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Improving the capabilities of the Town Energy Balance model with up-to-date building energy simulation algorithms: an application to a set of representative buildings in Paris

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ABSTRACT

Buildings' energy systems release heat to the atmosphere that contributes to the urban heat island. In return, the energy demand from buildings depends on the meteorological conditions of their surroundings. Consequently, urban canopy models such as Town Energy Budget (TEB) have progressively included the representation of the main processes of building energetics: solar and internal heat gains, heat transmission through the enclosure and the heat exchange by infiltration and ventilation. The objective of this study is to extend the evaluation of the Building Energy Model (BEM) implemented in TEB. Five buildings representative of the morphological and thermal characteristics that can be encountered in European urban areas have been selected. The evaluation has been conducted with EnergyPlus building energy model and for two contrasted climates. The TEB model is able to estimate the heating and the cooling energy demand with an accuracy better than 5 kWh/m^2/year for heating and 3 kWh/m^2/year for cooling. This paper also discusses on the importance of computing the building's surrounding surface temperature for energy demand calculations. TEB is able to account for this effect whereas EnergyPlus assumes that building surroundings are at air temperature.

1. Introduction

The releases of heat by buildings in urban areas are an additional source of energy in comparison to most of other environments and are one of the causes leading to the urban heat island phenomenon. These releases can be dominated by the use of energy for space heating during the winter period [1,2] but, generally, the releases by air cooling condensers have retained most of the attention. The impact of the massive use of air cooling systems in Asian and North-American cities has been documented in the literature, for example in Houston City (Texas) [3] and in Tokyo [4]. In both studies, an increase of night temperatures up to 2 °C has been calculated using a numerical method based on a building energy model and an urban canopy model coupled with a mesoscale atmospheric model. Whereas the use of air cooling systems is not currently spread out in all types of climates and cities such as in mid-latitude Europe, the use of these systems is expected to increase in response to higher standards of living requirements and the climate warming. In France, a doubling of the energy consumption due to air conditioners is expected by 2030 [5]. Based on these figures, De Munck et al. [6] have estimated an increase in the urban heat island of 2 °C over Paris while they estimated the current impact of air cooling condensers to be 0.5 °C.

At the same time, the energy demand of buildings responds to climate variation of their environment. In the case of urban areas with a high level of air cooling systems, the increase of temperature leads to an increase in the energy demand. For example in Tokyo, Ohashi et al. [7] reported an increase of 1.6 GW per degree of the outdoor air temperature. Based on numerical simulations, Bueno et al. [8] reported that the urban climate mainly influences the energy performance by the process of infiltration and ventilation and that a 5% increase in cooling energy demand can be expected per degree increase of air temperature for residential buildings (historical collective) and a similar decrease in heating energy demand of a residential building can be expected for the

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wintertime period (temperate climate). Consequently, the knowledge of the intensity of the urban heat island is of interest for the energy design of buildings in urban areas and some methods have recently been developed [9] to respond to this purpose. In urban planning, there is also a demand for building stock models to assist with the implementation of policy. Swan and Ugursal [10] review the various modelling techniques used to estimate the energy consumption at neighbourhood or city scale. The top-down approach utilizes historic aggregate energy data, deriving the energy consumption of building stocks as a function of top-level variables such as macroeconomic indicators, energy price, and general climate. Bottom-up models account for the energy consumption of individual end-users and extrapolate it to represent an urban area based on the representative weight of the modelled sample. A number of physically-based bottom-up models can be found in the literature [11]. However, none of these models specifically accounts for the interactions between buildings and the urban environment. The Urban Canopy and Building Energy Models (UC–BEMs) can overcome this limitation and have the potential to become fully-operative building stock models.

