto, H.  
24 Kondo, E.S. Krayenhoff, S.H. Lee, T. Loridan, A. Martilli, V. Masson, S. Miao, K. Oleson, R. Ooka, G. Pigeon, A.  
25 Porson, Y.H. Ryu, F. Salamanca, G.J. Steeneveld, M. Tombrou, J.A. Voogt, D. Young, N. Zhang, Initial results from  
26 Phase 2 of the international urban energy balance model comparison, International Journal of Climatology 31  
27 (2011) 244–272.
- 28 [26] F. Salamanca, A. Krpo, A. Martilli, A. Clappier, A new building energy model coupled with an urban canopy  
29 parameterization for urban climate simulations—part I. formulation, verification, and sensitivity analysis of the  
30 model, Theoretical and applied climatology 99 (2010) 331-344.
- 31 [27] F. Chen, H. Kusaka, R. Bornstein, J. Ching, C.S.B. Grimmond, S. Grossman-Clarke, T. Loridan, K.W. Manning, A.  
32 Martilli, S. Miao, D. Sailor, F.P. Salamanca, H. Taha, M. Tewari, X. Wang, A.A. Wyszogrodzki, C. Zhang, The  
33 integrated WRF/urban modeling system: development, evaluation, & applications to urban environmental  
34 problems, International Journal of Climatology 31 (2011) 273–288.
- 35 [28] B. Bueno, L. Norford, G. Pigeon, R. Britter, Combining a Detailed Building Energy Model with a Physically-Based  
36 Urban Canopy Model, Boundary Layer Meteorology 140 (2011) 471–489.
- 37 [29] J. Bouyer, C. Inard, M. Musy, Microclimatic coupling as a solution to improve building energy simulation in an  
38 urban context, Energy and Buildings 43 (2011) 1549-1559.

- 1 [30] Fluent, Fluent 6.3 User Guide, Fluent Inc., Centerra Resource Park, 10 Cavendish Court, Lebanon, NH 03766,  
2 USA, 2006.
- 3 [31] E.S. Krayenhoff, J.A. Voogt, A microscale threedimensional urban energy balance model for studying surface  
4 temperatures, *Boundary Layer Meteorology* 123 (2007) 433–46.
- 5 [32] N. Yaghoobian, J. Kleissl, E.S. Krayenhoff, Modeling the thermal effects of artificial turf on the urban  
6 environment, *Journal of Applied Meteorology and Climatology* 49 (2010) 332–345.
- 7 [33] D. Brown, An Improved Meteorology for Characterizing Atmospheric Boundary Layer Turbulence Dispersion,  
8 Ph.D. Thesis, Department of Mechanical and Industrial Engineering, University of Illinois, Urbana, IL, 1997.
- 9 [34] F.C. McQuiston, D.J. Parker, J.D. Spitler, Heating Ventilating and Air Conditioning, John Wiley & Sons Inc., New  
10 York, 2000.
- 11 [35] F. Haghghat, H. Liang, Determination of Transient Heat Conduction through Building Envelops-A review.  
12 *ASHRAE Transactions*, 98: No. 1, 1992, pp. 284-290.
- 13 [36] M.G. Davies, Transmission and Storage Characteristics of Sinusoidally Excited Walls-A review, *Applied Energy*  
14 15 (1983) 167-231.
- 15 [37] P.T. Lewis, D.K. Alexander, HTB2: A Flexible Model for Dynamic Building Simulation, *Building and Environment*  
16 25 (1990) 7-16.
- 17 [38] J.A. Clarke, Energy Simulation in Building Design, Adam Hilger Ltd., Boston, 1985.
- 18 [39] J.R. Waters, A.J. Wright, Criteria for the Distribution of Nodes in Multi-layer Walls in Finite Difference Thermal  
19 Modeling, *Building and Environment* 20 (1985) 151-162.
- 20 [40] D.C. Hittle, Response Factors and Conduction Transfer Functions, Unpublished, 1992.
- 21 [41] J.E. Seem, Modeling of Heat Transfer in Buildings, Ph.D. Thesis, University of Wisconsin, Madison, WI, 1987.
- 22 [42] J. Seem, S. Klein, Transfer functions for efficient calculation of multidimensional transient heat transfer,  
23 *Journal of Heat Transfer* 111 (1989) 5–12.
- 24 [43] D. Hillel, Introduction to soil physics. Academic Press, San Diego, CA, 1982.
- 25 [44] J. Wu, D.L. Nofziger, Incorporating temperature effects on pesticide degradation into a management model,  
26 *Journal of Environmental Quality* 28 (1999) 92-100.
- 27 [45] B.M. Caruta, New Developments in Materials Science research, Nova Science publisher, Inc., 2007.
- 28 [46] D.A. Vries De, Thermal properties of soils. In Van Wijk, W. R. (ed.), *Physics of Plant Environment*, North-  
29 Holland Publishing Co., Amsterdam, 1963.
- 30 [47] S.S. Zilitinkevich, Non-local turbulent transport: pollution dispersion aspects of coherent structure of  
31 convective flows. In: H. Power, N. Moussiopoulos, and C.A. Brebbia (eds.), *Air pollution III – Volume I. Air pollution*  
32 *theory and simulation*, Computational Mechanics Publications, Southampton, Boston, 1995, pp 53–60.
- 33 [48] E. Guilloteau, Optimized computation of transfer coefficients in surface layer with different momentum and  
34 heat roughness length, *Boundary Layer Meteorology* 87 (1998) 147–160.
- 35 [49] R.J. Cole, N.S. Sturrock, The Convective Heat Exchange at the External Surface of Buildings, *Building and*  
36 *Environment* 12 (1977) 207-214.

