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

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Abstract

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

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

Nomenclature

A_0	amplitude of the soil surface temperature (˚C)
abs	window absorptance as a function of incidence angle
c	effective volumetric heat capacity (J kg^{-1} K^{-1})
COP	coefficient of performance of the air conditioning system
$C_{p_{air}}$	air specific heat capacity (J kg^{-1} K^{-1})
D	thermal damping depth (m) due to temperature fluctuations
H	building height (m)
h	heat transfer coefficient
k	effective thermal conductivity (W m^{-1} K^{-1})
L	building length (m)
LW	longwave radiation (W m^{-2})
P	time period
Q_A	anthropogenic heat from air conditioning systems (W)
Q_c	sensible heat generated inside the building (W)
Q_e	latent heat from internal loads (W)
Q_h	turbulent sensible heat flux (W m^{-2})
q_{CE}	convection from internal loads (W m^{-2})
q_{cond}	conduction heat flux (W m^{-2})
q_{conv}	convection heat flux from the zone surfaces (W m^{-2})
q_{IV}	sensible load due to infiltration and ventilation (W m^{-2})
q_{LWS}	longwave radiation flux from internal sources in a zone (W m^{-2})
q_{LWX}	net longwave radiant exchange flux between zone surfaces (W m^{-2})
q_{sol}	transmitted solar radiation flux absorbed on indoor surfaces (W m^{-2})
q_{SW}	net shortwave radiation flux to the zone surface from interior light (W m^{-2})
q_{sys}	heat transfer to/from the HVAC system (W m^{-2})
R_{aa}	outdoor air-to-indoor air thermal resistances (m^2 K W^{-1})
R_{ai}	outdoor air-to-indoor wall surface thermal resistances (m^2 K W^{-1})
$SHGC$	solar heat gain coefficient of window

SW	shortwave radiation (W m^{-2})
SW_s	shortwave radiation from internal sources (W m^{-2})
T_a	average soil surface temperature (˚C)
V_{can}	air volume inside the urban canopy (m^3)
W	building width (m)

Greek letters

α	thermal diffusivity (m^{2}s^{-1})
ρ	air density (kg m^{-3})
τ	transmittance of window

Subscripts

down	downwelling radiation
dir	direct component of solar irradiation
diff	diffuse component of solar irradiation

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

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

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

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

2. Model description

2.1 Outdoor energy balance model

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

$$SW_{net} + LW_{net} = q_{cond} + q_{conv} \tag{1}$$

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

Fenestration model

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

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

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

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

Transient heat conduction model

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

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

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

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

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

In this equation $T_{soil}(z,t)$ is the boundary condition for deep soil temperature at time t and depth z (m), T_a is the average surface temperature (˚C) over P, A_0 is the amplitude of the surface temperature (˚C) over P. $D = \sqrt{\alpha P/\pi}$ is the thermal damping depth (m) of temperature fluctuations over P, and α is the thermal diffusivity (m^2s^{-1}). t_0 is the time lag from an arbitrary starting time to the occurrence of the minimum temperature in period P. To avoid stability problems, the maximum allowed z is initialized as $3D$ for $P = 86400$ s where the soil temperature amplitude is 5% of the diurnal surface temperature A_0. Instead of computing T_a and A_0 from soil temperatures (usually not available), hourly air temperature is used [44]. Since soil is composed of heterogeneous horizontal layers, the effective thermal conductivity (k) is calculated as the harmonic average of thermal conductivities of the soil layers [45]. The effective volumetric heat capacity (c) is derived from the weighted sum of the thermal capacities of each separate layer [46]. k and c weighted by volume fraction of each layer are used to define an effective and constant thermal diffusivity $\alpha = k/(\rho_{soil}c)$, where ρ_{soil} is the soil density. CTF is then used to compute the soil surface temperature using the boundary condition obtained through Eq. 3.

Convection model

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

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

Forcing data: Annual weather data file

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

2.2 Indoor energy balance model

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

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

where q_{LWX} is the net longwave radiant exchange flux between zone surfaces modeled using Walton's mean radiant temperature with balance method [53], q_{SW} is the net shortwave radiation flux to the surface from interior light which is assumed to be distributed over the surfaces in the zone (walls, floor, and ceiling) through a user defined fraction, q_{LWS} is the longwave radiation flux from equipment, people, and lights in a zone modeled using the method of radiative/convective split of heat, q_{cond} is conduction flux through the wall simulated using CTF method, q_{sol} is the transmitted solar radiation flux absorbed on indoor surfaces, and q_{conv} is the convective heat flux to zone air based on air and surface temperature difference. Eq. 4 yields the indoor surface temperatures. Since the unknown surface temperature in the net longwave radiant exchange flux between surfaces (q_{LWX}) is fourth order (Stefan-Boltzmann law), Eq. 4 is a nonlinear equation which is solved by Newton's method (unlike the ASHRAE Toolkit which linearizes this equation).

