PREDICTION OF THE URBAN HEAT ISLAND EFFECT TO BE USED IN BUILDING ENERGY ANALYSES

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ABSTRACT

The increase in air temperature produced by urbanization, a phenomenon known as the Urban Heat Island (UHI) effect, is often neglected in current building energy simulation practices. The UHI effect can have an impact on the energy consumption of buildings, especially those with low internal heat gains or with an inherent close interaction with the outdoor environment (e.g. naturally-ventilated buildings). This paper presents an Urban Weather Generator (UWG) to calculate air temperatures inside urban canyons from measurements at an operational weather station located in an open area outside a city. The model is evaluated against field data from Basel (Switzerland) and Toulouse (France). The expected error of UWG predictions is about 1 K, which stays within the range of air temperature variability observed in different locations of the same urban area.

INTRODUCTION

Urban areas are geometrically complex. Due to inter-reflections between urban surfaces, shortwave radiation is more efficiently absorbed relative to rural terrain. Furthermore, urban surface roughness decreases the mean wind velocity and reduces the convective heat removal. Added to this is the heat gain due to anthropogenic sources (Sailor 2011) and the lower evaporation due to the reduction of vegetated areas. In consequence, the mean temperature tends to be higher in urban than in rural areas (Oke 1987). This phenomenon is known as the Urban Heat Island (UHI) effect and has been measured in different cities around the world (Roth 2007; Hicks, Callahan, and Hoekzema 2010).

Building simulation programs use standard meteorological databases compiled from measurements at operational weather stations for annual energy calculations. Operational weather stations are usually located in open areas, without nearby obstructions, and outside the city, typically at the airport. Therefore, air temperature measurements might not include the UHI effect.

Bueno et al. (2012a) show that the energy consumption of residential buildings can be modified by 20% for a typical 4 K daily-maximum UHI effect. Commercial buildings are less affected by this phenomenon unless they include building systems based on direct air exchange with the outdoor environment, such as natural ventilation systems or economizers. At the same time, the energy performance of buildings can have an impact on outdoor air temperatures, mainly through the waste heat emissions from outdoor air-conditioning equipment. We therefore realize that there are reciprocal interactions between buildings and the urban climate that are often neglected in current building simulation practices.

This paper presents an Urban Weather Generator (UWG) to calculate urban air temperatures using meteorological information measured at an operational weather station. Other studies that calculate urban weather information through meteorological modeling can be found in the literature. Erell and Williamson (2006) presented a rural-to-urban weather transformation (the CAT model), which requires the calibration of empirical parameters at the location of analysis and does not account for the reciprocal interactions between buildings and the urban climate. Oxizidis, Dudek, and Papadopoulos (2008) proposed a method of generating urban weather files by coupling EnergyPlus with CFD and mesoscale atmospheric simulations. In our opinion, the application of computationally expensive fluid dynamics models is not appropriate for annual energy analyses. The UWG is a computationally efficient model based on energy conservation principles. Its computational cost is intentionally kept at the same order of magnitude as annual building energy simulations. The UWG can be incorporated into existing simulation programs in order to calculate site-specific urban weather files.

This paper first describes the physics behind the UWG. Then, the model is evaluated against field data from two boundary-layer experiments, one carried out in Basel, Switzerland (Rotach et al. 2005); and another one carried out in Toulouse, France (Masson et al. 2008). A discussion of the limitations and prospects of the UWG is presented at the end.

MODEL DESCRIPTION

The UWG calculates hourly values of urban air temperature and humidity given the weather data measured at an operational weather station located outside a city. The model is composed of four coupled modules (Fig. 1): the Rural Station Model (RSM), which calculates sensible heat fluxes at the weather station; the Vertical Diffusion Model (VDM), which calculates vertical profiles of air temperature above the rural site; the Urban Boundary-Layer (UBL) model, which calculates air temperatures above the urban canopy layer (above urban canyons); and the Urban Canopy and Building Energy Model (UC-BEM), which calculates urban sensible heat fluxes and urban canyon air temperature and humidity.

Rural Station Model

The RSM is a rural canopy model that reads hourly values of meteorological fields measured at the rural site and calculates sensible heat fluxes, which are then provided to the VDM and the UBL model.

