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ARTICLE

Combining a Detailed Building Energy Model with a Physically-Based Urban Canopy Model

Bruno Bueno · Leslie Norford · Grégoire Pigeon · Rex Britter

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Abstract A scheme that couples a detailed building energy model, EnergyPlus, and an urban canopy model, the Town Energy Balance (TEB), is presented. Both models are well accepted and evaluated within their individual scientific communities. The coupled scheme proposes a more realistic representation of buildings and heating, ventilation and air-conditioning (HVAC) systems, which allows a broader analysis of the two-way interactions between the energy performance of buildings and the urban climate around the buildings. The scheme can be used to evaluate the building energy models that are being developed within the urban climate community. In this study, the coupled scheme is evaluated using measurements conducted over the dense urban centre of Toulouse, France. The comparison includes electricity and natural gas energy consumption of buildings, building façade temperatures, and urban canyon air temperatures. The coupled scheme is then used to analyze the effect of different building and HVAC system configurations on building energy consumption, waste heat released from HVAC systems, and outdoor air temperatures for the case study of Toulouse. Three different energy efficiency strategies are analyzed: shading devices, economizers, and heat recovery.

Keywords Anthropogenic heat · Building simulation model · Heating ventilation air-conditioning · Town energy balance · Urban heat island

1 Introduction

In the context of analyzing and mitigating the increase in air temperature produced by urbanization and known as the urban heat island (UHI) effect, heat release from buildings at night and anthropogenic sources play a critical role (Sailor 2010). To account for building effects,

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B. Bueno (✉) · L. Norford · R. Britter
Massachusetts Institute of Technology, 77 Massachusetts Ave., R.5-414, Cambridge, 02139 MA, USA
e-mail: bbueno@mit.edu

G. Pigeon
CNRM-GAME, Météo France and CNRS, Toulouse, France

urban climatologists have developed simplified building energy models integrated into urban canopy models (Kikegawa et al. 2003; Salamanca et al. 2010). The ability of these models to analyze the interactions between buildings and the urban environment has been verified (Kondo and Kikegawa 2003; Salamanca and Martilli 2010), including the effect of the waste heat released from heating, ventilation and air-conditioning (HVAC) systems (Kikegawa et al. 2006; Ihara et al. 2008).

While these building parametrizations represent a significant advancement in integrating building energy and urban climate studies, they still have limitations that affect the evaluation of building energy consumption and the calculation of waste heat released from HVAC systems. In particular, they use an idealized representation of HVAC systems that neglects the specificities of the different HVAC configurations and that does not allow the assessment of energy efficiency strategies. In addition, they usually do not implement models of passive building systems such as shading devices or natural ventilation and they do not perform daylighting analyses.

This article presents a method to integrate building energy and urban climate studies, by coupling a detailed building energy model, EnergyPlus (Crawley et al. 2001), and an urban canopy model, the Town Energy Balance (TEB) (Masson 2000). The Energy Plus-TEB coupled scheme intentionally combines models that have already been extensively used and evaluated and are well known and accepted within their respective communities, building engineering and urban climatology.

The coupled scheme makes it possible to analyze the effect on urban climate of all building and building system parameters included in a detailed building model. It also enables the identification of building and building system configurations whose analysis and design are more sensitive to urban climate conditions. Furthermore, it can be used in the evaluation process of simplified building models integrated into urban canopy models. As a backdrop to this article, the authors recognize the opportunities arising at the intersection of the building engineering and the urban climatology communities in the context of climate modification, increasing urbanization, and future energy scarcity.

We first present an overview of building energy modelling as related to urban climate studies. Next, the coupled scheme is described and evaluated against field data from the experiment CAPITOUL conducted in Toulouse, France (Masson et al. 2008). The coupled scheme is then used to study the impact of different building and HVAC system configurations on the energy consumption of buildings, HVAC waste heat emissions, and outdoor air temperatures. Conclusions and applications are presented in Sect. 6.

2 Urban Climate and Building Energy Modelling

2.1 The Town Energy Balance (TEB) Model

The TEB model (Masson 2000) is a physically based urban canopy model that represents the fluid dynamic and thermodynamic effects of an urbanized area on the atmosphere. The TEB model has been evaluated with observations in various urban sites and weather conditions (Masson et al. 2002; Lemonsu et al. 2004; Offerle et al. 2005; Pigeon et al. 2008). The model considers a two-dimensional approximation of an urban canyon formed by three generic surfaces: a wall, a road, and a roof, and calculates the climate conditions, the drag force and energy fluxes of a town or neighbourhood formed by identical urban canyons, where all orientations are possible and all exist with the same probability.

The TEB model implements a simple representation of building energy processes by solving a transient heat conduction equation through a multi-layered wall and roof. The force-restore method is applied to calculate indoor conditions from the contributions of the different building surfaces. Further developments of the TEB model include a minimum threshold to calculate the heating loads of the building associated with transmission through building surfaces (Pigeon et al. 2008). Other phenomena, such as transmission through windows, internal heat gains, infiltration and the calculation of cooling loads, are not yet included.

2.2 Building Parametrizations

A further step in representing the effects of buildings on urban climate was carried out by Kikegawa et al. (2003), who implemented a simplified building energy model in an urban canopy parametrization for mesoscale models. In addition to solving the diffusion equation for walls, this model takes into account the internal sources of heat, solar radiation transmitted through windows, and the energy loads due to ventilation. Applying sensible and latent heat balances, the model calculates the energy demand required to maintain certain indoor conditions.

Recently, Salamanca et al. (2010) developed a new building energy model, coupled with a multi-layer urban canopy model (Martilli et al. 2002). This model allows the definition of multiple-story buildings and incorporates a more detailed treatment of windows, including the calculation of the transmitted solar radiation as a function of the angle of incidence. A range of comfort conditions and a maximum capacity of the HVAC system can also be specified in this model.

The building energy models of Kikegawa and Salamanca are able to capture the main heat transfer processes that occur inside buildings (Salamanca et al. 2010). They are also able to predict the energy demand of a basic building configuration and to estimate the energy consumption and waste heat emissions of an HVAC system (Ihara et al. 2008; Salamanca and Martilli 2010). Generally, these building parametrizations have been developed within the urban climatology community.