The Town Energy Budget (TEB) model [12] has been recently modified by adding a Building Energy Model (BEM) [13]. TEB proposes a physically-based (bottom-up) approach to estimate building energy consumption at city scale (∼10 km) with a resolution of a neighbourhood (∼100 m). Modelling building energy consumption at urban scale has the advantage of building aggregation but requires taking into account the energy interactions between buildings and the urban environment. Building aggregation allows the simplification of the building thermal definition. The underlying assumption is that the average building of a certain urban area is more representative and generic than each particular building. The main hypotheses adopted in this new component of TEB have been evaluated using a numerical model specifically dedicated to building energy use. Then, the new version of TEB has been evaluated against observations, as it was done before for previous versions of TEB [14,15]. As for every numerical model, the evaluation of urban canopy layer models is a critical step before they can be used inside mesoscale, regional or global climate atmospheric models. In this sense, a recent international exercise has been conducted for a large number of them [16,17] for a residential suburban area. However, given the heterogeneity of the urban environment and the large number of building types that compose the urban landscape, the work of evaluation of such models is still necessary to estimate their ability to reproduce the urban climate and to estimate their level of precision.

Given these considerations on the urban climate and the Urban Climate Models, the objective of this study is to complete the evaluation of the TEB model for a set of buildings representative of the Paris area. This set of buildings includes different kinds of morphology and envelope. The study is based on comparisons with the EnergyPlus building energy model [18]. Indeed, the real energy consumptions of buildings are difficult to use for this purpose since they are strongly influenced by the behaviour of the dwellers and other information about the building that are often unknown and that can have large variations from one building to another. For that reason, the use of a numerical benchmark such as EnergyPlus is a better alternative since it has been validated against controlled buildings equipped with sensors. The paper describes, first, the general methodology adopted in the study and, then, the set of buildings selected. The different modifications implemented in the TEB model are presented before the results. Based on the use of the TEB model, the sensitivity of the model to the surface temperature of the surrounding used in the longwave infrared balance of the wall is presented.

2. Modelling differences between TEB and EnergyPlus

During this study, the differences between TEB and EnergyPlus have been considered and some improvements have been implemented in the BEM module. Since the improving of TEB is the objective of this study, a brief description of this model is presented and then the differences with the EnergyPlus model that have been investigated.

2.1 TEB brief description

The TEB model has been developed to simulate the energy and water exchanges between the city and the atmosphere. The most important processes that influence urban-atmosphere energy exchanges are taken into account in TEB, viz:

- radiative trapping and shadows resulting from the 3D geometry of a city;
- heat exchanges between the buildings and the environment;
- water interception and evaporation, and also snow mantel evolution on roads and roofs (evaluated against Montreal data [15]);
- drag, heat and water turbulent exchanges between the urban canopy layer and the atmosphere.

Meanwhile, the parameterization conceptualization allows fast computation time. For example:

- The 3D shape of a city is parameterized by an idealized 2D canyon geometry while keeping the main features driving the radiative interactions and the energy exchanges [12].
- Likewise, energy balance computations are carried out by azimuthal averaging solar and wind forcing in order to represent neighbourhoods with random-oriented urban canyons. For impact studies, a version of the model with specific canyon orientations is also available [19].
- The air flow within urban canyons is solved by applying aerodynamic resistances and, in the latest version, by applying an original 1D vertical turbulence scheme that simulates the mean characteristics of the flow in the canyon, skipping unnecessary (and computationally expensive) details [20].

The BEM [13] implemented in TEB considers a single thermal zone, a generic thermal mass to represent the thermal inertia of the indoor materials, the heat gains resulting from transmitted solar radiation and the internal sources of heat, infiltration and ventilation. The heat conduction through the envelope of the building is calculated using a finite difference method individually for each surface (roof, wall and floor). The morphological parameters of the TEB model are summarized in Table 1.

2.2 Sky model

The first difference concerns the representation of the diffuse solar radiation from the sky. In the original version of the BEM implemented in TEB, the diffuse solar radiation has no directional effect and each surface of the canyon receives this energy flux according to its sky view factor. In EnergyPlus a more detailed sky radiance model is applied and the diffuse radiation is not isotropic. When comparing both models, it resulted in an overestimation of the total solar radiation received by the wall around midday in TEB (Fig. 1, points) driven by the contribution of the diffuse solar radiation. On average, during the summer period (future climate), the overestimation was about 12 W/m^2 which represents more than 7% of the solar heat flux. Consequently, the calculation of the diffuse solar radiation has been modified in TEB. The contribution of the circumsolar brightening, which is the diffuse solar radiation