The model is based on an energy balance at the soil surface. A transient heat diffusion equation represents the storage and release of heat from the ground. Dividing the soil in discrete layers, the RSM solves the following system of equations:

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

for the first layer,

$$d_i(\rho c_p)_i \frac{\partial T_i}{\partial t} = C_{i,i+1}(T_{i+1} - T_i) + C_{i,i-1}(T_{i-1} - T_i) \quad (2)$$

for each intermediate layer, and

$$d_{n-1}(\rho c_p)_{n-1} \frac{\partial T_{n-1}}{\partial t} = C_{n-i,n}(T_{deep} - T_{n-1}) \quad (3)$$

for the deepest layer. In Eqs. [1-3], d_i, $(\rho c_p)_i$, and T_i represent the depth, the volumetric heat capacity [J

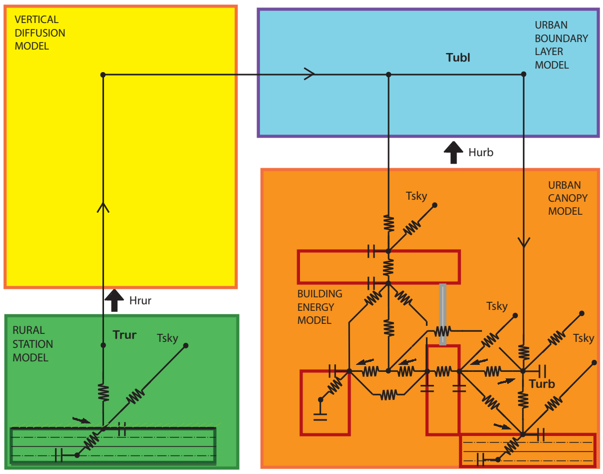

Figure 1: Diagram of the Urban Weather Generator (UWG) scheme, which is composed of four modules: the Rural Station Model (RSM), the Vertical Diffusion Model (VDM), the Urban Boundary Layer (UBL) model and the Urban Canopy and Building Energy Model (UC-BEM). Thermal networks indicate the main heat transfer processes included in the RSM and UC-BEM. T_{rur}, T_{ubl} and T_{urb} represent the air temperature measured at the weather station, calculated at the urban boundary layer, and calculated at the urban site. The RSM provides rural sensible heat fluxes (H_{rur}) to the VDM and the UBL model. The UC-BEM provides urban sensible heat fluxes (H_{urb}) to the UBL model.

m^{-3} K^{-1}] and the average temperature of the layer i, respectively; $C_{i,j}$ is the mean thermal conductance over the distance between two layers [W m^{-2} K^{-1}]; Q_{surf} is the sum of net-radiation, sensible and latent heat fluxes at the surface; and T_{deep} is the annual-average air temperature of the site, used as boundary condition deep into the ground. The latent heat flux due to the evapotranspiration of vegetation (if present) is calculated as a fraction of the absorbed shortwave radiation (Shashua-Bar and Hoffman 2002).

Vertical Diffusion Model

The VDM reads air temperatures and velocities measured at the weather station, as well as sensible heat fluxes calculated by the RSM, and calculates vertical profiles of air temperature above the weather station (Fig. 2), which are then provided to the UBL model.

The VDM solves the following heat diffusion equation:

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

where θ is the potential temperature of the air, which is a variable commonly used in meteorology and represents the temperature that a parcel of fluid at a certain pressure would acquire if is brought adiabatically to a standard reference pressure. In Eq. 4, z is the vertical space component, ρ is the air density, and K_d is a diffusion coefficient. The lower boundary condition of Eq. 4 is the temperature measured at the weather station, $\theta_{rur}(z_r)$ (z_r = 2 m). The upper boundary condition accounts for the fact that at a certain height ($z_{ref} \sim 200$ m), the profile of potential temperature is uniform and $\frac{\partial\theta}{\partial z}|_{z_{ref}} = 0$.

The difficulty of calculating vertical temperature profiles through a diffusion equation lies in the calculation of the diffusion coefficient K_d. In some atmospheric models, this coefficient is related to the turbulent kinetic energy (TKE) at each vertical level (Bougeault and Lacarrere 1989):

$$K_d = C_k l_k E^{1/2}, \quad (5)$$

where E is the TKE, C_k is a model parameter set equal to 0.4, and l_k is a length scale. In these models, a prognostic equation for the TKE is then solved as a function of the temperature and velocity fields (Martilli, Clappier, and Rotach 2002), so coupled equations for the air velocity components must also be computed. This approach adds excessive complexity and computational cost to this particular application, in which the uncertainties associated with urban climate prediction limit the reachable accuracy level. A simpler approach, proposed by Hong, Noh, and Dudhia (2006), calculates K_d based on correlations as a function of a mixed-layer velocity scale and the planetary boundary layer height, which has to be calculated iteratively.

The VDM proposes an alternative and robust solution, which combines the two approaches mentioned above. The diffusion coefficient is calculated by Eq. 5 and the TKE at each vertical level is approximated by:

$$E = max\left(w_s^2, E_{min}\right), \quad (6)$$

where w_s is the mixed-layer velocity scale (Hong, Noh, and Dudhia 2006) and E_{min} is set equal to 0.01 $m^2\ s^{-2}$. Atmospheric models usually establish of a minimum TKE given the difficulties of predicting very stable boundary layers (Bravo et al. 2008).