2.3 EnergyPlus

One industry-standard building energy model, EnergyPlus (Crawley et al. 2001), developed by the building engineering community, calculates the energy demand of a building by applying a heat balance method (DOE 2010a), somewhat similar to that used in the above-mentioned building parametrizations. It also implements detailed models for external heat transfer calculations such as convection, solar radiation (including shadows and reflections), and longwave radiation exchange with the sky (DOE 2010a). EnergyPlus has been extensively evaluated according to building simulation standards (e.g. DOE 2010b,c).

One difference with respect to building parametrizations is that EnergyPlus can calculate the energy consumption of a specific HVAC system by solving the sensible and latent energy transformations of a working fluid (air or water) when this passes through the different HVAC components (coils, fans, heating and cooling plant equipment, economizers, cooling towers, etc.). Examples of specific HVAC systems are variable-air-volume, fan-coils, or chilled ceilings with dedicated outdoor air systems.

This detailed definition is intended to capture the real performance of HVAC systems that supply energy to cover the energy demand of the building and to counteract thermal losses through the system. The capacity of the system depends on the conditions inside and outside the building, and there are situations where the system is not able to supply the required energy, affecting the resulting indoor conditions. Cooling-system efficiency (as measured by the coefficient of performance (COP), the dimensionless ratio of thermal output to fuel input) also depends on the conditions inside and outside the building and on the part load ratio of the cooling plant. The latter takes into account the loss of efficiency when the cooling plant is not working at its maximum capacity.

In an ideal building energy model, the indoor air humidity is assumed constant and the latent energy supplied or removed by the HVAC system is directly equal to the latent energy demand of the building. On the contrary, a detailed definition solves for the dehumidification of the air passing through a cooling system. In many HVAC system configurations, the indoor air humidity is not controlled in the same way as the air temperature, so the calculation of the air humidity requires a psychrometric model of the air crossing the system. This capability allows a more realistic analysis of the latent heat exchange between the indoor and the outdoor environments.

Another difference between detailed building energy models and building parametrizations is the capability of modelling building demand reduction strategies or passive systems. Passive systems take advantage of the sun, the wind and environmental conditions to reduce or eliminate the need for HVAC systems. Accurate simulation of their effect is sometimes crucial in predicting the overall energy performance of buildings and consequently the heat released from buildings into the environment. Examples of passive systems are shading devices, double-skin façades, natural ventilation, heat storage devices, evaporative cooling, earth tubes for pre-heating or pre-cooling ventilation air, and cool or green roofs.

Finally, detailed building energy models can make daylighting calculations and include them in the thermal energy balance of buildings. Lights can contribute significantly to building energy end-use, both directly (11.3% according to DOE 2009) and by adding heating loads, which affect the eventual waste heat released from HVAC systems.

3 The Coupled Scheme

The coupled scheme combines EnergyPlus and the TEB model to calculate the energy performance of buildings and the urban climate around the buildings, taking into account the reciprocal interactions between the two.

3.1 Definition of a Reference Building in EnergyPlus

The current version of the coupled scheme is able to analyze an average-oriented urban canyon (Masson 2000). A box-type reference building is defined in EnergyPlus assuming an urban area composed of a regular grid of square-plan buildings (Fig. 1). The geometry of the reference building is obtained using TEB urban morphology parameters: building height (h_{bld}), building horizontal area density (ρ_{bld}), and vertical to horizontal urban surface ratio (*VH*), viz.

$$\rho_{\mathrm{bld}} = a^2/\,(a/2 + b/2)^2\,, \tag{1}$$

$$VH = 4ah_{\mathrm{bld}}/\,(a/2 + b/2)^2\,. \tag{2}$$

In these expressions, a is the side of the square-plan building and b is the side of the square formed by the projection of the surrounding buildings façades on the ground (Fig. 2). The geometric unit of the urban grid used to derive Eqs. 1 and 2 is indicated with a broken-dash

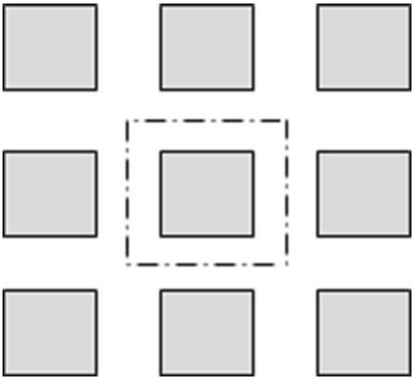

Fig. 1 Plan view of an urban area composed of a homogeneous grid of square-plan buildings. The geometric unit of the grid is indicated with a *broken-dash line*

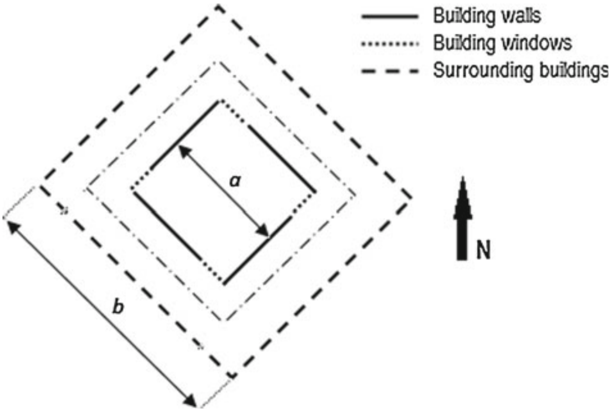

Fig. 2 Plan view of the reference building defined in the EnergyPlus model, indicating building walls, building windows and surrounding buildings. The building is rotated 45° with respect to the north–south axis. The geometric unit of the grid is indicated with a *broken-dash line*. The dimension parameters *a* and *b* are calculated from the TEB model's morphology parameters

line in both Figs. 1 and 2. The reference building is composed of a single zone with an internal thermal mass representing intermediate floor constructions. Windows are defined such that their vertical dimension matches the vertical dimension of building façades, and their horizontal dimension is a fraction of the horizontal dimension of building façades according to the glazing ratio. Surrounding buildings are represented by shadowing surfaces. The solar radiation received by the four vertical surfaces of the reference building approaches the solar radiation received by walls in the average-oriented canyon calculated by the TEB model. A closer agreement to the average-oriented canyon approach can be achieved by rotating the building 45° with respect to the north–south axis (Fig. 2).

