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Development and evaluation of a building energy model integrated in the TEB scheme

B. Bueno[1,2], **G. Pigeon**[1], **L. K. Norford**[2], **and K. Zibouche**[3]

[1]CNRM-GAME, URA1357, CNRS – Météo France, Toulouse, France
[2]Massachusetts Institute of Technology, Cambridge, USA
[3]Université Paris-Est, Centre Scientifique et Technique du Bâtiment (CSTB), France

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Correspondence to: B. Bueno (bbueno@mit.edu)

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Abstract

The use of air-conditioning systems is expected to increase as a consequence of global-scale and urban-scale climate warming. In order to represent future scenarios of urban climate and building energy consumption, the Town Energy Budget (TEB) scheme must be improved. This paper presents a new building energy model (BEM) that has been integrated in the TEB scheme. BEM-TEB makes it possible to represent the energy effects of buildings and building systems on the urban climate and to estimate the building energy consumption at city scale (~10 km) with a resolution of a neighbourhood (~100 m). The physical and geometric definition of buildings in BEM has been intentionally 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 a difference with respect to other building parameterizations used in urban climate, BEM includes specific models for real air-conditioning systems. It accounts for the dependence of the system capacity and efficiency on indoor and outdoor air temperatures and solves the dehumidification of the air passing through the system. Furthermore, BEM includes specific models for passive systems, such as window shadowing devices and natural ventilation. BEM has satisfactorily passed different evaluation processes, including testing its modelling assumptions, verifying that the chosen equations are solved correctly, and validating the model with field data.

1 Introduction

The energy consumption of heating, ventilation and air-conditioning (HVAC) systems in buildings has become an important factor in the design and analysis of urban areas.

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HVAC systems are responsible for waste heat emissions that contribute to the increase in air temperature observed in urban areas with respect to their undeveloped rural surroundings (Sailor, 2010). This phenomenon, known as the urban heat island (UHI) effect, can affect the energy consumption of HVAC systems and the waste heat emissions associated with them. The use of HVAC systems is expected to increase in the following years as a consequence of global-scale and urban-scale climate warming (Adnot, 2003); therefore, urban climate models, such as the Town Energy Budget (TEB) scheme (Masson, 2000), must be improved in order to represent future scenarios of climate conditions and energy consumption in urban areas.

The TEB model is a physically based urban canopy model that represents the fluid dynamic and thermodynamic effects of an urbanized area on the atmosphere. This 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; Lemonsu et al., 2010). Previous versions of the TEB model implement 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. A minimum indoor air temperature threshold is used to calculate the heating loads of the building associated with transmission through building surfaces (Pigeon et al., 2008).

In order to improve the representation of buildings in TEB, we have considered two different approaches. The first approach is to couple a well-known building energy model, such as EnergyPlus (Crawley et al., 2001), with TEB. This is the strategy adopted in Bueno et al. (2011). However, the coupled scheme (CS) developed in this study requires a number of iterations between the two models, which makes it unsuitable for coupling with atmospheric models.

The second approach is to develop a new building energy model (BEM) integrated in the urban canopy model. This is the approach taken by Kikegawa et al. (2003) and Salamanca et al. (2010). They developed simplified building energy models that are able to capture the main heat transfer processes that occur inside buildings and to

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calculate building energy demand, HVAC energy consumption and waste heat emissions (Kondo and Kikegawa, 2003; Salamanca and Martilli, 2010, Kikegawa et al., 2006; Ihara et al., 2008). However, they consider idealized HVAC systems and do not take into account passive building systems. Following this approach, this paper presents a BEM integrated in the TEB model that overcomes the above-mentioned limitations of the previous models.

In this study, BEM-TEB is evaluated at three levels: modelling assumptions; model verification, based on a comparison with the CS (Bueno et al., 2011); and model validation, based on a comparison with field data from two experiments, Toulouse (Masson et al., 2008) and Athens (Synnefa et al., 2010).

2 Model description

2.1 Objective and main features

The objective of BEM is to represent the energy effects of buildings on the urban climate and to calculate the building energy consumption at city or neighbourhood scale.

BEM calculates the energy demand of a building by applying a heat balance method. It considers a single thermal zone and represents the thermal inertia of various building levels by a generic thermal mass. The model accounts for solar radiation through windows, heat conduction through the enclosure, internal heat gains, infiltration and ventilation (Fig. 1).

BEM includes specific models for active and passive building systems. It considers the dependence of the cooling system efficiency on indoor and outdoor temperatures and solves the dehumidification of the air passing through the system. Passive building systems such as window shadowing devices and natural ventilation are represented in BEM.

The model has been kept as simple as possible, while maintaining the required features of a comprehensive building energy model. We have intentionally avoided

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detailed building calculations that would have affected the computational efficiency of the TEB model without providing a significant gain in accuracy.

2.2 Geometry and building definition

BEM uses the same geometric principles as the TEB model, which can be summarized as:

- Homogenous urban morphology. Building enclosure is defined by an average-oriented façade and a flat roof.
- Uniform glazing ratio. BEM assumes that all building façades have the same fraction of glazed surface with respect to their total surface.

In addition, the following is assumed to define buildings in BEM:

- Single thermal zone. BEM assumes that all buildings in a particular urban area have the same indoor air temperature and humidity. This approach is justified if the objective is to calculate the overall energy consumption of a building (or neighbourhood), rather than the energy performance of a specific building zone.
- Internal thermal mass. In the single-zone approach, an internal thermal mass represents the thermal inertia of the construction materials inside a building (e.g. separation between building levels). The transmitted solar radiation and the radiant fraction of internal heat gains are perfectly absorbed by the internal thermal mass and then released into the indoor environment.
- Adiabatic ground floor. The current version of BEM assumes that the surface of the building in contact with the ground is well-insulated.

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2.3 Heat balance method

BEM uses a heat balance method to calculate indoor thermal conditions and building energy demand. An energy balance is applied to each indoor surface (wall, window, floor, roof, and internal mass), accounting for conduction, convection, and radiation heat components, viz.

$$Q_{cd} + Q_{cv} + \sum_{si} Q_{rd} = 0. \quad (1)$$

The convection and radiation terms are calculated from a standard heat transfer coefficient formulation, $Q = h\Delta T$ (see Appendix). Convective heat transfer coefficients depend on the relative position between the surface and the indoor air. Radiative heat transfer coefficients are obtained from linearization of the Stefan-Boltzmann equation, assuming only one bounce of radiative heat fluxes between surfaces. The transient heat conduction through massive building elements (walls, floor, roof, and internal mass) is calculated using TEB routines, which are based on the finite difference method.

To calculate the dynamic evolution of indoor air temperature between a cooling and a heating thermal set point, BEM solves a sensible heat balance at the indoor air. The sensible heat balance is composed of the convective heat fluxes from indoor surfaces, the convective fraction of internal heat gains, the infiltration sensible heat flux, and the sensible heat flux supplied by the HVAC system.

$$V_{bld}\rho c_p \frac{dT_{in}}{dt} = \sum_{si} A_{si} h_{cv,si} (T_{si} - T_{in}) + Q_{ig}(1 - f_{rd})(1 - f_{lat}) + \dot{V}_{inf/vent}\rho c_p (T_{urb} - T_{in}) + \dot{m}_{sys} c_p (T_{sys} - T_{in}), \quad (2)$$

where V_{bld}, ρ, and c_p are the volume, density and specific heat of the indoor air, respectively; A_{si} is the area of the indoor surface; Q_{ig} represents the internal heat gains; f_{rd} and f_{lat} are the radiant and latent fractions of internal heat gains; $\dot{V}_{inf/vent}$ is the infiltration/ventilation air flowrate; T_{urb} is the outdoor air temperature; and $\dot{m}_{sys}$ and T_{sys} are the mass flowrate and temperature of the air supplied by the HVAC system.