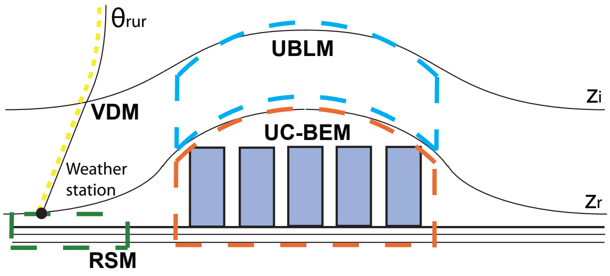

Figure 2: Representation of a city and the physical domain of the different UWG modules. The diagram corresponds to nighttime conditions (not at scale). The RSM calculates sensible heat fluxes based on a energy balance at the rural soil. The VDM calculates vertical profiles of potential temperature (θ_{rur}) at the rural site. The UBL model solves an energy balance at the urban boundary layer between the the blending height (z_r) and the boundary-layer height (z_i) to calculate air temperatures above the urban canopy layer. The UC-BEM calculates air temperature and humidity inside urban canyons.

Urban Boundary-Layer Model

The UBL model calculates air temperatures above the urban canopy layer from the temperatures at different heights provided by the VDM and the sensible heat fluxes provided by the RSM and the UC-BEM.

The model is based on an energy balance for a selected control volume inside the urban boundary layer delimited by the blending height (z_r) and the boundary-layer height (z_i) (Fig. 2). It differentiates between nighttime and daytime urban boundary layers, and between the advection effect driven by a geostrophic wind (forced problem) and by the urban breeze circulation (convective problem) (Hidalgo, Pigeon, and Masson 2008).

The energy balance of the UBL model is expressed as:

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

where V_{CV} is the control volume, ρ is the air density, c_p is the air specific heat, θ_{urb} is the average potential temperature of the control volume, H_{urb} is the sensible heat flux at the surface of the control volume [W], θ_{ref} is a reference potential temperature outside the control volume, u_{ref} is a reference air velocity, and A_f is the lateral area of heat exchange between the control volume and its surroundings. In Eq. 7, the term on the LHS represents the thermal inertia of the control volume and the second term on the RHS represents the advection effect. The model assumes that the potential temperature is uniform inside the control volume and that there is no significant heat exchange at the top of it.

At daytime, a control volume of the size of the city and height $[z_i]_{day}$ is selected. The lateral area of heat exchange, A_f, includes the width of the city orthogonal to the wind direction. The reference temperature of Eq. 7 is taken as the potential temperature outside the city at a height at which the vertical profile is considered uniform, $\theta_{rur}(z_{ref})$. This temperature is provided by the VDM.

In presence of geostrophic wind, the reference velocity is taken as the air velocity measured at the weather station, $u_{wind}(z_m)$ (z_m = 10 m). Under urban-breeze circulation at daytime, Hidalgo, Masson, and Gimeno (2009) proposed the following expression for the characteristic circulation velocity (u_{circ}):

$$u_{circ} = k_w \left(\beta z_i \frac{H_{urb} - H_{rur}}{\rho c_p} \right)^{1/3}, \qquad (8)$$

where k_w is a constant ($k_w \sim 1$), β is the buoyancy coefficient ($\beta = g\theta^{-1}$), and H_{urb} and H_{rur} are the sensible heat fluxes [W m^{-2}] from the urban and the rural sites, respectively. The problem is assumed to be convective if the circulation velocity is greater than the air velocity measured at the weather station. For this situation, the circulation velocity (Eq. 8) is used in the energy balance and the lateral area of heat exchange includes its entire perimeter, P_{city}.

At night, in presence of geostrophic wind, the urban boundary layer is horizontally divided in various control volumes. For the first control volume, the one upstream of the city, the reference potential temperature and wind velocity are assumed to have the following linear vertical profiles:

$$\theta_{rur}(z) = (\theta_{rur}(z_i) - \theta_{rur}(z_r)) \frac{z}{z_i} + \theta_{rur}(z_r), \qquad (9)$$

and

$$u_{wind}(z) = u_{wind}(z_m) \frac{z}{z_m}, \qquad (10)$$

where $\theta_{rur}(z_r)$ is the air temperature measured at the weather station. $\theta_{rur}(z_i)$ is provided by the VDM, where the boundary-layer height (z_i) is an input of the model. For simplicity, Eq. 10 assumes that the air velocity is zero at z_r. For the control volumes downstream of the first one, the reference temperature is assumed to be uniform and given by the temperature of the control volume immediately upstream.

Under urban-breeze circulation at nighttime, the circulation velocity obtained by Eq. 8 is also used for the reference air velocity of Eq. 7, although this velocity scale was initially developed for daytime conditions. The reference air temperature is assumed to have also a linear vertical profile (Eq. 9).