3.2 Exchanged Information

Both EnergyPlus and the TEB model are able to calculate exterior wall and roof surface temperatures. In the coupled scheme, these surface temperatures are calculated by TEB and then used in EnergyPlus as boundary conditions. One of the reasons for this choice is that EnergyPlus simplifies the calculation of longwave radiation between a building surface and the surrounding urban surfaces, assuming that the latter are at the outdoor air temperature. Wall convective heat transfer correlations (CHTC) also differ between the two models. Palyvos (2008) presented a literature review of CHTC applied to building surfaces, and proposed a generic correlation more similar to the one used in TEB (Masson 2000) than to that used in EnergyPlus (DOE 2010a).

The original version of the TEB model is only able to calculate surface temperatures associated with the fraction of façades covered by walls, neglecting the effect of windows in the outdoor energy balance. Window surface temperatures can be significantly different from wall surface temperatures and are more affected by the indoor environment. The coupled scheme uses an adapted version of TEB that is able to use the window temperatures calculated by EnergyPlus in its outdoor energy balance according to the glazing ratio of building façades. Solar reflections, convective and radiative heat exchanges are modified in TEB accordingly.

EnergyPlus also calculates the waste heat released from HVAC systems. In compression refrigeration cycles (the most common cooling systems), waste heat emissions (Q_{waste}) can be calculated by adding the heat exchanged between the HVAC system and the building (Q_{exch}) and the energy consumption of the HVAC system (Q_{cons}), $Q_{\mathrm{waste}} = Q_{\mathrm{exch}} + Q_{\mathrm{cons}}$. In fuel-combustion heating systems, waste heat emissions correspond to the combustion gases exhausted from chimneys and are calculated as $Q_{\mathrm{waste}} = Q_{\mathrm{cons}} - Q_{\mathrm{exch}}$. The energy exchanged between the HVAC system and the building, and the energy consumed by the system, are calculated by EnergyPlus taking into account the interactions among system, building, and environment. The resulting waste heat emissions are included in the outdoor energy balance of TEB as a wall-distributed energy source.

3.3 Iterative Coupling Method

The coupled scheme uses an iterative method to calculate the interactions between EnergyPlus and the TEB model. The iterative coupling process starts from a preliminary TEB simulation using off-line meteorological forcing information (for details, see Masson et al. 2002). The wall temperatures, roof temperatures, and urban canyon climate conditions calculated by TEB are supplied as boundary conditions to an EnergyPlus simulation. Then, window temperatures and HVAC waste heat emissions calculated by EnergyPlus are used in a new iteration of TEB. This process (Fig. 3) is repeated until a convergence criterion is satisfied. In the present study, convergence was assumed to be reached when the average canyon temperature difference between iterations fell below 0.05°C. This was typically achieved after two or three iterations.

4 Comparison with Field Data

4.1 Observations

This section presents a comparison between the coupled scheme, the original TEB model, and the measurements obtained during the experiment CAPITOUL carried out in Toulouse (France) from February 2004 to March 2005 (Masson et al. 2008). During the experiment, forcing measurements were taken in the dense urban centre of Toulouse at 27.5 m above the average building height and 47.5 m above the ground. In the same area, urban air temperatures were obtained from a sensor installed at the top of a street canyon. Surface temperatures

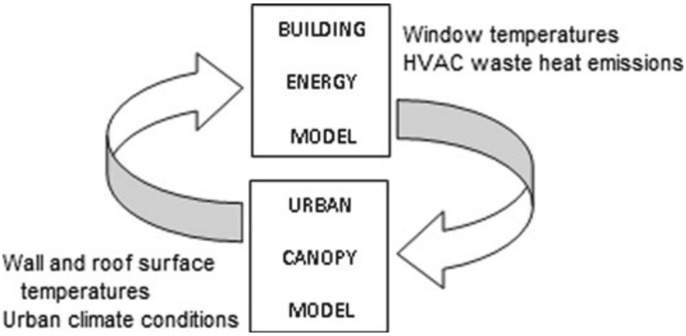

Fig. 3 Iterative method of the coupled scheme. The building energy model (EnergyPlus) calculates window temperatures and waste heat release from HVAC systems. The urban canopy model (TEB) calculates wall and roof surface temperatures, as well as climate conditions inside the urban canyon. Both models iterate until a convergence criterion is satisfied

of building façades were measured with infrared radiometers for different urban canyon orientations (Pigeon et al. 2008). A city-scale inventory of electricity and natural gas energy consumption of buildings was also conducted during the experiment. Anthropogenic heat fluxes from traffic and building energy uses were obtained from the residual of the surface energy balance (SEB) equation (Oke 1988). A detailed description of the inventory approach and the residual method is presented in Pigeon et al. (2007).

4.2 Model Set-Up

Table 1 presents the set-up of the original TEB model and the coupled scheme for this case study. A number of modelling assumptions were made given the lack of detailed information about the buildings of the site. In the comparison between TEB simulations and CAPITOUL observations carried out by Pigeon et al. (2008), walls and roof were assumed to have no insulation. However, preliminary comparisons between simulation results and observations showed that both TEB and EnergyPlus consistently overpredict exterior wall temperatures in winter when no insulation is considered in the walls and roof. Furthermore, it is reasonable to think that many of the buildings in Toulouse are provided with some kind of insulation to reduce heating energy consumption in winter. This can be a simple air-cavity or an insulation material installed after a rehabilitation process. In this study, an interior insulation layer 30 mm thick was assumed.