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A latent heat balance is also solved to calculate the dynamic evolution of indoor air humidity. The latent heat balance is composed of the latent fraction of internal heat gains, the infiltration latent heat flux, and the latent heat flux supplied by the HVAC system.

$$V_{\mathrm{bld}}\rho l_{\mathrm{v}}\frac{dq_{\mathrm{in}}}{dt} = Q_{\mathrm{ig}}f_{\mathrm{lat}} + \dot{V}_{\mathrm{inf}}\rho l_{\mathrm{v}}(q_{\mathrm{urb}} - q_{\mathrm{in}}) + \dot{m}_{\mathrm{sys}}l_{\mathrm{v}}\left(q_{\mathrm{sys}} - q_{\mathrm{in}}\right), \quad (3)$$

where l_{v} is the water condensation heat, and q_{in} and q_{sys} are the specific humidity of the indoor air and of the air supplied by the HVAC system, respectively.

The building energy demand is calculated by applying the same sensible and latent heat balances at the indoor air, but assuming that this is at set point conditions. The specific humidity set point used for latent energy demand calculations is obtained from the relative humidity set point and the cooling or the heating temperature set point, which are provided by the user.

$$Q_{\mathrm{dem,sens}} = \sum_{\mathrm{si}} Q_{\mathrm{cv,si}} + Q_{\mathrm{ig,sens}} + Q_{\mathrm{inf,sens}}, \quad (4)$$

$$Q_{\mathrm{dem,lat}} = Q_{\mathrm{ig,lat}} + Q_{\mathrm{inf,lat}}. \quad (5)$$

2.4 Windows and solar heat transmission

Window effects have been introduced in the outdoor energy balance of the TEB model. The external surfaces of windows participate in the outdoor energy balance in the same manner as other urban surfaces (walls, road, garden, etc.). Window surfaces are semi-transparent and therefore have three optical properties (albedo, absorptivity, and transmittance). Two coupled surface energy balances are solved to calculate the internal and external surface temperatures of windows. Each surface energy balance accounts for the convective and radiative heat fluxes reaching the surface and the steady-state heat conduction through the window.

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Building energy models usually consider the dependence of the solar heat transmitted through windows on the angle of incidence of the sun. However, simulations with EnergyPlus for different window orientations show that for an average-oriented canyon, the solar transmittance of windows (τ_{win}) can be approximated by a uniform value of 0.77 times the solar heat gain coefficient (SHGC). The SHGC can be found in window catalogues and represents the fraction of incoming solar radiation that participates in the indoor energy balance. The solar heat transmitted through windows $(Q_{sol,win})$ is then calculated as:

$$Q_{sol,win} = Q_{sol,w}\tau_{win}GR, \quad (6)$$

where $Q_{sol,w}$ is the solar radiation reaching the building façade and GR is the glazing ratio.

The solar absorptivity of windows is calculated as a function of the U-factor and the SHGC, by using the equations proposed in EnergyPlus documentation (DOE, 2010). The U-factor can also be found in window catalogues and measures the window conductance, including the convective and longwave heat transfer coefficients at both sides of the window.

The window albedo is calculated so that the three optical properties (albedo, absorptivity, and transmittance) sum to unity. Then, the model uses an area-averaged façade albedo to calculate solar reflections by weighting the albedo of walls and windows with the glazing ratio of buildings.

2.5 Passive building systems

Passive building 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. Moreover, they are among the strategies promoted by governments throughout the world to reduce the energy consumption and green-house gas emissions of buildings.

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2.5.1 Natural ventilation

In residential buildings in summer (especially when an active cooling system is not available), occupants usually open their windows to naturally ventilate indoor spaces. To represent this situation, BEM includes a natural ventilation module, which modifies the indoor air energy balance (Eqs. 2 and 3) by including an outdoor air flowrate term, similarly to the infiltration term. If the conditions are favourable for natural ventilation, the HVAC system is assumed to be turned off at least during one hour. The natural ventilation air flowrate is calculated from a correlation that depends on the outdoor air velocity, the indoor and outdoor air temperatures, and the geometry of buildings and windows (see Appendix).

2.5.2 Window shades

BEM also includes a simplified model to account for window shadowing devices. If the solar radiation reaching the window is above a predefined threshold, the model considers that shades are placed outside and in front of the windows. These shades are characterized by a predefined transmittance. The model reduces the solar radiation reaching the windows by changing its optical properties. The solar radiation that is not reflected, absorbed, or transmitted by the windows is assumed to be converted into a sensible heat flux towards the urban canyon.

2.6 HVAC system

2.6.1 Ideal and realistic definitions of an HVAC system

BEM includes both an ideal and a realistic definition of an HVAC system. In the ideal definition, the system capacity is infinite, and the system supplies the exact amount of energy required to maintain indoor thermal and humidity set points. On the contrary, the realistic definition considers a finite capacity that can be provided by the user or calculated by the *autosize* function (see Sect. 2.6.7).

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In the case of a cooling system, the realistic definition also takes into account the dependence of the system capacity and efficiency on outdoor and indoor conditions. Furthermore, the system efficiency is affected by part-load performance, when the system does not work at its nominal capacity. The realistic definition of the cooling system solves for the dehumidification of the air passing through the cooling coil. In most 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. Figure 2 represents a psychrometric chart of humid air and the significant points of the HVAC model for a cooling situation (summer).

2.6.2 Mixing conditions

To calculate the supply air conditions and the energy consumption of the HVAC system, the model first calculates the mixing conditions of the air recirculated from the building and the outdoor air required for ventilation. This calculation is the same for both the cooling and the heating system models. The mixing ratio (X_{mix}) is calculated as $X_{mix} = \dot{V}_{vent}\rho/\dot{m}_{sys}$, where $\dot{m}_{sys}$ is the supply air mass flowrate and $\dot{V}_{vent}$ is the ventilation air volume flowrate, which are given by the user (or calculated by the *autosize* function in the case of the air mass flowrate) . Then, the mixing air temperature and humidity are calculated from the building air temperature and the outdoor air temperature as follows:

$$T_{mix} = X_{mix}T_{urb} + (1 - X_{mix})T_{in}, \quad (7)$$

and

$$q_{mix} = X_{mix}q_{urb} + (1 - X_{mix})q_{in}. \quad (8)$$

2.6.3 Cooling system

In the ideal cooling system model, the energy consumption is calculated by adding the sensible and the latent energy demand of the building and dividing by the system

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coefficient of performance (COP), $Q_{HVAC,cool} = Q_{dem,cool}/COP$. The supply conditions are then calculated to meet the building energy demand:

$$T_{sys} = T_{mix} - H_{dem,cool} / \left(\dot{m}_{sys} c_p\right), \quad (9)$$

and

$$q_{sys} = q_{mix} - LE_{dem,cool} / \left(\dot{m}_{sys} l_v\right), \quad (10)$$

where $H_{dem,cool}$ and $LE_{dem,cool}$ are the sensible and latent cooling demand of the building.

In the realistic cooling system model, the model solves a pychrometric model based on the apparatus dewpoint (ADP) temperature. The current version of BEM considers a constant-volume direct-expansion cooling system, but other system configurations can be added in future versions of the model. At each time step, the supply air temperature and humidity are calculated by satisfying two conditions. First, the supply point in the psychrometric chart (Fig. 2) must be contained in the line connecting the mixing point and the ADP point. Second, the supply temperature should meet the sensible energy demand of the building (Eq. 9). If the energy demand of the building is greater than the system capacity, the system capacity is used to calculate the supply temperature.

