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A new validation protocol for an urban microclimate model based on temperature measurements in a Central European city

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ABSTRACT

In this paper, we provide further evidence of the reliability of a lumped parameter urban canopy model coupled with an EnergyPlus building energy model to estimate urban temperatures. In a previous paper, we presented a preliminary validation of the model using data measured at Masdar Institute, Abu Dhabi, United Arab Emirates. At present, we conduct a more comprehensive validation based on BUBBLE experimental data measured in the Sperrstrasse, a street canyon located in Basel downtown, Switzerland. To extend the coupled scheme for the Sperrstrasse and future work, we developed methods for approximating waste heat releases generated by a heating system, anthropogenic heat gains created by traffic, and direct normal solar irradiance. Based on a baseline coupled scheme model for the Sperrstrasse, we evaluate the sensitivity of urban temperature estimates to ±20% variations of each parameter. We finally show, through Monte-Carlo analysis, that the coupled scheme can achieve satisfactory accuracy in a dense Central European city.

1. Introduction

Since the beginning of urbanization, the Urban Heat Island (UHI) effect has been one of the most studied micro climatic phenomena in the literature [1]. Meteorologists and urban planners are concerned by its impact on electricity demand, emissions of pollutants, and outdoor thermal comfort. Among the first studies of the UHI effect, Oke [2] sets forth a UHI intensity[1] formulation based on the urban population and the rural wind speed. Nevertheless, the extreme complexity of this phenomenon encouraged scientists coming from different fields to develop more accurate urban microclimate models. To determine the main causes of the UHI effect, their work mainly consists in observing and modeling heat fluxes exchanged between different atmospheric layers and those generated from building energy use.

Anthropogenic heat gains play a major role in the creation of the UHI effect inside a city [1]. In its widest sense, anthropogenic heat gain means heat released from energy consumption by humans; it encompasses metabolic heat, waste heat of indoor space conditioning systems, artificial lighting, electrical equipment use, traffic, and industry [3]. According to Taha [4], the anthropogenic heat intensity varies between 16 and 159 W/m^2 in different North American urban areas. In Tokyo, Ichinose et al. [5] reported that downtown anthropogenic heat intensity might exceed 400 W/m^2. Due to the high intensity of anthropogenic heat gains in dense urban area, one major focus in the development of urban microclimate models is the evaluation of their impact on urban temperature and heating/cooling energy demand. For instance, Ohashi et al. [6] discovered that waste heat from air-conditioners might have caused a temperature increase of between 1 °C and 2 °C in Tokyo office areas. A similar study was carried out by Bueno et al. [7] in which the increase in diurnal average urban temperature caused by waste heat releases was estimated to be 0.8 °C for residential neighborhoods and 2.8 °C for commercial areas.

To evaluate the sensitivity of urban temperatures to variations of energy consumption, some urban microclimate models couple urban canopy models with building energy models. An urban canopy model aims at estimating weather conditions at the urban canopy layer taking into consideration climatic conditions at urban boundary layer, heat fluxes from building surfaces, and anthropogenic heat releases. Urban boundary layer conditions can be defined by measurements [8] or approximated by a mesoscale model [6,9–14]. Urban canopy models can be divided in two categories: single-layer and multi-layer urban canopy models. While multi-layer urban canopy models consider that urban temperatures can vary as function of height [6,9,10,12,13,15],

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[1] The UHI intensity corresponds to the temperature difference between an urban and rural site.

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η	boiler efficiency (W/W or %)
δ	fraction (0–1)
λ	zenith angle (°)
G	irradiance (W/m^2)
I	intensity (W/m^2)
k	diffuse fraction (0–1)
k_t	clearness index (0–1)
Q	sensible heat (W)
Q_e	energy consumption (W)
t, τ	time (s)
Δt	sampling rate (s)

single-layer urban canopy models assume that the urban canyon can be modeled as a homogeneous volume with uniform temperature [7,8,11,16,17]. Weather conditions estimated by an urban canopy model are then defined as boundary conditions of the reference building (i.e. building energy model). After that, the building energy model is employed for computing the heating/cooling consumption required to maintain indoor comfort. Finally, heat releases caused by heating/cooling are calculated based on specifications of the heating, ventilation, and air-conditioning (HVAC) system. Urban canopy models might be coupled with either a simplified [6,9,10,12,13,15,17,18] or a detailed [7,8] building energy model.

In the literature, there is no standard protocol for evaluating the reliability of an urban microclimate model. A first approach was proposed by Grimmond et al. [19,20]. The proposed validation method is essentially heat flux based and therefore can only be applied to a specific kind of urban microclimate model following the scheme defined by Masson [16]. Among all urban temperature based validation protocols, a few use metrics to determine how close their approximations are to measurements [8,13,14]. When a metric is used for evaluating the accuracy of the urban microclimate model, the uncertainty associated with parameters is rarely considered. Most studies compute (or only illustrate) the similarity between estimates and measurements via several discrete cases [8–10,12,13]. Some validation protocols compare measurements to estimates of urban temperature in time [6,9,10], while others analyze dissimilarities between measured and estimated distributions [7,8,11,12]. Distribution-based validation protocols assess the frequency distribution [8,12] or the average diurnal cycle [7,8,11] of urban temperature. Frequency distributions and average diurnal cycles for urban temperature were calculated from 1200 to 8760 samples [8,12].