Figure 4 represents the daily average observations of electricity consumption of buildings and outdoor air temperatures during 2 months in summer. As can be seen, variations of air temperature do not have a noticeable impact on electricity consumption, which presents a typical-week profile. This fact suggests that air-conditioning systems are not extensively used in Toulouse during the summer and that the electricity consumption of buildings is dominated by the use of domestic electricity devices. This conclusion is used to obtain an average internal heat gain value of 38.6 $\mathrm{W\,m^{-2}}$ (building plan area) to be used in the model, assuming that the fraction of internal heat gains associated with electricity is 0.7. These values typically correspond to the residential sector, which represents the majority of the buildings of the urban area under study.

Infiltration level in buildings is an important source of modelling uncertainty, above all in the residential sector. Our analysis uses a generic infiltration/ventilation airflow rate value of

Table 1 Simulation parameters used for the evaluation of the coupled scheme with field data from the experiment CAPITOUL conducted in Toulouse (France)

Parameters	Settings
Average building height	20 m
Building density	0.68
Vertical to horizontal surface ratio	1.05
Roughness length	2.0 m
Anthropogenic heat from traffic	8.0 $\mathrm{W\,m^{-2}}$ (urban area) (Pigeon et al. 2007)
Glazing-to-wall ratio	0.3
Window construction	Double pane clear glass (6 mm glass with 6 mm gap)
Wall and roof construction	
Outside layer	Brick (thickness 0.3 m; thermal conductivity 1.15 $\mathrm{W\,m^{-1}\,K^{-1}}$; volumetric heat capacity 1.58 × 10^6 $\mathrm{J\,m^{-3}\,K^{-1}}$; emissivity 0.95; albedo 0.32)
Inside layer	Insulation board (thickness 0.03 m; thermal conductivity 0.03 $\mathrm{W\,m^{-1}\,K^{-1}}$; volumetric heat capacity 5.203 × 10^4 $\mathrm{J\,m^{-3}\,K^{-1}}$)
Road construction	
Outside layer	Asphalt (thickness 0.24 m; thermal conductivity 1.95 $\mathrm{W\,m^{-1}K^{-1}}$; volumetric heat capacity 2.016 × 10^6 $\mathrm{J\,m^{-3}\,K^{-1}}$; emissivity 0.94; albedo 0.08)
Inside layer	Ground (thickness 1 m; thermal conductivity 0.4 $\mathrm{W\,m^{-1}\,K^{-1}}$; volumetric heat capacity 1.4 × $10^6 \mathrm{J\,m^{-3}K^{-1}}$)
Infiltration/ventilation air flow rate	7.46 $\mathrm{m^3\,s^{-1}}$ = 0.5 air changes per hour
Internal gains	Residential: 38.61 $\mathrm{W\,m^{-2}}$(building plan area). Latent fraction: 0.2; Radiant fraction: 0.2; Electric fraction: 0.7. Schedule: weekdays, 1; weekend, 0.71.
HVAC system	
Cooling system	None
Heating system	Gas furnace
Heating efficiency	0.9
Thermal set points	19°C—No max.
Schedule	Operative 24 h
Fraction of electric heating systems over gas heating systems	2/3

0.5 ACH (room air volume changes per hour). Finally, a fraction of electric heating systems over gas heating systems of 2/3 was also assumed.

4.3 Building Energy Consumption

Figure 5 shows the daily average electricity and natural gas consumption for 2 months in winter. Observations are compared with the simulation results of the TEB model and the coupled scheme. The original TEB model, which does not account for heat losses due to windows and infiltration, underestimates the heating energy consumption of buildings. A better agreement was obtained by Pigeon et al. (2008) assuming that building walls did not

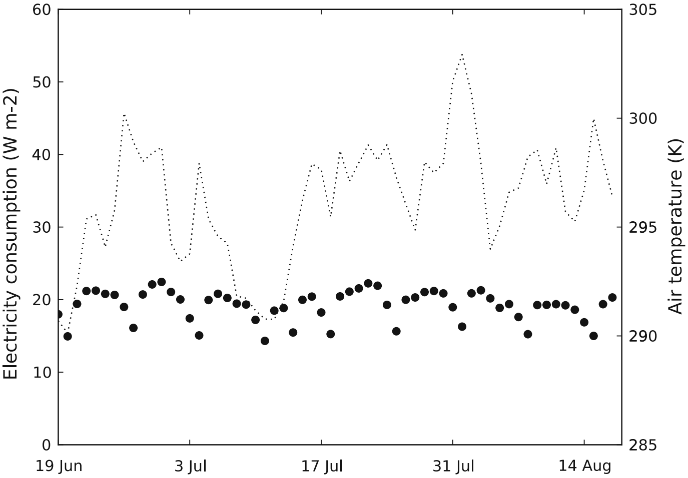

Fig. 4 Daily average observations of electricity consumption per unit of urban area (*solid*) and urban canyon air temperature (points) between 19 June 2004 and 17 August 2004

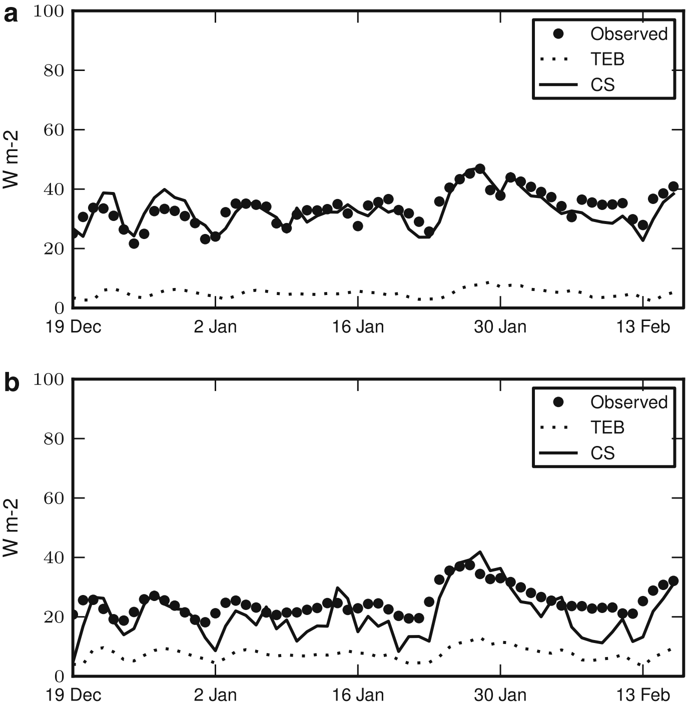

Fig. 5 Daily average electricity (*top*) and natural gas (*bottom*) consumption per unit of urban area from observations, calculated by TEB, and calculated by the coupled scheme between 19 December 2004 and 17 February 2005