The system capacity $\left(Q_{cap,sys}\right)$ is calculated from the nominal system capacity multiplied by a coefficient that depends on outdoor and indoor conditions (see Appendix). The electricity consumption of the cooling coil ($Q_{HVAC,sys}$) is calculated by the following expression:

$$Q_{HVAC,sys} = Q_{cap,sys} PLR f_{PLR} / COP, \quad (11)$$

where PLR is the part-load ratio, calculated as the fraction between the energy supplied and the system capacity, and f_{PLR} is a coefficient that depends on the PLR and accounts for the loss of the system efficiency due to part-load performance. The actual COP of the system is calculated from the nominal COP (provided by the user) multiplied by a coefficient that depends on outdoor and indoor conditions (see Appendix).

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2.6.4 Heating system

The current version of BEM considers a fuel-combustion heating system. Other heating systems, such as heat pumps, can be added in future versions of the model. The supply air temperature of the heating system is calculated to meet the sensible heating energy demand of the building (Eq. 12). If the energy demand of the building is greater than the heating system capacity, the system capacity is used to calculate the supply temperature.

$$T_{sys} = T_{mix} + H_{dem,heat} / \left(\dot{m}_{sys} c_p \right). \quad (12)$$

The heating system model assumes that the indoor air humidity is not controlled and that the supply air humidity is the same as the mixing humidity (Eq. 8). The energy consumption of the heating system is calculated from the heating energy supplied by the system divided by a constant efficiency(η_{heat}), supplied by the user.

$$Q_{HVAC,heat} = Q_{supply,heat} / \eta_{heat}. \quad (13)$$

2.6.5 Fan electricity consumption

The fan electricity consumption is calculated from the following correlation extracted from EnergyPlus documentation (DOE, 2010):

$$P_{fan} = \dot{m}_{sys} \Delta P_{fan} \eta_{fan} / \rho, \quad (14)$$

where ΔP_{fan} is the fan design pressure increase, predefined as 600 Pa; and η_{fan} is the fan total efficiency, predefined as 0.7.

2.6.6 Waste heat emissions

The waste heat released by an HVAC system is calculated from the energy exchanged between the system and the building and the energy consumption of the system. For the cooling system, the waste heat flux is given by:

$$Q_{waste,cool} = Q_{exch,cool} + Q_{HVAC,cool}. \quad (15)$$

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The user can specify the sensible-latent split of the waste heat produced by the cooling system, depending on whether the system is air-condensed, water-condensed, or both. For the heating system, the waste heat flux is related to the energy contained in the combustion gases and is given by:

$$Q_{\text{waste,heat}} = Q_{\text{HVAC,heat}} - Q_{\text{exch,heat}}. \quad (16)$$

2.6.7 Autosize function

For the realistic model of an HVAC system, BEM requires information about the size of the system. The parameters that determine the size of a system are the rated cooling capacity and the maximum heating capacity. For a constant-volume cooling system, the model also requires its design mass flowrate. This information can be provided to the model manually, or it can be automatically calculated by the *autosize* function.

The *autosize* function first calculates the maximum heating capacity by applying a sensible heat balance at the indoor air (Eq. 4), assuming steady-state heat conduction through the enclosure. An equivalent outdoor air temperature is calculated as the average between the design minimum air temperature (provided by the user) and a generic sky temperature (253 K). The required air flowrate is then obtained from Eq. (17), assuming a supply air temperature of 323 K.

$$\dot{m}_{\text{sys,rat}} = \frac{Q_{\text{heat,max}}}{c_{\text{p}} \left(T_{\text{supply}} - T_{\text{heat,target}} \right)} \quad (17)$$

To calculate the rated cooling capacity, the model dynamically simulates the building during four days, between 12 July and 15 July. The rated cooling capacity corresponds to the maximum cooling energy required to maintain indoor set point conditions for the last day of simulation. This dynamic simulation uses a predefined diurnal cycle of outdoor air temperature and incoming solar radiation (see Appendix). Incoming solar radiation depends on the specific location of the urban area, using the solar zenith angle calculated by the TEB model. Outdoor air humidity, air velocity, and air pressure are considered constant during this simulation.

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Once the rated cooling capacity is calculated, the required air flowrate is obtained assuming a supply air temperature of 287 K. The rated air flowrate will be the maximum of those calculated for cooling and for heating conditions.

3 Model evaluation

3.1 Modelling assumptions

A methodology is proposed to evaluate BEM assumptions. This methodology compares the simulations of two models of the same building with different levels of detail. These simulations are carried out with EnergyPlus. The first model, which is referred as the detailed model (DM), includes the exact geometry of the building enclosure, defines each building level as a separate thermal zone, and introduces internal heat gains in terms of people, lighting, and equipment. The second model, which is referred as the simplified model (SM), maintains the assumptions of BEM. It considers a square-base building defined as a single thermal zone with internal mass. The building height, vertical-to-horizontal building area ratio, roof-to-horizontal building area ratio, glazing ratio, construction configuration of the enclosure (materials and layers), internal heat gains, and infiltration air flowrate are the same as the DM (Table 1).

To avoid orientation-specific results, DM is simulated for eight different orientations, every 45°, and SM is simulated for two different orientations, rotated 45° between each other. This is due to the fact that SM has a square base and its four façades are the same. Then, the average results from each set of simulations are compared.

The results presented in this section correspond to a Haussmannian building (Fig. 3), which can be found in the old neighbourhoods of many European cities. The weather data used in the simulations corresponds to Paris Orly Airport.

Figures 4 and 5 represent the daily average and monthly-averaged diurnal cycles, respectively, of heating energy demand in winter and cooling energy demand in summer calculated by the simplified and the detailed EnergyPlus models. It can be seen

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that there is reasonable agreement between the two models. Differences in heating and cooling energy demands, computed as root-mean-square error (RMSE) and mean bias error (MBE) between the SM and the DM, are presented in Table 2. The RMSE ranges between 0.8 and 1.7 $W m^{-2}$ of floor area. Positive values of MBE indicate an over-prediction of the cooling and heating energy demand calculated by the SM with respect to the energy demand calculated by the DM.

3.2 Model verification

To check that the chosen equations are solved correctly, BEM-TEB is compared to the EnergyPlus-TEB coupled scheme (CS) (Bueno et al., 2011). Table 3 describes the parameters of the case study, which corresponds to residential buildings in the dense urban centre of Toulouse.

Figures 6 and 7 represent the daily average and monthly-averaged diurnal cycles, respectively, of heating energy demand in winter and cooling energy demand in summer calculated by BEM and the CS. Scores for this comparison are presented in Table 2. The RMSE ranges between 0.8 and 1.1 $W m^{-2}$ of floor area. As can be seen, BEM slightly overestimates cooling energy demand in summer (negative MBE) and underestimates heating energy demand in winter (positive MBE), compared to the CS.

Figure 8 compares the daily average cooling energy consumption and waste heat emissions of the building system calculated by BEM and the CS. An RMSE of 0.7 $W m^{-2}$ of floor area (Table 2) indicates that BEM's air-conditioning system model is able to reproduce the energy consumption of the system calculated by the CS. The fact that the MBE changes sign between the cooling energy demand and the cooling energy consumption suggests that there are still small differences in the calculation of the supply air humidity between the two models. The RMSE of waste heat is 13.31 $W m^{-2}$ of urban area (Table 2), being the average waste heat 50.16 $W m^{-2}$.