Martin et al. [8] developed an urban microclimate model consisting of a lumped thermal parameter model coupled with an EnergyPlus model. This approach retains a tight linkage between an urban canopy model and a representation of a building that can include the full array of features modeled by EnergyPlus. The coupled scheme was employed for estimating urban temperature and specific humidity. For validation purposes, Martin et al. used a multitude of HOBO loggers to record temperature and relative humidity of the urban canopy layer, and two meteorological stations to measure rural and urban boundary conditions. The similarity between estimates and measurements was evaluated with two metrics: the Kolmogorov–Smirnov (K–S) distance and the Root Mean Square of Hellinger (RMSH). Compared to other metrics between two frequency distributions, the K–S distance can easily be used as goodness of fit test for non-parametric distributions [21]. The RMSH was developed by [8] to evaluate the discrepancy hourly means and standard deviations of two diurnal cycles. In more than 95% of cases observed in [8], the agreement between estimates and measurements of urban temperature was between 20 and 36 in terms of K–S distance. According to the RMSH, the accuracy of urban temperature estimates provided by the coupled scheme reaches a value between 0.2 and 0.25. In addition to this analysis, estimates of temperature differences between urban and rural temperatures (i.e. UHI intensity) were also compared to measurements. The uncertainty of the UHI intensity was higher than that of urban temperature. While the K–S distance between estimated and measured UHI intensities was between 11 and 69 in more than 95% of cases, the RMSH between their respective average diurnal cycles was between 0.2 and 0.35.

In this study, we introduce an extension of the single layer urban canopy model coupled with an EnergyPlus model previously elaborated by Martin et al. [8]. Specific methods for estimating waste heat releases, traffic heat gains, and direct normal irradiance are introduced in order to design an urban microclimate model suitable for Central European cities. There is significant demand for energy retrofits of existing buildings in this region [22]. Validation of the coupled scheme in a Central European climate zone will make it possible to evaluate retrofit strategies in terms of energy use and UHI mitigation. To provide a detailed understanding of the coupled scheme accuracy in a Central European city, we carried out a sensitivity and uncertainty analysis on the urban temperature as well as on the UHI intensity. Model error is analyzed in time and frequency domains. The proposed metrics are appropriate for assessing the reliability of different types of urban microclimate models.

2. BUBBLE experimental campaign

Located at the intersection between France, Germany, and Switzerland, Basel (47.57° North, and 7.6° East) is one of the most highly populated Swiss cities with 195,000 inhabitants. The city is surrounded by the Jura mountains, crossed by the Rhine river, and experiences cold winters and mild summers. Between November 30th 2001 and July 14th 2002 [23], a total of nine rural stations (Re1 to Re3, Re5, and Rp7 to Rp11), five suburban stations (Se1, Sp2, Sp3, Sp7 and Sp8), and 10 urban stations (Ue1 to Ue5 and Up6 to Up10) were installed all around the city. Fig. 1 illustrates the location of all meteorological sites inside and around the city of Basel. For instance, the Lange Erlen weather station (Re3) is one of the nine rural sites. This 10-meter station is located 5 km. from Basel downtown at an altitude of 275 m. To evaluate temperature differences with urban sites, four temperature sensors (Psychrometer Pt100; 1 to 3, and 5) were installed on that station. Like all sites of the BUBBLE network, measurements were collected with a sampling rate of 10 min. Fig. 2 shows the weather station installed at the Lange Erlen site.

The Sperrstrasse, the main urban canyon under study, is located downtown at an elevation of 255 m. According to Hamid and Masson [24], the height to width ratio of the Sperrstrasse is about one with an average building height of 14.6 m. Asphalt and concrete cover 84% of the street surface. The remaining 16% consists of unpaved soil covered by trees and grass. Walls of surrounding buildings consist of plaster, concrete, and brick; roofs are built with tiles, gravel, and corrugated iron. During the BUBBLE experiment, a tower station (Ue1) of 32 m. was installed in the Sperrstrasse. This facility mainly consists of six temperature and humidity sensors (Psychrometer Pt100; 1 to 6), ultrasonic anemometers (Gill R2/Metek USA-1, Gill HS; A to F), 12 3-cup anemometers (Vaisala WAA15; 1 to 11), one pressure sensor (PTB 427), and two global horizontal irradiance sensors (Kippt & Zonen CNR1 and CNR11, 1 and 3, respectively). A picture of the Sperrstrasse and the installed weather station is shown in Fig. 3. Based on measurements of temperature at 26 m, relative humidity at 26 m, wind speed at 26.10 m, wind direction at 31.70 m, global horizontal irradiance at 31.70 m, and pressure at Basel altitude, we created an EnergyPlus weather