The numerical method used to solve Eq. 7 is implicit Euler, in which $\frac{d\theta_{urb}}{dt} = \frac{\theta_{urb} - \theta_{urb}^{-}}{\delta}$, where δ is the simulation timestep. Then, Eq. 7 can be expressed as:

$$\theta_{urb} - \theta_{urb}^{-} = C_{surf} + C_{adv}\theta_{eq} - C_{adv}\theta_{urb}, \qquad (11)$$

where C_{surf}, C_{adv} and θ_{eq} are calculated for each scenario according to Table 1.

Table 1: Surface coefficient (C_{surf}), advection coefficient (C_{adv}), and equivalent temperature (θ_{eq}) used in Eq. 11 for each scenario. θ_{rur} is the potential temperature outside the city at different heights $\{z_r$, z_i, and $z_{ref}\}$. θ_{n-1} is the average potential temperature of the control volume upstream of the one considered. H_{urb} is the urban sensible heat flux [W m^{-2}].

Night	C_{surf}	C_{adv}	θ_{eq}
Forced (first)	$\frac{H_{urb}\delta}{z_i \rho c_p}$	$\frac{u_{wind}(z_m) z_i \delta}{2 z_m dx}$	$\frac{2}{3}\theta_{rur}(z_i) + \frac{1}{3}\theta_{rur}(z_r)$
Forced (rest)			θ_{n-1}
Convective	$\frac{H_{urb}\delta}{z_i \rho c_p}$	$\frac{P_{city} u_{circ} \delta}{A_{city}}$	$\frac{1}{2}\theta_{rur}(z_i) + \frac{1}{2}\theta_{rur}(z_r)$
Day			
Forced	$\frac{H_{urb}\delta}{z_i \rho c_p}$	$\frac{W u_{wind}(z_m) \delta}{A_{city}}$	$\theta_{rur}(z_{ref})$
Convective	$\frac{H_{urb}\delta}{z_i \rho c_p}$	$\frac{P_{city} u_{circ} \delta}{A_{city}}$	$\theta_{rur}(z_{ref})$

Urban Canopy and Building Energy Model

The UC-BEM calculates urban canyon air temperature and humidity from radiation and precipitation data, air velocity and humidity measured at the weather station, and from the air temperature above the urban canopy layer calculated by the UBL model.

The model is based on the Town Energy Balance (TEB) scheme (Masson 2000), including its building energy model (Bueno et al. 2012b). The UC-BEM assumes that the air inside the urban canopy layer is well mixed. Window surfaces are not specifically solved in the outdoor energy balance and their effect on the indoor and outdoor environments is represented by a thermal resistance characterized by the window U-factor (Fig. 1).

Urban canyon air temperatures are obtained by the heat balance method, taking into account the heat capacity of the urban canyon air. The urban canyon energy balance accounts for the heat fluxes from walls, windows and the road, the sensible heat exchange between the canyon air and the atmosphere, the heat fluxes due to exfiltration, the waste heat from HVAC equipment and other anthropogenic heat sources, and the radiant heat exchange between the canyon air and the sky. Thus, the urban canyon energy balance is given by:

$$V_{can}\rho c_p \frac{dT_{urb}}{dt} = A_w h_w (T_w - T_{urb}) + A_r h_r (T_r - T_{urb}) + A_r h_{rd,sky} (T_{sky} - T_{urb}) \quad (12)$$
$$A_{win} U_{win} (T_{in} - T_{urb}) + \dot{V}_{inf/vent} \rho c_p (T_{in} - T_{urb}) + u_{ex} \rho c_p (T_{ubl} - T_{urb}) + H_{waste} + H_{traffic},$$

where T_{urb}, T_{in} and T_{ubl} are the air temperature of the urban canyon, the indoor air temperature, and the air temperature of the urban boundary layer above the urban canyon, respectively; T_{sky} is the effective sky temperature; V_{can} is the volume of the urban canyon air; U_{win} is the U-factor of windows including heat exchange coefficients at both sides; $\dot{V}_{inf/vent}$ is the exfiltration airflow rate; H_{waste} is the sensible component of waste heat flux released by heating, ventilation and air-conditioning systems into the urban canyon; $H_{traffic}$ represents other anthropogenic sources of heat; and u_{ex} is the exchange velocity between the in-canopy and above-canopy flows. An analogous latent heat balance is solved to calculate the humidity content of the urban canyon air by computing the latent heat fluxes from the atmosphere, buildings and road. The UWG assumes that the air humidity above urban canyons is the same as the one measured at the weather station for each time step.

The exchange velocity (u_{ex}) is obtained from an expression extracted from Bentham and Britter (2003):

$$u_{ex} = \frac{u_*}{\frac{u_{atm}}{u_*} - \left(\frac{8}{VH_{urb}}\right)^{1/2}}, \quad (13)$$

where u_* is the friction velocity (Louis 1979) and u_{atm} is a reference air velocity above the urban canopy assumed equal to the air velocity measured at the weather station.