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3.3 Model validation

Field data from two different experiments are used to evaluate BEM. The first one is the CAPITOUL experiment, carried out in Toulouse (France) from February 2004 to March 2005 (Masson et al., 2008). During the experiment, forcing measurements were taken at 50 m above the ground. In the same area, urban air temperatures were obtained from a sensor installed at the top of a street canyon. 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).

Table 3 presents the model set-up for this case study, which is the same as in Sect. 3.2. A number of modelling assumptions were made given the lack of detailed information about the buildings of the site. From those, the most relevant are the internal heat gain value, the wall insulation thickness, and the fraction between electric and gas heating systems. A justification of the values chosen is presented in Bueno et al. (2011).

Electricity consumption, natural gas consumption, and anthropogenic heat data from the CAPITOUL experiment were compared to BEM simulation results for two months in winter (Fig. 9). Electricity and natural gas consumption computed as a MBE and RMSE between BEM and observations are presented in Table 2. As can be seen, BEM is able to capture the variations of electricity and gas consumption during the winter with MBE and RMSE lower than 14 $W\,m^{-2}$, averaged on the urban area.

The second experiment was carried out in Athens (Greece) between May and September 2009, framed in the European project BRIDGE (Synnefa et al., 2010). Indoor air temperatures were measured in ten representative residential buildings of the Egaleo neighbourhood. Simultaneous outdoor air temperature measurements are also available. Most of the analysed buildings were constructed between 1950 and

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1980. These buildings were made of reinforced concrete with poor or no insulation and single-pane windows. Cooling systems are generally absent and buildings are naturally ventilated. Air temperature sensors were placed in the centre of the living room of an intermediate floor. Three of the ten buildings share the same modelling parameters used in BEM (Table 4). Reasonable modelling assumptions were made in terms of shadowing and natural ventilation, given the lack of detailed information about the buildings of the site.

The measured indoor air temperatures are compared to BEM simulation results for two months in summer (Fig. 10). Indoor air temperatures in naturally-ventilated buildings are very sensitive to occupant behaviour (occupation schedules, shades and window operation, etc.); thus, even if the buildings have similar parameters in terms of the simulation, their performance can be significantly different. As can be seen, BEM is able to reproduce the daily average evolution, as well as the daily cycle amplitude, of indoor air temperatures measured in building 1 with an RMSE of 1.1 K (Table 2); but it overestimates the indoor air temperatures measured in building 2 and, to a lesser extent, those measured in building 3. This can be explained by the fact that the first building performs more regularly than building 2; therefore, it can be better captured by the simulation. Compared to building 1, BEM slightly overestimates the indoor air temperature during daytime (positive MBE), probably because BEM does not consider occupation schedules, which would decrease internal heat gains during working hours.

4 Conclusions

A new building energy model (BEM) integrated in the TEB scheme is developed in order to represent the building effects on urban climate and to estimate the energy consumption of buildings at city or neighbourhood scale. The model introduces simplifying assumptions in terms of building demand calculations in order to keep the computational cost of simulations low. On the other hand, it includes specific models for active and passive building systems, which allows comparing the performance of different energy

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efficiency strategies in an urban context. An evaluation of the model composed of three steps (modelling assumptions, verification, and validation) has been presented. BEM is able to reproduce the results of a more sophisticated building energy program, such as EnergyPlus, and the comparison with field data shows reasonable agreement. Next steps include extending the evaluation to other building configurations and climates; introducing new HVAC configurations, such as heat-pumps or variable-air-volume systems; and improving the current models of shadowing devices and natural ventilation systems.

Appendix A

Heat balance method

The convection term of Eq. (1) is calculated from:

$$Q_{cv} = h_{cv}(T_{si} - T_{in}), \tag{A1}$$

where T_{si} and T_{in} are the temperature of an interior surface and of the indoor air, respectively. The convective heat transfer coefficient has the following values: $h_{cv} = 3.076\,W\,m^{-2}\,K^{-1}$ for a vertical surface; $h_{cv} = 0.948\,W\,m^{-2}\,K^{-1}$ for a horizontal surface with reduced convection (floor surface with $T_{si} < T_{in}$ and ceiling surface with $T_{si} > T_{in}$); and $h_{cv} = 4.040\,W\,m^{-2}\,K^{-1}$ for a horizontal surface with enhanced convection. The radiation term is calculated as:

$$Q_{rd1-2} = h_{rd}F_{1-2}\left(T_{s,1} - T_{s,2}\right), \tag{A2}$$

where h_{rd} is a radiative heat transfer coefficient and F_{1-2} is the configuration factor between surfaces 1 and 2. Radiative heat transfer coefficients are calculated as:

$$h_{rd} = 4\varepsilon^2\sigma T_{rd}^3, \tag{A3}$$

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where $\varepsilon = 0.9$ is the surface emissivity, σ is the Stefan-Boltzmann constant, and T_{rd} is an average surface temperature. View factors (F) between surfaces are given by:

$$F_{fl-m} = \left((h/w)_{fl}^2 + 1 \right)^{1/2} - (h/w)_{fl}, \quad \text{(A4)}$$

$$F_{fl-wi} = (1 - F_{fl-m})(1 - GR), \quad \text{(A5)}$$

$$F_{fl-win} = (1 - F_{fl-m})\,GR, \quad \text{(A6)}$$

$$F_{aux} = \left((h/w)_{fl} + 1 - \left((h/w)_{fl}^2 + 1 \right)^{1/2} \right) / (h/w)_{fl}, \quad \text{(A7)}$$

$$F_{wi-m} = F_{win-m} = F_{aux}(2N_{fl} - 2)/(2N_{fl}), \quad \text{(A8)}$$

$$F_{wi-win} = (1 - F_{aux})\,GR, \quad \text{(A9)}$$

$$F_{wi-fl} = F_{win-fl} = F_{aux}/2N_{fl}, \quad \text{(A10)}$$

$$F_{win-wi} = (1 - F_{aux})(1 - GR), \quad \text{(A11)}$$

$$F_{m-wi} = F_{wi-m} A_{wi}/A_m, \quad \text{(A12)}$$

$$F_{m-win} = F_{win-m} A_{win}/A_m, \quad \text{(A13)}$$

and

$$F_{m-fl} = F_{fl-m}/A_m, \quad \text{(A14)}$$

where the subscripts fl, m, wi, and win represent floor, internal mass, internal wall, and window, respectively; GR is the glazing ratio of the building; and $(h/w)_{fl}$ represents the aspect ratio of one building level.

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A1 Natural ventilation

The natural ventilation module first compares indoor and outdoor air temperatures. If $T_{in} > T_{urb} + 1\,K$, the modules estimates a natural ventilation potential, by calculating the indoor air temperature with and without natural ventilation, T_{open} and T_{close}, respectively. The conditions are considered favourable for natural ventilation if $T_{open} < T_{cool,target}$, $T_{open} < T_{close,}$ and $T_{open} > T_{heat,target} + 4\,K$.

The natural ventilation air flowrate per unit of building plan area is calculated from the following equation developed by Truong (personal communication) and based on the orifice and Bernoulli equations:

$$\dot{V}_{nv}/A_{bld} = \frac{1}{3}\left[g\frac{T_{in}-T_{urb}}{T_{urb}}\right]^{1/2}\left[h_{win} + \frac{T_{in}}{g(T_{in}-T_{urb})}\frac{1}{2}U_{urb}^2\Delta C_p\right]^{3/2}\frac{VH_{urb}GR}{4N_{fl}\rho_{bld}h_{win}} \quad \text{(A15)}$$

where $h_{win} = 1.5\,m$ is the height of the air inlet opening, $\Delta C_p = 0.1$ is the pressure coefficient difference between the windward and the leeward sides of the building, and U_{ref} is the outdoor mean air velocity.