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

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

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

2.3 Dynamic coupling of indoor and outdoor energy balance models

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

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

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

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

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

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

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

3. Validation

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

3.1 Analytical validation for a step change in outdoor air temperature

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

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

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

FIG. 1 Temporal variation of the inside surface temperature ($T_i(t)$) of a 0.28 m brick cavity wall after a step change in outdoor air temperature of ΔT_0 at time zero. The y-axis scale is the relative change of the hourly interior surface temperature with respect to the drop in OAT at initial time based on Zmeureanu et al. [54]

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

3.2 Inter-program validation

3.2.1 Annual cooling/heating load

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

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

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

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

3.2.2 BESTEST Daily cooling/heating load

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

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

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

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

A second test is performed to compare TUF-IOBES daily variation of thermal load in an office space to other building energy models. We simulated the conditions provided in Zmeureanu et al. [54] which consist of an intermediate-floor office with dimension $L \times W \times H$ = 30 m × 30 m × 3.6 m, with four exterior walls and windows. The air temperature of the under and overlying floor is equal to the air temperature of the analyzed space making vertical heat transfer in floor and ceiling slabs negligible. In TUF-IOBES the setup is approximated by a single story office building with thermally thick roof and floor constructions such that the effects of the roof surface temperature (affected by OAT and solar radiation) on the ceiling temperature and effects of the deep soil temperature on the floor temperature are negligible. Since thermal and radiative properties of the materials are not provided in Zmeureanu et al. [54], typical properties for the windows and building construction materials are assumed (see Table A1 in the appendix for details). The glazing-to-wall-ratio is 0.5 and windows are double glazing with U = 2.8 W m^{-2} K^{-1}.

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

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

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

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

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

3.3. Discussion

Overall the validation results indicate that TUF-IOBES performs well. TUF-IOBES accurately simulates an analytical case that demonstrates the performance of the conduction and interior heat balance components. Analytical testing of all components of the TUF-IOBES simulation is not possible due to the complexity of urban heat transfer. Instead, for heating loads TUF-IOBES is comparable to other standard building energy models. For cooling loads the inconsistent results between the model intercomparison for BESTEST (TUF-IOBES smaller than other building energy models) and Zmeureanu et al. [54] (TUF-IOBES larger than other building energy models) indicate that TUF-IOBES does not have a fundamental bias; rather unknown parameter settings could explain the variable results. For example for BESTEST, window diffuse optical properties were unknown and set to 0.6 for diffuse transmittance, and 0.086 and 0.06 for diffuse absorptance of outer and inner panes, respectively. Diffuse optical properties have a greater effect on (summer) cooling loads than (winter) heating loads, since beam irradiance is the dominant radiative source term during the winter. So if the diffuse absorptance and/or transmittance were specified too small this could explain the reduction in cooling load.

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

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

4.1 Simulation setup

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

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

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

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

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

4.2 Results and Discussion

Fig. 6 shows a comparison of temperatures of ground surface, canopy air, outside building wall, inside building surfaces with the transmitted shortwave radiation into the building and hourly thermal loads for July 10th (a clear day with average wind speed of 3 m s^{-1}) between the simulations using asphalt and concrete ground surfaces. Roof surface temperature is not shown since in TUF-IOBES it is independent of the ground surface material.

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

The difference in albedo and (less so) other material thermal properties causes a higher ground surface temperature on asphalt than concrete with the maximum difference of 9.9˚C. Since TUF-IOBES assumes perfect advection from inside the canopy to the atmospheric surface layer, the air temperature above the asphalt is only up to 0.25˚C higher than that over concrete surface. Ground surface materials affect building surfaces directly (through radiation) and indirectly (through convection). Fig. 6c shows that despite the higher ground surface temperature and canopy air temperature over asphalt, building walls are cooler (with maximum difference of 1.24˚C) than over concrete. With the simpler TUF3D model, Yaghoobian et al. [32] similarly demonstrated that the thermal exchange between ground surfaces and walls is dominated by the effects of net shortwave radiation. Consequently, the larger building wall temperature over concrete is directly related to the higher albedo of concrete (0.35) than asphalt (0.18). Higher reflection from concrete also results in a 19.8% increase in total transmitted shortwave radiation into the building (Fig. 6e). Together, the larger transmitted shortwave radiation and larger heat conduction through the building envelope result in larger inside building wall (Fig. 6d) and indoor air temperatures. The contribution of transmitted shortwave radiation through windows on indoor temperatures is larger than the effects of conductive heat transfer through the building envelope (Fig.6c, 6e). Consequently, the daily AC energy use to keep the indoor air temperature at the cooling setpoint increases 10.2% for the concrete ground surface (Fig. 6f).

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

5. Conclusion

An indoor-outdoor dynamically coupled urban model has been presented. The Temperature of Urban Facets Indoor-Outdoor Building Energy Simulator (TUF-IOBES) provides scientific and engineering results with policy relevance, for example by studying the holistic impact of heat island mitigation measures. TUF-IOBES was validated against analytical heat transfer results and against previously validated and well-known building energy models. Results of these carefully conducted tests indicate that TUF-IOBES can accurately simulate the thermal behavior of a building. Simulations of annual thermal loads on about two days of a single processor are possible in this two-way coupled model. The effect of a large number of parameters such as building conditions (e.g. infiltration rate, construction materials, window size and type), canopy aspect ratio, and weather type (very hot and cold cities) on building thermal loads can be investigated [57].

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

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6. Appendix

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

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Figure Captions

FIG. 1 Temporal variation of the inside surface temperature ($T_i(t)$) of a 0.28 m brick cavity wall after a step change in outdoor air temperature of ΔT_0 at time zero. The y-axis scale is the relative change of the hourly interior surface temperature with respect to the drop in OAT at initial time based on Zmeureanu et al. [54]

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

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

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

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

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