In large spaces such as urban canyons, the water vapor present in the air participates in the radiant heat exchange. The air emissivity is calculated as a function of the humidity content and the size of the space (Siegel and Howell 1981). In Eq. 12, h_w and h_r are the heat transfer coefficients of walls and road, respectively, which combine convective and radiative effects ($h = h_{cv} + h_{rd}$); and $h_{rd,sky}$ is the radiant heat transfer coefficient between the urban canyon air and the sky.

External surface temperatures of walls, road and roof are calculated by solving a similar surface energy balance to the one described for the rural soil (Eqs. [1-3]). The boundary conditions of the road are the same as the rural soil. In the case of walls and roof, the indoor boundary condition is a heat flux calculated by the building energy model.

The outdoor surface heat flux is composed of shortwave radiation, longwave radiation, sensible and latent heat components. The solar radiation received by walls and road is calculated by assuming an average urban canyon orientation (Masson 2000). The longwave radiation among walls, road, urban canyon air and the sky is computed by linearization of the Stefan-Boltzmann equation accounting for the transmittance of the urban canyon air and assuming only one bounce of radiative heat fluxes between surfaces. In terms of longwave radiation, window surfaces are assumed to have the same temperature as wall surfaces. Surface sensible heat fluxes are computed by using convective heat transfer coefficients, which are calculated as a function of the air velocity above the urban canopy layer (u_{atm}) by using a correlation extracted from Palyvos (2008).

Urban sensible heat fluxes (required by the UBL model) are calculated as the sum of the heat exchange between the canyon air and the atmosphere and the convective heat flux from building roofs, including the fraction of waste heat emissions from the outdoor air-conditioning equipment located there.

The vegetation model of the UC-BEM follows the shade-convection approach (Shashua-Bar and Hoffman 2002). The solar radiation that reaches urban canyons is partially blocked by the tree canopy according to the horizontal vegetation density of the site. The solar radiation absorbed by the trees is split into sensible and latent heat fluxes. These fluxes then participate in the energy balance of the urban canyon.

The building energy model is based on the one developed by Bueno et al. (2012b). The physical and geometric definition of buildings is kept as simple as possible, while maintaining the required features of a comprehensive building energy model. The model considers a single thermal zone, where the thermal inertia of building materials associated with multiple levels is represented by a generic thermal mass. The model accounts for heat gains due to transmitted solar radiation, heat conduction through the enclosure, infiltration, ventilation, and internal heat gains, as well as for the dynamical evolution of indoor air temperature (between thermal setpoints) and humidity.

To calculate cooling energy consumption, the model solves the dehumidification of the air passing through the cooling system by assuming that the air leaves the cooling coil at 90% relative humidity. The model includes the mixture of recirculated air and outdoor air according to the ventilation air flowrate.

Waste heat fluxes are calculated as a function of the building energy consumption (Q_{cons}) and building energy demand (Q_{dem}). For example, for a cooling system the waste heat flux is given by:

$$Q_{\text{waste}} = Q_{\text{cons}} + Q_{\text{dem}}. \quad (14)$$

MODEL EVALUATION

The UWG scheme is compared with field data from two boundary-layer experiments: the intensive observational period (IOP) of the BUBBLE experimental campaign, carried out in Basel (Switzerland) between June 10 and July 10, 2002 (Rotach et al. 2005); and the CAPITOUL experimental campaign carried out in Toulouse (France) from February 2004 to March 2005 (Masson et al. 2008).

In both experiments, weather data is measured simultaneously at rural and urban stations. The evaluation of the UWG consists of introducing rural weather data as inputs in the model and comparing the calculated and observed urban air temperatures.

The system parameters of the UWG used in this comparison are summarized in Table 2. The parameters of the VDM-UBL scheme are the daytime and nighttime boundary layer heights (z_i), the reference height (z_{ref}), and the urban-breeze scaling coefficient (k_w). In addition, the sensible-latent heat split is assumed to be 0.5 in the vegetation model and the vegetation albedo is taken as 0.25, which is the average value reported in the experiments. Finally, the model accounts for the effect of vegetation from May to November (deciduous vegetation).

Comparison with field data from Basel, Switzerland

The main urban experimental site in BUBBLE is Basel-Sperrstrasse. The site represents a heavily built-up part of the city center of Basel, mainly composed of residential buildings. A detailed characterization of this urban site can be found in previous studies that use the field data from BUBBLE (Hamdi and Masson 2008). The input parameters used in this analysis are the same as in these studies (Table 3). For those magnitudes for which detailed information is not available (e.g. building use), reasonable assumptions based also in previous studies have been made. A city diameter of 5 km is estimated based on the areal view of the city. A sensitivity analysis of the model varying the city diameter between 3 km and 7 km produced small changes in the results. The Grenzach weather station, inside the valley of the Rhine River, is used as the reference rural station.

Table 2: System parameters of the UWG used in the model comparison with field data from Basel, Switzerland, and Toulouse, France.