A2 Cooling system

BEM accounts for the dependence of a cooling system on outdoor and indoor conditions, through the definition of characteristic performance curves (DOE, 2010). The total cooling capacity is calculated from the rated capacity, modified by the following curve:

$$\varphi_Q = A_1 + B_1 T_{wb,i} + C_1 T_{wb,i}^2 + D_1 T_{c,i} + E_1 T_{c,i}^2 + F_1 T_{wb,i} T_{c,i}, \quad \text{(A16)}$$

where $T_{wb,i}$ (°C) is the wet-bulb temperature of the air entering the cooling coil and $T_{c,i}$ (°C) is the dry-bulb outdoor air temperature, in an air-cooled condenser (wet-bulb outdoor air temperature in an evaporative condenser). The actual COP of the system is calculated from the nominal COP, divided by the following curve:

$$\varphi_{COP} = A_2 + B_2 T_{wb,i} + C_2 T_{wb,i}^2 + D_2 T_{c,i} + E_2 T_{c,i}^2 + F_2 T_{wb,i} T_{c,i}. \quad \text{(A17)}$$

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The coefficients used in Eqs. (A16) and (A17) are $A_1 = 0.942587793$, $B_1 = 0.009543347$, $C_1 = 0.00068377$, $D_1 = -0.011042676$, $E_1 = 0.000005249$, $F_1 = -0.00000972$, $A_2 = 0.342414409$, $B_2 = 0.034885008$, $C_2 = -0.0006237$, $D_2 = 0.004977216$, $E_2 = 0.000437951$, and $F_2 = -0.000728028$.

The coefficient f_{PLR} of Eq. (11) is given by:

$$f_{PLR} = 0.85 + 0.15\mathrm{PLR}, \tag{A18}$$

where PLR is the part-load ratio, calculated as the fraction between the energy supplied and the system capacity.

A3 Autosize function

The rated cooling capacity is calculated by dynamically simulating the building with predefined diurnal cycles of outdoor air temperature and incoming solar radiation. The diurnal cycle of outdoor air temperature has a maximum defined by the user and an amplitude of 10.7 K. The evolution is sinusoidal according to the following equation:

$$T_{canyon} = T_{size,max} - 5.35 + 5.35\sin\left(2\pi(t + 57600)/86400\right). \tag{A19}$$

The solar radiation at each time step is given by:

$$S^{\downarrow} = K_{sol} D_{corr} \cos(Z), \tag{A20}$$

where $K_{sol} = 1367\,\mathrm{W\,m^{-2}}$, $D_{corr} = 1 + 0.0334\cos\left(0.01721 D_{julian} - 0.0552\right)$, and Z is the solar zenith angle; and where D_{julian} is the Julian day of the year.

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Table 1. Simulation parameters used to build the simplified EnergyPlus model from the detailed EnergyPlus model of a Haussmannian building.

Property	Value	Unit
Vertical-to-horizontal building area ratio	3.14	
Building height	21.50	m
Length of the side of the square building plan	27.36	m
Roof-to-horizontal building area ratio	0.69	
Internal heat gains	5.58	$W\,m^{-2}$
Radiant fraction of internal heat gains	0.40	
Latent fraction of internal heat gains	0.20	
Window solar heat gain coefficient (SHGC)	0.43	
Window U-factor	4.95	$W\,m^{-2}\,K^{-1}$
Glazing-to-wall ratio	0.2	
Floor height	2.90	m
Infiltration	0.90	ACH
Ventilation	0.35	ACH
Internal mass-to-horizontal building area ratio	12.83	
Internal thermal mass construction	Concrete (100 mm)	
Indoor thermal set points	19–24	°C

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Table 2. RMSE and MBE of the variables compared in each of the three evaluation levels. Surface area refers to building floor area (fl) or urban area (urb).

	RMSE	MBE
Modelling assumptions (Simplified-Detailed)		
Heating energy demand ($W\,m^{-2}$ f)	1.7	0.1
Cooling energy demand ($W\,m^{-2}$ fl)	0.8	0.2
Model verification (CS-BEM)		
Heating energy demand ($W\,m^{-2}$ fl)	0.8	0.3
Cooling energy demand ($W\,m^{-2}$ fl)	1.1	−0.4
Cooling energy consumption ($W\,m^{-2}$ fl)	0.7	0.5
Waste heat emissions ($W\,m^{-2}$ urb)	13.3	3.7
Model validation (BEM-Observations)		
Electricity consumption ($W\,m^{-2}$ urb)	14.1	13.1
Gas consumption ($W\,m^{-2}$ urb)	1.1	−1.0
Indoor air temperature (K)	1.1	0.1

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Table 3. Simulation parameters used in the comparison between the coupled scheme and BEM and between BEM and observations, corresponding to the dense urban centre of Toulouse.

Property	Value	Unit
Average building height	20	m
Building density	0.68	
Vertical-to-horizontal urban area ratio	1.05	
Roughness length	2.0	m
Anthropogenic heat from traffic	8.0	$W\,m^{-2}$ urb
Glazing-to-wall ratio	0.3	
Window construction	Double pane clear glass (6 mm glass with 6 mm gap)	
Wall and roof construction	Brick (30 cm), insulation board (3 cm)	
Road construction	Asphalt, ground	
Infiltration/ventilation air flow rate	0.5	ACH
Internal heat gains	5.8	$W\,m^{-2}$ fl
Radiant fraction of internal heat gains	0.2	
Latent fraction of internal heat gains	0.2	
Electric fraction of internal heat gains	0.7	
Cooling system	Single speed fan on the air side, with evaporating refrigerant in the coils	
Heating system	Gas furnace	
Indoor thermal set points	19–24	°C
Fraction of electric heating systems over gas heating systems	2/3	

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Table 4. Simulation parameters used for the comparison between BEM and observations, corresponding to the Egaleo neighbourhood in Athens.

Property	Value	Unit
Average building height	9.5	m
Building density	0.64	
Vertical-to-horizontal urban area ratio	1.05	
Roughness length	0.95	m
Anthropogenic heat from traffic	8.0	$W\,m^{-2}$ urb
Glazing-to-wall ratio	0.25	
Window construction	Single pane clear glass (6 mm)	
Wall and roof construction	Concrete (30 cm)	
Road construction	Asphalt, ground	
Infiltration air flowrate	0.5	ACH
Internal heat gains	4.0	$W\,m^{-2}$ fl
Radiant fraction of internal heat gains	0.2	
Latent fraction of internal heat gains	0.2	
Electric fraction of internal heat gains	0.7	
HVAC system	None	
Natural ventilation	Activated	
Shading devices	Exterior shades; solar radiation on windows for which shades are ON: 250 W m-2; solar transmittance of shades: 0.3	

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Table A1. Nomenclature.