Table 2 Bias and *RMSE* between the coupled scheme simulations and observations for electricity consumption, natural gas consumption, façade temperatures, and urban canyon-air temperatures

	Winter		Summer	
	Bias	*RMSE*	Bias	*RMSE*
Electricity consumption				
Daily average (W m^{-2})	0.74	3.79	2.87	4.69
Natural gas consumption				
Daily average (W m^{-2})	4.18	6.58	–	–
Façade temperature				
Hourly average (K)	0.3	1.25	0.66	0.95
Urban canyon-air temperature				
Hourly average (K)	0.26	0.57	0.21	0.96

Winter period is from 19 December 2004 to 17 February 2005. Summer period is from 15 June 2004 to 14 August 2004. For facade and urban canyon air temperature results, only the last 30 days of each period is considered, due to limitations in measured data availability

have insulation. Electricity and natural gas consumption computed as a bias and root-mean-square error (RMSE) between the coupled scheme and observations are presented in Table 2. Given the modelling hypothesis indicated in Sect. 4.2, the coupled scheme is able to capture the variations of electricity and gas consumption during the winter with bias and *RMSE* lower than 7 W m^{-2}, averaged on the urban area. The underestimation in the gas consumption can be related to the uses of gas other than for indoor air heating, for example, for cooking.

4.4 Anthropogenic Heat Fluxes

Daily average values of anthropogenic heat fluxes are represented for two months in winter and two months in summer (Fig. 6). Observations are available for a certain number of days (Pigeon et al. 2007). In winter, the original TEB accounts for anthropogenic heat fluxes due to traffic and building heating, without including other building energy uses. As a result, overall anthropogenic heat fluxes are underpredicted. In summer, assuming that a negligible number of cooling systems operate in the urban area, anthropogenic heat fluxes are dominated by the internal heat gains calculated in Sect. 4.2. Despite the inherent uncertainties in the residual method, it is possible to appreciate that the order of magnitude calculated by the coupled scheme agrees with observations, both in winter and in summer.

4.5 Façade Temperatures

Surface temperature measurements were taken in different locations and for different urban canyon orientations. The results are the area-weighted façade temperature resulting from the surface temperatures of the wall and the windows included in the view angle of the sensor. For the coupled scheme simulations, a glazing ratio of 0.3 is assumed based on the reported glazing ratio of the different measurement locations. Figure 7 presents a comparison between the measured façade surface temperatures, the wall temperatures calculated by the original TEB, and the window and façade temperatures calculated by the coupled scheme for winter and for summer. Statistical parameters of the comparison between the coupled scheme and observations are presented in Table 2.

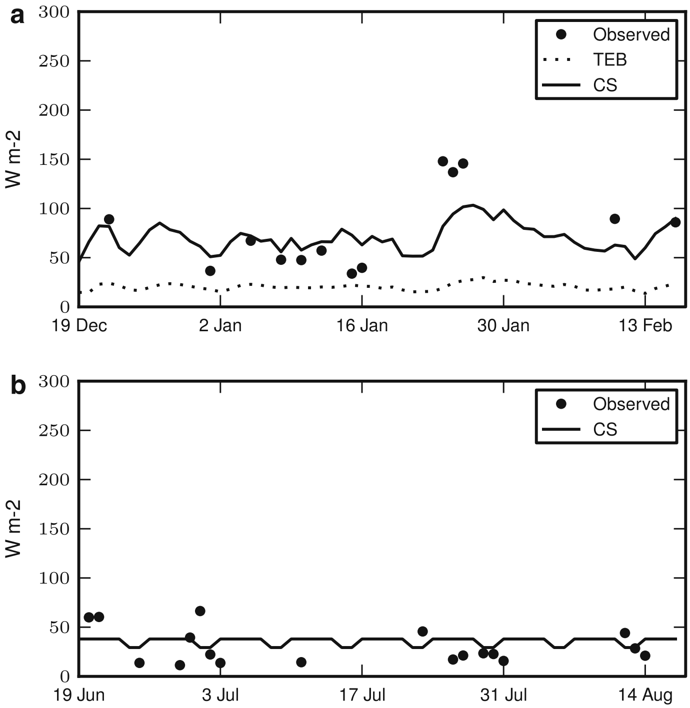

Fig. 6 Daily average anthropogenic heat per unit of urban area from observations, calculated by the TEB model, and calculated by the coupled scheme between 19 December 2004 and 17 February 2005 (*top*); and from observations and calculated by the coupled scheme between 19 June 2004 and 17 August 2004 (*bottom*)

Exterior window surface temperatures have a very different behaviour with respect to exterior wall surface temperatures between winter and summer. Apart from thermal inertia and solar considerations, window surface temperatures are more affected by the indoor environment than exterior wall surface temperatures, because windows are less insulated. In winter, indoor air temperatures are significantly higher than outdoor air temperatures; thus, window surface temperatures are in general higher than exterior wall surface temperatures (Fig. 7, top). In summer, the difference between indoor and outdoor air temperatures is lower than in winter, and wall and window surface temperatures are similar. In Fig. 7 (bottom), window temperatures are slightly higher than wall temperatures during the night, which is related to the fact that the indoor air is not conditioned (no cooling system).

The façade temperatures calculated by the coupled scheme present a reasonably good agreement with the observed façade temperatures with bias and *RMSE* that range between 0.3 and 1.3 K. The wall temperatures calculated by the TEB model also match the observations, but TEB excludes the presence of windows in the analysis.