Parameter	Setting
Daytime mixing height	1000 m
Nighttime boundary-layer height	50 m
Reference height at which the vertical profile of potential temperature is assumed uniform	200 m
Urban-breeze scaling coefficient	1.2
Latent fraction of vegetation	0.5
Albedo of vegetation	0.25
Begin month for vegetation participation	May
End month for vegetation participation	November

Figure 3 compares hourly values of urban air temperatures calculated by the UWG with the air temperatures measured at the urban and rural sites for a week in June. The monthly-average diurnal cycle for the IOP of the BUBBLE campaign is represented in Fig. 4. As can be seen, the UWG is able to capture both the UHI effect observed at night and the Urban Cool Island (UCI) effect observed during the day, although it overpredicts the later partly due to the simplifying assumptions of the vegetation model.

Statistical results of this comparison are presented in Table 4. The root-mean-square-error (RMSE) between the model and observations is 1.1 K, where the average daily-maximum UHI effect is 5.2 K. Errors of around 1 K are acceptable given the important uncertainties associated with urban climate predictions (see next section). The mean-bias-error (MBE) is -0.5 K, which reproduces the overprediction of the UCI effect observed in Fig. 4.

Comparison with field data from Toulouse, France

The CAPITOUL campaign is an extensive boundary-layer experiment, which includes (among other types of measurements) a network of weather stations inside and at the periphery of Toulouse (Fig. 5). In this analysis, the station located at the central location of the city, next to the Monoprix building (MNP), is selected as representative of urban conditions. Five of the surrounding urban stations are also included in the analysis (MIC, CIT, MIN, ILE, and CYP) to show the variability of air temperatures

Table 3: Inputs of the UWG used in the model comparison with field data from Basel, Switzerland, and Toulouse, France. Both parameterizations represent densely populated residential areas and rural areas covered by grass.

Parameter	BUBBLE	CAPITOUL
Urban parameters		
Location	Basel	Toulouse
Latitude	47.33°	43.48°
Longitude	7.35°	1.3°
City diameter	5000 m	7500 m
Average building height	14.6 m	20 m
Horizontal building density	0.54	0.68
Vertical-to-horizontal urban area ratio	0.48	1.1
Horizontal vegetation density (trees)	0.16	0.08
Wall construction	Concrete - 20 cm Insulation - 3 cm	Brick - 20 cm Insulation - 3 cm
Wall albedo	0.15	0.25
Roof construction	Tiles - 6 cm Concrete - 20 cm Insulation - 3 cm	Tiles - 6 cm Wood - 20 cm Insulation - 3 cm
Roof albedo	0.15	0.25
Building floor construction	Concrete – 20 cm	Concrete – 20 cm
Road construction	Asphalt - 5 cm Stones - 20 cm Gravel and soil	Asphalt - 5 cm Stones - 20 cm Gravel and soil
Road albedo	0.08	0.08
Building parameters		
Glazing ratio	0.3	0.3
Window construction	Double-pane clear glass	Double-pane clear glass
Internal heat gains	Residential	Residential
Infiltration/ventilation	0.5 ACH	0.5 ACH
Cooling system	None	None
Heating system	Furnace	Furnace
Weather station parameters		
Construction	Soil	Soil
Albedo of the surface without vegetation	0.15	0.15
Vegetation fraction	0.8	0.8

within the same urban area. The characterization of the site is presented in previous studies that use field data from CAPITOUL (Bueno et al. 2011). The same input parameters are used here (Table 3). In this case, the city diameter is taken as 7.5 km. The reference weather station is located at Mondouzil (MON), an agricultural rural area at the North-East periphery of the city.

Figure 6 compares hourly values of urban air temperatures calculated by the UWG with the air temperatures measured at the urban and rural sites for a week in July. The monthly-average diurnal cycles for July and October, 2004, and January, 2005, are represented in Fig. 7. The error bar represents the root-mean-square-difference between the air temperatures observed in the five urban stations surrounding the MNP station and the air temperature measured at the MNP station (Fig. 5). The results

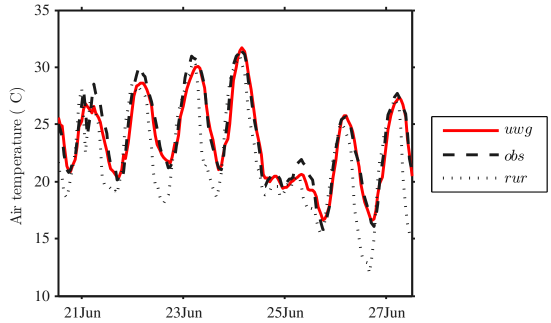

Figure 3: Hourly values of urban canyon air temperature calculated by the UWG and observed during the BUBBLE experiment between June 21 and June 28, 2002. Hourly values of measured rural air temperature (rur) for the same period are also represented.