Symbol	Designation	Unit
A	Area	m^2
COP	Coefficient of performance of an HVAC system	–
c_p	Air specific heat	$J\,kg^{-1}\,K^{-1}$
C_p	Pressure coefficient	–
f	Fraction	–
F	View factor	–
g	Gravity acceleration	$m\,s^{-2}$
GR	Glazing ratio	–
h	Heat transfer coefficient	$W\,m^{-2}\,K^{-1}$
h_{win}	Opening height for natural ventilation	m
H	Sensible heat	$W\,m^{-2}$
K_{sol}	Solar constant	$W\,m^{-2}$
l_v	Water condensation heat	$J\,kg^{-1}$
LE	Latent heat	$W\,m^{-2}$
$\dot{m}$	Air mass flowrate	$kg^3\,s^{-1}$
N_{fl}	Number of floors in a building	–
P	Electric power	W
PLR	Part-load ratio	–
q	Specific humidity	$kg\,kg^{-1}$
Q	Heat flux	$W\,m^{-2}$
$S^{\downarrow}$	Incoming solar radiation	$W\,m^{-2}$
t	Time	s
T	Temperature	°C, K
U_{urb}	Outdoor mean air velocity	$m\,s^{-1}$
V	Volume	m^3
$\dot{V}$	Air volume flowrate	$m^3\,s^{-1}$
VH_{urb}	Vertical-to-horizontal urban area ratio	–
X_{mix}	Mixing ratio	–
Z	Solar zenith angle	rad
ρ_{bld}	Building density	–
ε	Surface emissivity	–
σ	Stefan-Boltzmann constant	$W\,m^{-2}\,K^{-4}$
ρ	Air density	$kg\,m^{-3}$
τ	Transmittance	–
η	Efficiency	–
φ	Performance curve of an cooling system	–

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Table A1. Continued.

Symbol	Designation	Unit
Subscripts		
bld	Building	
can	Urban canyon	
cap	HVAC system capacity	
cd	Conduction	
cool	Cooling	
cv	Convection	
dem	Energy demand	
exch	Energy exchanged between the system and the building	
fl	Floor	
heat	Heating	
HVAC	HVAC system energy consumption	
ig	Internal heat gains	
in	Indoor air	
inf	Infiltration	
lat	Latent	
m	Building internal thermal mass	
mix	HVAC mixing conditions	
nt	Natural ventilation	
rat	Rated conditions	
rd	Radiation	
sens	Sensible heat	
si	Interior surface	
sol	Solar radiation	
supply	HVAC system supply conditions	
sys	HVAC system	
urb	Outdoor air	
vent	Ventilation	
w	Walls	
waste	Waste heat from HVAC systems	
wi	Inner layer of wall	
win	Windows	

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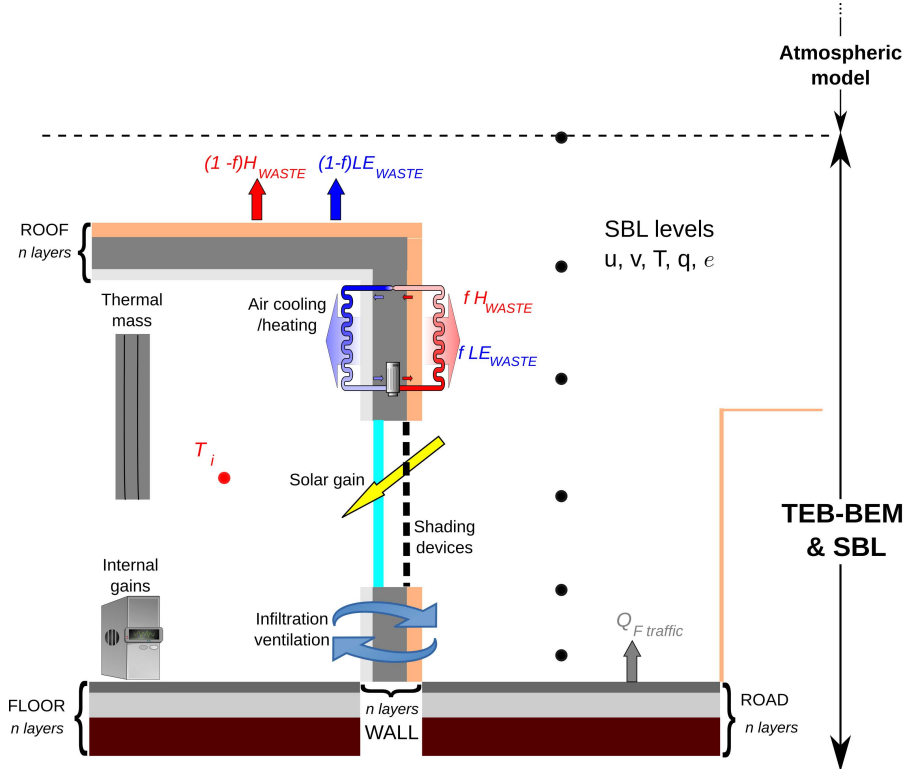

Fig. 1. Diagram of an urban canyon representing the main processes included in BEM-TEB.

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Development and evaluation of a building energy model

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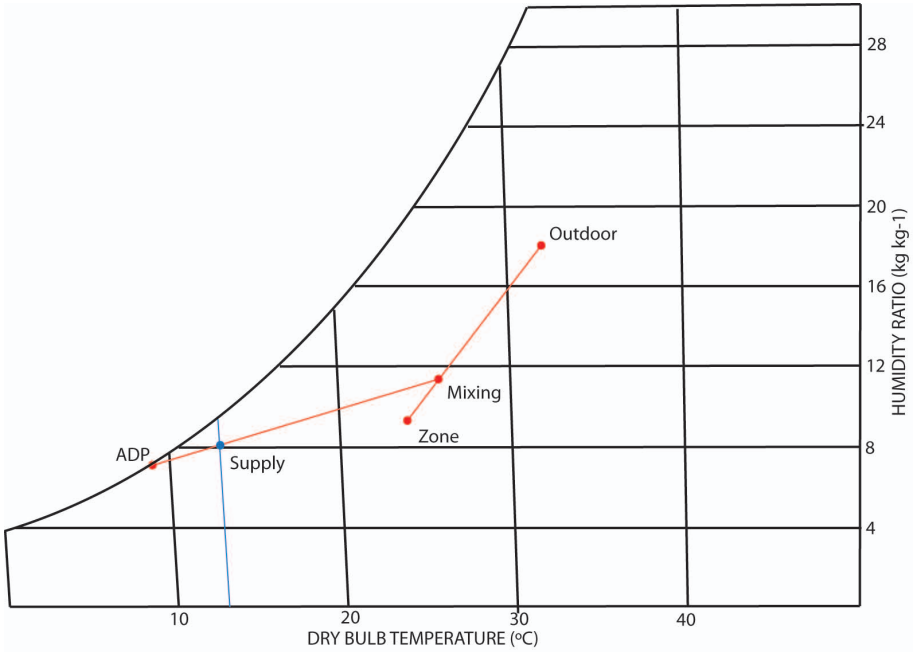

Fig. 2. Psychrometric chart of humid air indicating the significant points of the HVAC system model for a cooling situation.

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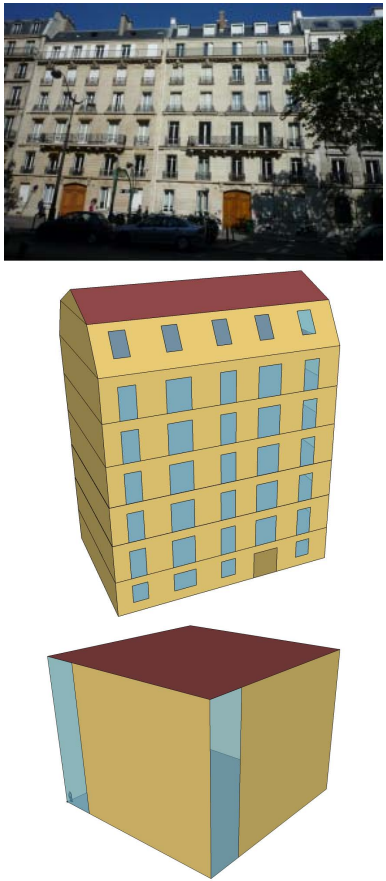

Fig. 3. Image of a Haussmannian building in Paris (top), the detailed model (middle), and the equivalent simplified model (bottom).