4.6 Outdoor Air Temperatures

Figure 8 compares the measured urban canyon air temperatures with the air temperatures calculated by TEB and by the coupled scheme for winter and for summer. Table 2 presents a statistical analysis of this comparison. In winter, waste heat emissions due to indoor air heating are small, and both models predict very similar outdoor air temperatures. In summer,

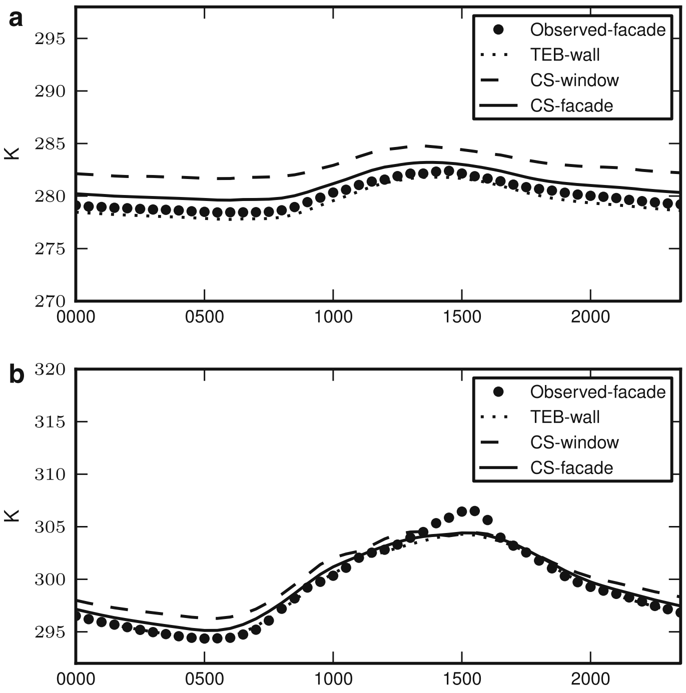

Fig. 7 Monthly average diurnal cycle of the façade temperature from observations, calculated by the TEB model, and calculated by the coupled scheme for winter, 16 January 2005 to 15 February 2005 (*top*); and for summer, 16 July 2004 to 15 August 2004 (*bottom*)

without waste heat emissions (no cooling system) and having very similar window and wall temperatures (Fig. 7, bottom), the prediction of outdoor air temperatures is almost identical between the two models. This comparison shows a reasonably good agreement between the simulation results and observations, with the bias and *RMSE* smaller than 1 K.

5 Case Studies

In Sect. 4, observations indicated that air-conditioning systems are not used in the urban centre of Toulouse, so HVAC waste heat emissions do not contribute significantly to urban heating. This situation is expected to change in the following years as a consequence of global-scale and urban-scale climate warming (Adnot 2003). In this section, the coupled scheme is used to analyze different scenarios of buildings and HVAC systems in Toulouse, including the presence of cooling systems and the waste heat emissions associated with them. Table 3 summarizes the new modelling parameters used in this analysis (other parameters are defined in Table 1).

5.1 HVAC System Simulations

The contribution of a detailed definition of HVAC systems with respect to an ideal representation was highlighted in Sect. 2.3. Here, the detailed definition will be referred to as a real HVAC simulation, in contrast to an ideal HVAC simulation. Figure 9 shows the difference in HVAC waste heat emissions between a real and an ideal HVAC simulation for summer,

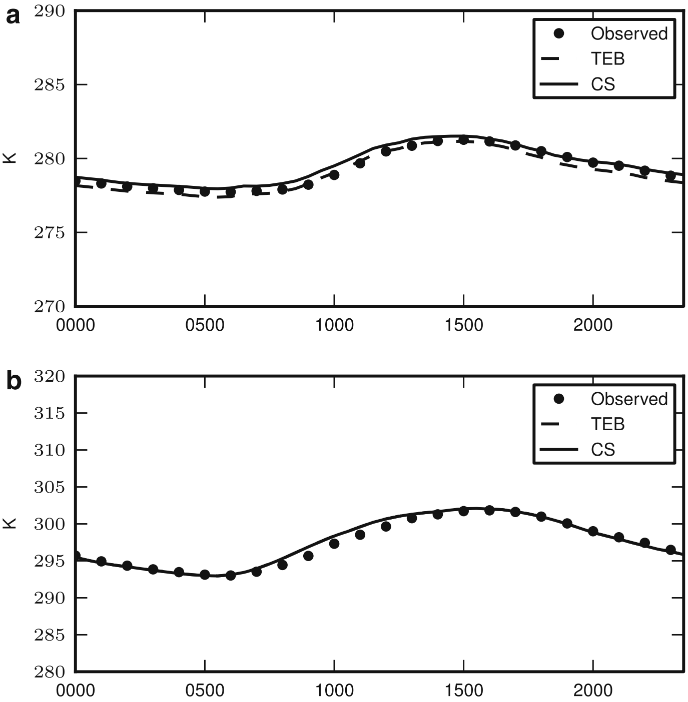

Fig. 8 Monthly average diurnal cycle of the urban canyon air temperature from observations, calculated by the TEB model, and calculated by the coupled scheme for winter, 16 January 2005 to 15 February 2005 (*top*); and for summer, 16 July 2004 to 15 August 2004 (*bottom*)

which ranges between 7 and 13%. Two different building uses are represented: residential and commercial (Table 3). Different levels of waste heat emissions are predicted for the residential and the commercial buildings, around 60 and 190 $\mathrm{W\,m^{-2}}$, respectively, averaged on the urban area. A similar study carried out by Salamanca and Martilli (2010) predicted waste heat emissions in Basel (Switzerland) at summertime that ranged between 90 and 160 $\mathrm{W\,m^{-2}}$.

The differences between the real and the ideal HVAC simulations are mainly related to the calculated latent heat exchanged between the HVAC system and the building. In the ideal simulation, the exchanged latent heat is directly equal to the latent energy demand of the building. In the real case, and in a typical situation where the system is only controlled by a thermostat (no humidity control), the exchanged latent heat is a consequence of the dehumidification of the air passing through the system, when this is cooled to meet the sensible energy demand of the building.