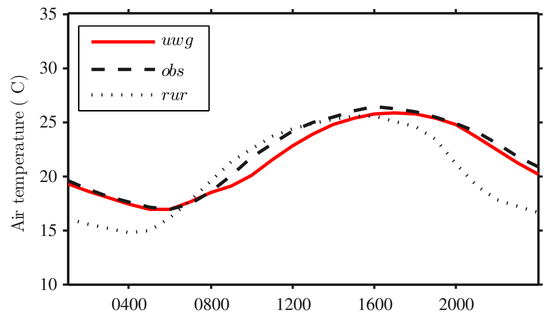

Figure 4: Monthly-average diurnal cycle of urban canyon air temperature calculated by the UWG and observed during the BUBBLE experiment between June 10 and July 10, 2002. Monthly-average diurnal cycle of measured rural air temperature (rur) for the same period is also represented.

show the capacity of the UWG to reproduce the UHI effect for different seasons. The observed variability of air temperature around the MNP weather station is about 1 K. This justifies the statement that the error associated with UWG's predictions is acceptable and within the air temperature range observed in different locations of the same urban area.

Statistical results of this comparison are presented in Table 4 for the three months. The RMSE between the model and observations ranges between 0.8 K and 1.2 K, where the average daily-maximum UHI effect ranges between 2.4 K and 3.6 K. The MBE is generally low, which indicates that there are no systematic errors in the model.

Observations show that the UHI effect at mesoscale level (due to the aggregate effects of the whole city) cannot be neglected. From the daily-maximum UHI effect observed inside urban canyons (e.g. 3.6 K in summer, Table 4), more than half (2.5 K for the previous example) is due to the mesoscale effect.

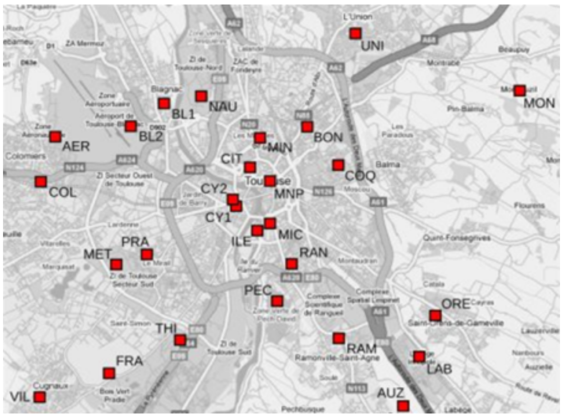

Figure 5: Map of the weather station network during the CAPITOUL experiment carried out in Toulouse, France, from February 2004 to March 2005.

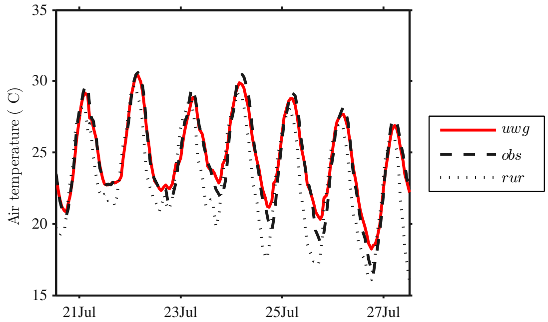

Figure 6: Hourly values of urban canyon air temperature calculated by the UWG and observed during the CAPITOUL experiment between July 21 and July 28, 2004. Hourly values of measured rural air temperature (rur) for the same period are also represented.

CONCLUSION

This paper presents a physically based and computationally fast model to predict the UHI effect in a city given meteorological information measured in an operational weather station outside the city. The UWG is a compact model that can be incorporated into existing programs for