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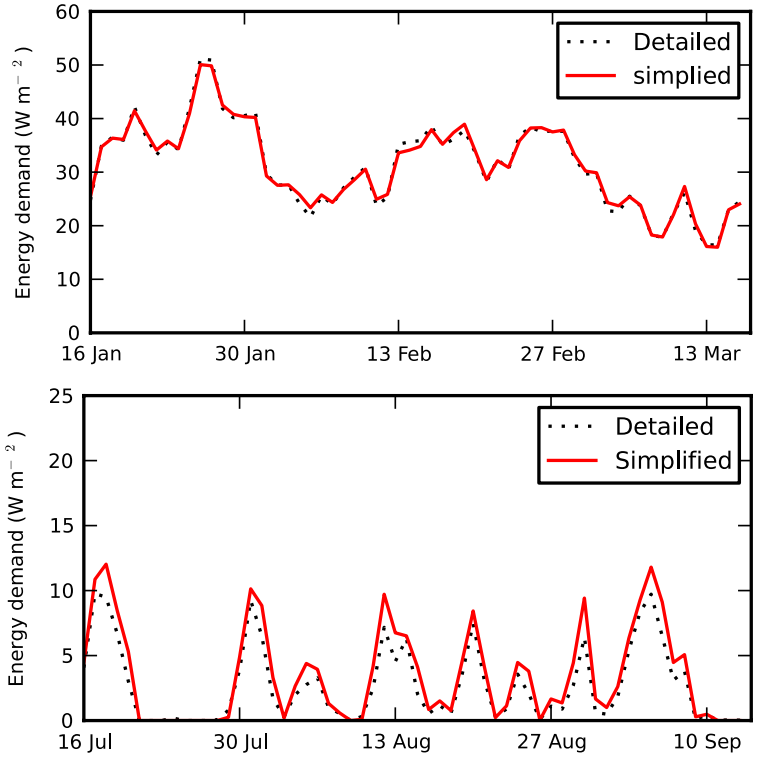

Fig. 4. Daily-average heating (top) and cooling (bottom) energy demand per unit of floor area for winter and summer calculated by the simplified and the detailed EnergyPlus models of a Haussmannian building in Paris.

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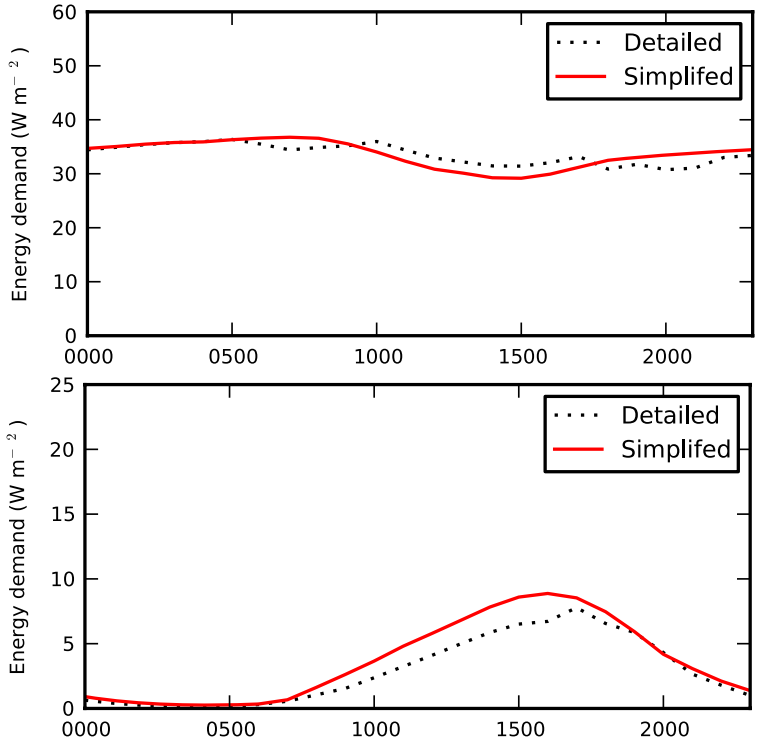

Fig. 5. Monthly-averaged diurnal cycles of heating energy demand between 16 January and 15 February (top) and cooling energy demand between 1 July and 30 July (bottom) per unit of floor area calculated by the simplified and the detailed EnergyPlus models of a Haussmannian building in Paris.

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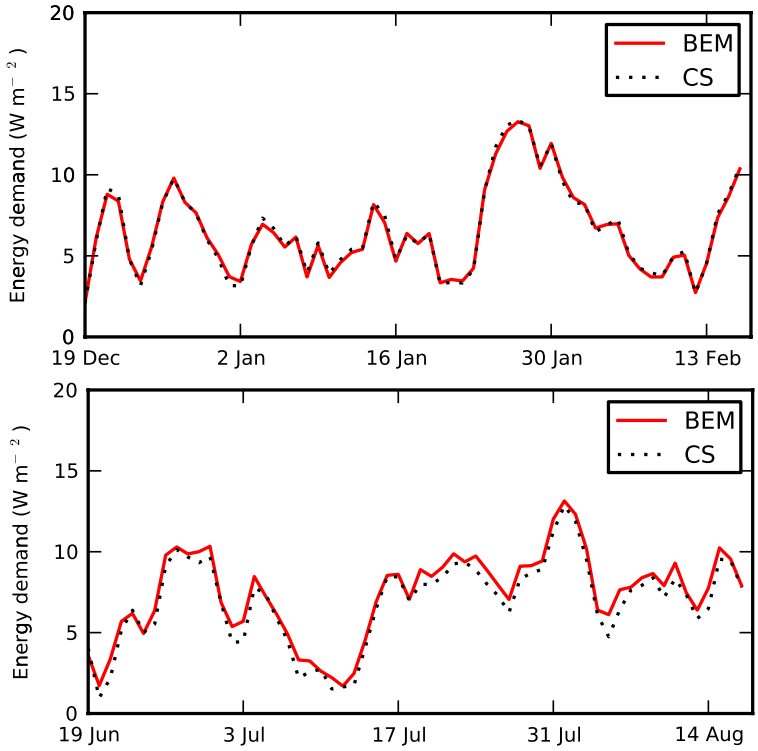

Fig. 6. Daily-average heating (top) and cooling (bottom) energy demand per unit of floor area for winter and summer calculated by the coupled scheme and by BEM-TEB for the dense urban centre of Toulouse.