The fact that the evolution of waste heat during the day is less dynamic in the real case than in the ideal case can be explained by two effects that are captured by the real simulation and not by the ideal simulation. First, when the system is working at night, it experiences a loss of efficiency due to working at part load. It also experiences a gain of efficiency due to lower condenser temperatures; but, in this case, the first effect dominates. As a result, the energy consumption from the real simulation is higher than the one obtained from the ideal simulation. Second, the real HVAC system has a limited capacity, which

Table 3 Coupled scheme simulation set-up used in the case studies

Parameters	Settings
Air infiltration	$1.49\,\mathrm{m^3\,s^{-1}} = 0.1$ air changes per hour
Internal gains	
Residential	$38.61\ \mathrm{W\,m^{-2}}$ (building plan area)
Office	$193.05\ \mathrm{W\,m^{-2}}$(building plan area)
Solar protections	
Residential	Exterior window shades are deployed if beam plus diffuse solar radiation incident on the window exceeds $100\ \mathrm{W\,m^{-2}}$.
Office	White painted metal blinds are controlled to block beam solar radiation on windows.
HVAC system	
Type	All-air unitary system (DOE 2010a)
Outdoor airflow rate	Residential: $6.09\ \mathrm{m^3\,s^{-1}} = 0.4$ air changes per hour
	Commercial: $8.91\ \mathrm{m^3\,s^{-1}} = 0.6$ air changes per hour
Thermal set points	19°C–24°C
Schedule	Operative 24 h
Cooling system	
Cooling coil type	Single speed fan on the air side, with evaporating refrigerant in the coils
Cooling COP	2.5 (this value is modified by EnergyPlus at each timestep)
Economizer	Set the outdoor airflow rate at maximum (5 times the minimum) if the outdoor air temperature is lower than 24°C and higher than 19°C.
Heating system	
Heating coil type	Gas furnace
Heating efficiency	0.9
Heat recovery	Type: sensible; efficiency: 0.7.

Other parameters are defined in Table 1

means that, during the peak hours of the warmest days, the system may not be able to provide the required energy and its energy consumption decreases with respect to the ideal simulation.

Over the entire cooling period, the seasonal-average difference in cooling energy between the real and the ideal HVAC simulations for residential and commercial buildings, normalized by façade area, is 2.5 and $9.6\ \mathrm{W\ m^{-2}}$, respectively, with maximum differences of 24.6 and $49.2\ \mathrm{W\ m^{-2}}$. This analysis corresponds to the simplest representation of a realistic HVAC system. Other common HVAC system configurations have associated energy losses (e.g. reheat systems) that would lead to greater differences between the real and the ideal simulation.

5.2 Effect of Waste Heat on Outdoor Air Temperatures

Figure 10 compares the calculated outdoor air temperatures for summer with and without waste heat from HVAC systems. For the residential case, which is associated with low energy

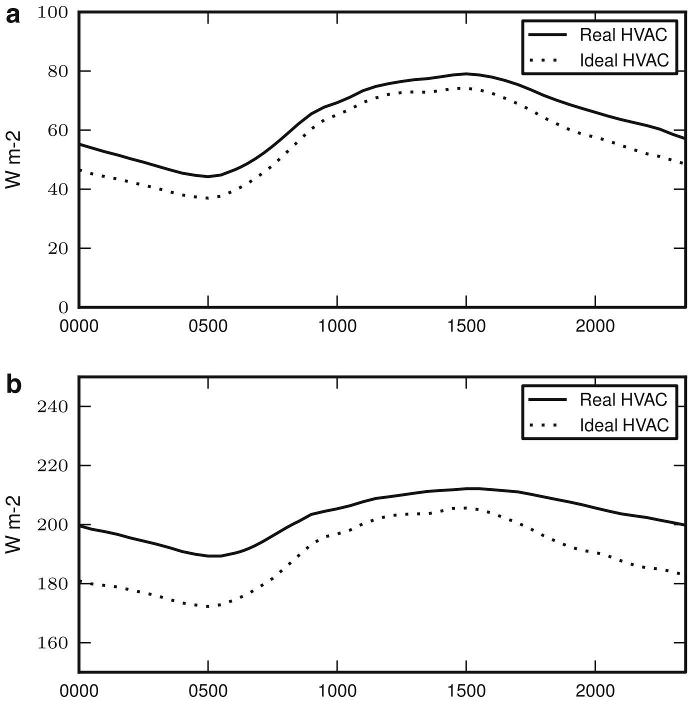

Fig. 9 Monthly average diurnal cycle of HVAC waste heat emissions per unit of façade area from a real and an ideal HVAC simulation of a residential (*top*) and a commercial building (*bottom*) for summer, 16 July 2004 to 15 August 2004

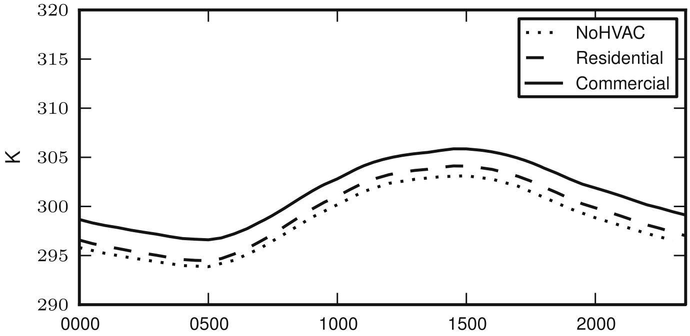

Fig. 10 Monthly average diurnal cycle of the urban canyon air temperature from a coupled scheme simulation of a residential and a commercial building for summer, 16 July 2004 to 15 August 2004

consumption and waste heat emissions, the average increase in outdoor air temperature is 0.8 K. In the commercial case, the average increase in the outdoor air temperature is 2.8 K. Similar values of air temperature increase due to HVAC systems have been reported previously (Kikegawa et al. 2003; Ohashi et al. 2007; Hamilton et al. 2009).