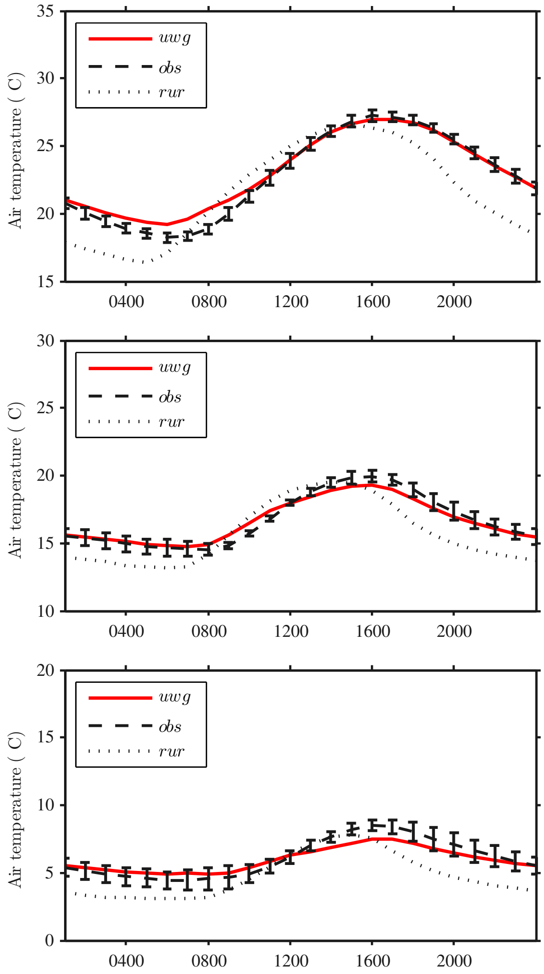

Figure 7: Monthly-average diurnal cycles of urban canyon air temperature calculated by the UWG and observed during the CAPITOUL experiment in July (top) and October (middle), 2004, and in January (bottom), 2005. Monthly-average diurnal cycles of measured rural air temperature (rur) for the same periods are also represented. The error bar represents the root-mean-square-difference between the air temperature observed in the five urban stations surrounding the MNP station and the air temperature measured at the MNP station.

the design and analysis of buildings and urban areas.

The UWG has been satisfactorily evaluated against field data from two cities: Basel, Switzerland, and Toulouse, France. The expected error associated with UWG predictions is around 1 K, which stays within the range of air temperature variability observed in different locations of the same urban area. The comparison with field data highlights that the UHI effect cannot be

Table 4: Root-Mean-Square-Error (RMSE) and Mean-Bias-Error (MBE) between the urban air temperatures calculated by the UWG and observed during BUBBLE experiment between June 10 and July 10, 2002; and between the urban air temperatures calculated by the UWG and observed during CAPITOUL experiment in July and October, 2004, and January, 2005. Errors are compared to the average daily-maximum UHI effect observed during each period.

Month	RMSE (K)	MBE (K)	$\overline{UHI_{max}}$ (K)
BUBBLE			
Summer	1.1	-0.5	5.2
CAPITOUL			
Summer	0.8	0.3	3.6
Fall	0.9	-0.1	2.5
Winter	1.2	-0.1	2.4

computed only from the urban canyon effect (vertical component), but must also include the aggregate effect of the whole city (horizontal component). As a consequence, urban climate prediction tools cannot be limited to an urban canopy model, but must also consider the effect of the urban boundary layer. This can be achieved by using mesoscale atmospheric simulations or by using the simplified approach of the VDM-UBL scheme.

The reference weather station for the UWG can be situated in any location in the periphery of the city as long as is not surrounded by urbanization and is not affected by site-specific micro-climate conditions produced by the orography or by the presence of large bodies of water. For example, a weather station nearby the sea would not be appropriate for applying the UWG. The current version of the UWG has performed well in European-type of cities in which the urban morphology is relatively homogeneous and the urban vegetation is scarce. Further developments of the model will address the heterogeneity of urban areas and the spatial distribution of the UHI effect within a city. They will also include a better treatment of latent heat fluxes, while maintaining the approach of keeping the model as simple as possible (but not simpler).

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NOMENCLATURE

A_{city}	City horizontal area, m^2
A_f	Lateral heat exchange area, m^2
c_p	Specific heat, J kg^{-1} K^{-1}
C	Coefficients/ Thermal conductance, /W m^{-2} K^{-1}
d	Layer thickness, m
E	Turbulent kinetic energy, m^2 s^{-2}
g	Gravity acceleration, m s^{-2}
h	Heat transfer coefficient, W m^{-2} K^{-1}
H	Sensible heat flux, W, W m^{-2}
k_w	Urban-breeze circulation scale constant
K_d	Diffusion coefficient, m^2 s^{-1}
l_k	Length scale, m
P_{city}	City perimeter, m
Q	Heat flux, W m^{-2}
t	Time, s
T	Temperature, C, K
u	Mean air velocity, m s^{-1}
u_{circ}	Urban-breeze circulation velocity, m s^{-1}
u_{ex}	Exchange velocity, m s^{-1}
u_*	Friction velocity, m s^{-1}
U_{win}	Window U-factor, W m^{-2} K^{-1}
V	Volume, m^3
$\dot{V}$	Air volume flowrate, m^3 s^{-1}
VH_{urb}	Vertical-to-horizontal urban area ratio
w_s	Mixed-layer velocity scale, m s^{-1}
z	Vertical space component, m
z_i	Boundary-layer height, m
z_r	Blending height , m
z_{ref}	Reference height, m
β	Buoyancy coefficient, m s^{-1} K^{-1}
δ	Timestep, s
θ	Potential temperature, K
ρ	Density, kg m^{-3}
Subscripts	
atm	Atmosphere
can	Urban canyon
cons	HVAC consumption
cv	Convection
dem	Building demand
inf/vent	Exfiltration
r	Road
rd	Radiation
ref	Reference
rur	Rural
urb	Urban
ubl	Urban boundary layer
w	Walls
waste	Waste heat from HVAC systems
win	Windows