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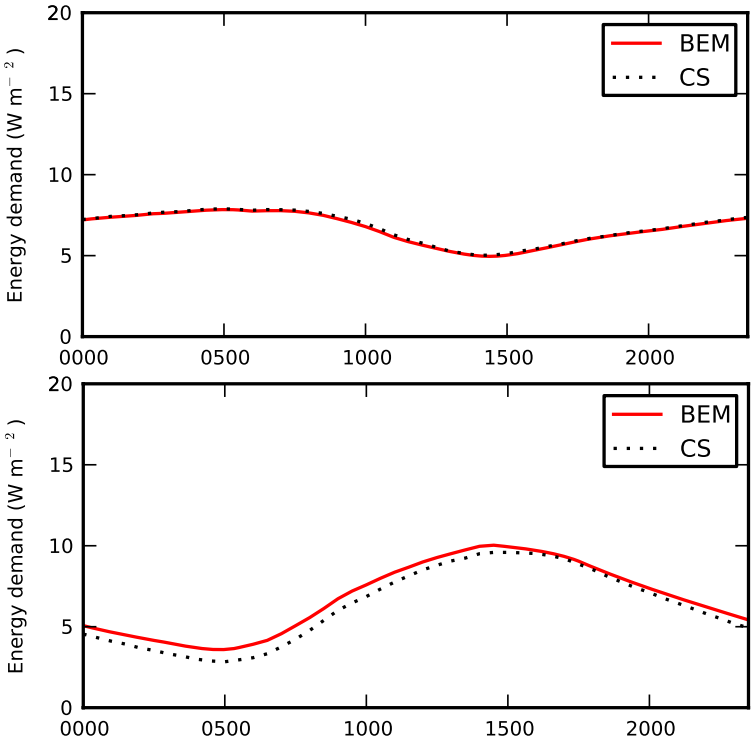

Fig. 7. Monthly-averaged diurnal cycles of heating energy demand between 1 January and 30 January (top) and cooling energy demand between 1 July and 30 July (bottom) per unit of floor area calculated by the coupled scheme and by BEM-TEB for the dense urban centre of Toulouse.

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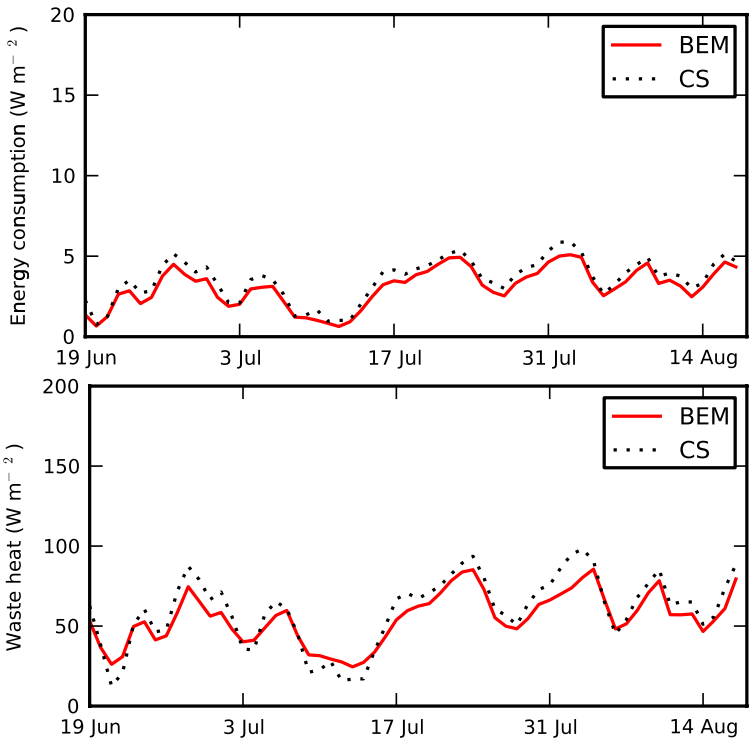

Fig. 8. Daily-average cooling energy consumption per unit of floor area (top) and waste heat emissions per unit of urban area (bottom) calculated by the coupled scheme and by BEM-TEB for the dense urban centre of Toulouse.

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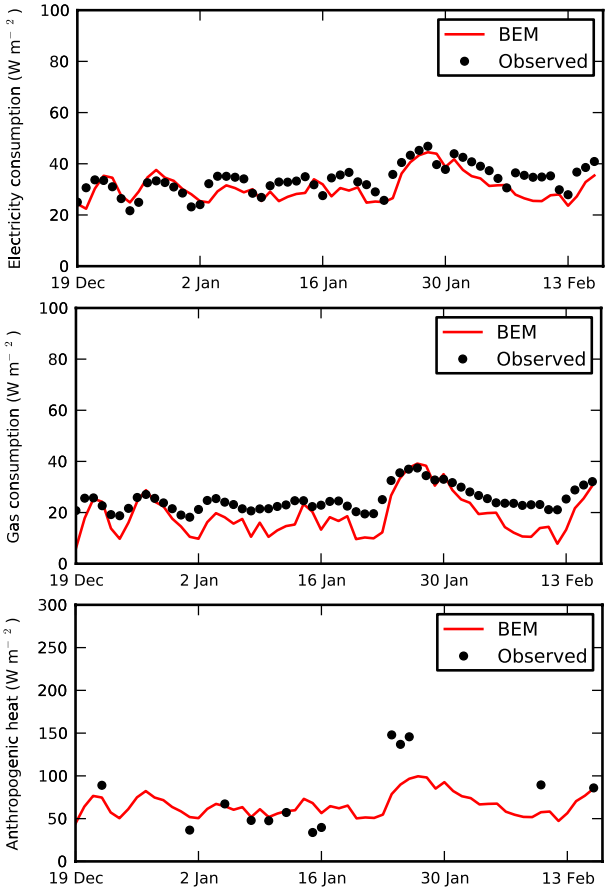

Fig. 9. Daily-average electricity consumption (top), natural gas consumption (middle) and anthropogenic heat (bottom) per unit of urban area from observations and calculated by BEM-TEB in winter for the dense urban centre of Toulouse.

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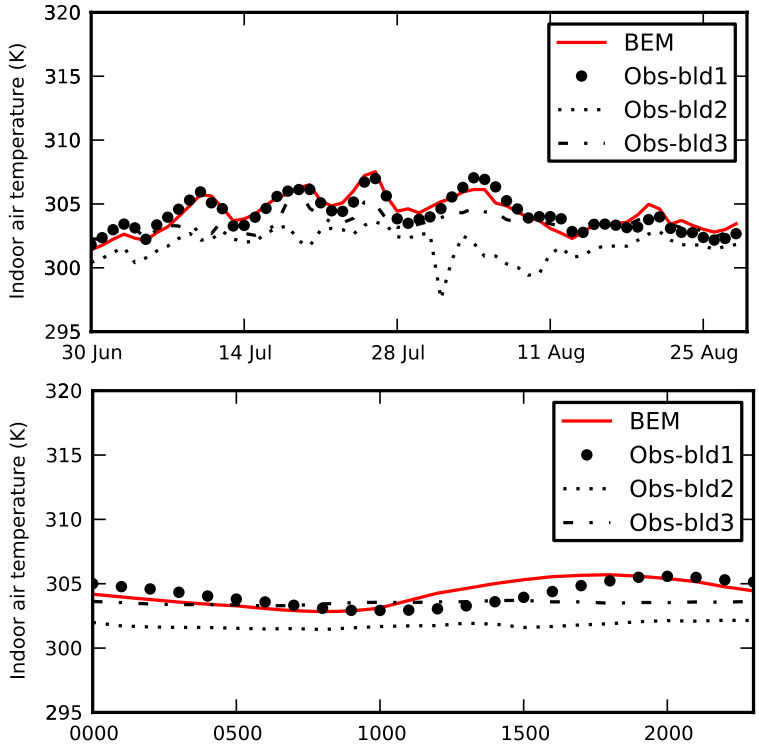

Fig. 10. Daily-average (top) and monthly-averaged diurnal cycle (bottom) of indoor air temperature from observations and calculated by BEM-TEB from 30 June to 30 August for the Egaleo neighbourhood of Athens.

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