- 1 [50] M. Yazdani, J.H. Klems, Measurement of the Exterior Convective Film Coefficient for Windows in Low-Rise  
2 Buildings. ASHRAE Transactions, Vol. 100, Part 1, 1994.
- 3 [51] G.N. Walton, Passive Solar Extension of the Building Loads Analysis and System Thermodynamics (BLAST)  
4 Program, Technical Report, United States Army Construction Engineering Research Laboratory, Champaign, IL,  
5 1981.
- 6 [52] Lawrence Berkeley Laboratory (LBL), DOE2.1E-053 source code, 1994.
- 7 [53] G.N. Walton, Algorithm for Calculating Radiation View Factors Between Plane Convex Polygons With  
8 Obstructions, National Bureau of Standards, NBSIR 86-3463, (1987--- shortened report in Fundamentals and  
9 Applications of Radiation Heat Transfer, HTD-Vol. 72, American Society of Mechanical Engineers), 1987.
- 10 [54] R. Zmeureanu, P. Fazio, F. Haghighat, Analytical and interprogram validation of a building thermal model,  
11 Energy and Buildings 10 (1987) 121–133.
- 12 [55] A.W. Pratt, Heat Transmission in Buildings, John Wiley and Sons Ltd, 1981.
- 13 [56] R. Judkoff, J. Neymark, Building Energy Simulation Test (BESTEST) and Diagnostic Method, National Renewable  
14 Energy Laboratory, Golden, Colorado, 1995.
- 15 [57] N. Yaghoobian, J. Kleissl, Effect of Reflective Pavements on Building Energy Use, 2012, In preparation.
- 16 [58] A.H. Rosenfeld, H. Akbari, S. Bretz, B.L. Fishman, D.M. Kurn, D. Sailor, H. Taha, Mitigation of urban heat  
17 islands: materials, utility programs, updates, Energy and Buildings 22 (1995) 255–265.
- 18 [59] S. Bretz, H. Akbari, A. Rosenfeld, Practical issues for using solar-reflective materials to mitigate urban heat  
19 islands, Atmospheric Environment 32 (1998) 95–101.
- 20 [60] L. Doulos, M. Santamouris, I. Livada, Passive cooling of outdoor urban spaces, The role of materials, Solar  
21 Energy 77 (2004) 231–249.
- 22 [61] F.P. Incropera, D.P. DeWitt, Fundamentals of Heat and Mass Transfer 5th Edition, John Wiley & Sons, 2001.
- 23 [62] E.S. Krayenhoff, J.A. Voogt, Impacts of Urban Albedo Increase on Local Air Temperature at Daily–Annual Time  
24 Scales: Model Results and Synthesis of Previous Work, Journal of Applied Meteorology and Climatology 49 (2010)  
25 1634–1648.

26

## 1 **Figure Captions**

2 FIG. 1 Temporal variation of the inside surface temperature ( $T_i(t)$ ) of a 0.28 m brick cavity wall  
3 after a step change in outdoor air temperature of  $\Delta T_0$  at time zero. The y-axis scale is the relative  
4 change of the hourly interior surface temperature with respect to the drop in OAT at initial time  
5 based on Zmeureanu et al. [54]

6

7 FIG. 2 a) Annual heating, b) annual cooling, c) peak heating, and d) peak cooling loads ( $q_{sys}$ )  
8 comparisons between TUF-IOBES and other building energy balance models provided in  
9 BESTEST

10

11 FIG. 3 Comparison of hourly variation of thermal loads ( $q_{sys}$ ) on January 4<sup>th</sup> for BESTEST case  
12 600 in Denver, CO. Positive thermal loads are heating loads and negative loads are cooling loads

13

14 FIG. 4 Heating (a) and cooling (b) load comparison between TUF-IOBES, BLAST, CBS-MASS,  
15 TARP, and BEM (a only) for an office space on a winter (a) and summer (b) design day in  
16 Montreal. The total load from BEM was digitized from Fig. 5b in Salamanca et al. [26]

17

18 Fig. 5 Surface temperatures in the TUF-IOBES simulation domain with canopy aspect ratio of  
19 0.38 at 1200 LST of January 1st in San Diego, CA. The length of each patch is 3.05 m. The  
20 center  $4 \times 5$  patches of each façade are windows.

21

22 FIG. 6 Comparison of a) ground surface, b) canopy air, c) outside building wall and d) inside  
23 building surface temperatures, e) transmitted shortwave radiation into the building, and f) hourly  
24 thermal loads for asphalt and concrete ground surface material for a summer day (July 10<sup>th</sup>) in  
25 San Diego, California. Outside building wall temperature is averaged over all four outside walls  
26 excluding windows. Inside building surface temperature is the average temperature of all surface  
27 temperatures inside the building excluding windows