Table 4 Annual energy savings and average waste heat reduction associated with the use of shading devices, economizers, and heat recovery systems

	Annual energy savings per unit of building plan area		Average waste heat reduction per unit of façade area	
	Absolute (kWh m^{-2})	Relative (%)	Absolute (W m^{-2})	Relative (%)
Shading devices (Cooling)				
Residential	24.0	20.50	8.5	28.83
Commercial	26.5	5.60	10.2	5.06
Economizers (Cooling)				
Residential	8.7	7.44	3.3	14.80
Commercial	27.1	3.60	4.3	3.21
Heat recovery (Heating)				
Residential	153.8	49.57	3.1	60.02

Energy savings and waste heat reductions are referred to the cooling system for shading devices and economizers and to the heating system for the heat recovery

5.3 Effect of Shading Devices on Energy Consumption and HVAC Waste Heat Emissions

Shading devices are passive systems that reduce the transmitted solar radiation into the building. Ideally, these devices should block direct solar radiation in the cooling period (summer), but allow the transmission of diffuse solar radiation for daylight purposes. They should also allow solar heat transmission in the heating period (winter) provided that there are no glare issues. In this analysis, two different shading devices typically used for residential and for commercial buildings in Toulouse are considered (Table 3).

Table 4 presents the annual cooling energy savings and average waste heat reduction associated with the use of shading devices in summer for residential and commercial buildings. Residential buildings, whose cooling loads are more sensitive to the transmitted solar radiation due to the low internal heat gains, can achieve reductions in energy savings and waste heat emissions of 21 and 29%, respectively, by using shading devices. Having a similar absolute value of waste heat reduction (similar impact on the outdoor environment), commercial buildings present lower relative values of energy consumption and waste heat reduction than residential buildings (around 5%).

5.4 Effect of Economizers on Energy Consumption and HVAC Waste Heat Emissions

An economizer allows more than the minimum outdoor airflow to enter the building when the outdoor temperature is favourable (cooler than indoors in summer). This reduces the consumption of the cooling plant and its waste heat emissions but penalizes the electricity consumption of fans. The application of economizers can be useful in commercial buildings when outdoor air temperatures are below the cooling set point and buildings still have cooling energy demand due to internal heat gains. In residential buildings, the same effect is usually achieved by means of natural ventilation (opening the windows), which does not require the electricity consumption of a fan. The effectiveness of these strategies is very sensitive to increases in outdoor air temperatures, which reduce the amount of time they can operate. For the purposes of this analysis, an economizer is also applied to the residential case instead of a natural ventilation system. The main difference is the outdoor airflow passing through the building, which is constant for an economizer and variable for a natural ventilation system. The results of this analysis provide an upper limit for natural ventilation potential.

Table 3 presents the modelling parameters of the economizer considered in this study. Energy savings and waste heat reduction are achieved when outdoor air temperatures are within the minimum and the maximum temperature thresholds of the economizer. This occurs during the warmest days in late spring and fall and during the coolest days in early summer and fall. For the warmest days in summer (from mid-July), the economizer cannot operate and there are no associated reductions in waste heat.

Table 4 presents the annual cooling energy savings and average waste heat reduction associated with the use of economizers for residential and commercial buildings in Toulouse. Residential buildings can achieve reductions in energy consumption and waste heat emissions of 7 and 15%, respectively. Commercial buildings can save around 3% in both energy consumption and waste heat emissions by using economizers. In both cases, the effect of waste heat reduction on the outdoor environment is negligible.

5.5 Effect of Heat Recovery on Energy Consumption and HVAC Waste Heat Emissions

A heat exchanger located between the exhaust air coming from the building and the ventilation air coming from outdoors reduces ventilation heat losses, which are an important fraction of the heating energy demand of buildings in winter. In summer, the temperature difference between indoor and outdoor conditions is lower than in winter and heat recovery systems are less effective. Due to the close interaction with the outdoor environment, heat recovery systems are also sensitive to the UHI effect.

Table 3 presents the parameters of the heat recovery system considered in this analysis. Table 4 presents the annual heating energy savings and average waste heat reduction associated with the use of heat recovery systems for residential buildings in Toulouse. Reductions in energy consumption and waste heat emissions of 50 and 60%, respectively, can be achieved by this strategy. However, due to the low waste heat emissions associated with fuel-combustion heating systems, the effect of heat recovery systems on the outdoor environment is negligible. This analysis does not include commercial buildings because their heating energy consumption is very small in this case.

6 Conclusion

A coupled scheme between a detailed building energy model, EnergyPlus, and an urban canopy model, TEB, has been presented. The coupled scheme is evaluated with field data from the urban centre of Toulouse, France, showing its capacity to predict energy consumption in buildings and thermal conditions in urban canyons.

The coupled scheme allows a detailed analysis of the two-way interactions between the energy performance of buildings and the urban climate around the buildings. In this study, the scheme has been used to analyze the impact on waste heat emissions and outdoor air temperatures of a realistic definition of HVAC systems. The study shows that waste heat emissions can raise outdoor air temperature between 0.8 K for residential neighbourhoods and 2.8 K for commercial neighbourhoods in summer, under possible future scenarios in which air conditioning is widely used. The scheme has also been used to evaluate the effect on the energy consumption and waste heat emissions of three different energy efficiency strategies for Toulouse. The study shows that shadowing devices are an effective strategy to reduce the cooling energy consumption of buildings and to mitigate the UHI effect associated with HVAC waste heat emissions. The use of heat recovery systems can also achieve important reductions of heating energy consumption, but it does not have a significant effect on the outdoor environment due to the low waste heat emissions associated with fuel-combustion heating systems. The use of economizers in HVAC systems does not yield important benefits in terms of energy savings or waste heat reduction for this particular case study.

Building energy models are being developed within the urban climate community and integrated into urban canopy models. Their objective is to account for HVAC waste heat emissions in the outdoor energy balance and to include the energy consumption of buildings as an important parameter for the analysis and design of urban areas. The coupled scheme, which already incorporates a detailed building energy model, can be used in the evaluation process of these new building energy models. The type of analyzes carried out in this study are useful for determining which building and HVAC system configurations are the most important for each particular application, so that developers can more effectively focus their modelling efforts.

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