Validation of a lumped thermal parameter model coupled with an EnergyPlus model using BUBBLE data

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dated : 15 May 2015

Abstract

In this study, we describe a lumped thermal parameter model coupled with an EnergyPlus model. This urban micro climate model is used to estimate urban temperature in Basel, Switzerland. Based on information reported in the literature, we developed a coupled scheme model to be tested using measurements in the Sperrstrasse. Despite the variety of different measurements recorded in the BUBBLE dataset, direct normal and diffuse horizontal irradiance have to be estimated from a method taking global horizontal irradiance as input. To select the most suitable model of direct normal irradiance estimation, we first tested several methods from weather conditions of Strasbourg (France) and Geneva (Switzerland), the two closest cities to Basel where typical meteorological data over the year are available. Secondly, we evaluated the sensitivity of the agreement between estimated and measured urban temperature to direct normal irradiance estimates provided by the two most accurate methods in Strasbourg and Geneva. As a result, urban temperature estimates are insensitive to the use of one method rather than the other. Comparing measured and estimated urban temperature in the Sperrstrasse, we show that the coupled scheme can achieve a satisfactory accuracy in an urban area located in Central Europe.

1. Introduction

Studies of the urban environment have been carried out around the world for many years (Asimakopoulos et al., 2001). Nevertheless, a few data sets are commonly used to evaluate the reliability of newly developed urban mico climate models. The CAPITOUL (Masson et al., 2008) is one of the most frequently employed data sets for urban micro climate model validation. This experimental campaign took place in Toulouse (France) for a one year period. Between February 2004 and 2005, measurements of urban conditions were made at the intersection of Alsace-Lorraine and Pomme road. The BUBBLE effort (Rotach et al., 2005) also aimed at producing a data set suited for validation of urban micro climate models. For a one-year period (2001-2002), urban conditions of the Sperrstrasse (Basel, Switzerland) were measured at seven different levels.

A significant number of urban micro climate models have been developed to approximate meteorological conditions in the urban canopy layer, the lowest layer in the urban boundary layer. Among all of them, the coupled scheme developed by Martin et al. (2015) is the first urban micro climate model through which the accuracy of urban temperature and specific humidity estimates was evaluated in a desert environment. The fidelity between measurements and estimates was calculated using two metrics: the Kolmogorov-Smirnov (K-S) distance between two frequency distributions, and the Root Mean Square of Hellinger (RMSH) between two average diurnal cycles. Through Monte-Carlo analysis, these two metrics were computed over a thousand urban temperature and specific humidity estimates within a canyon of Masdar Institute. In the best case, urban temperature estimates achieved a fidelity of 20 in terms of K-S distance, and 0.2 in terms of RMSH.

In this paper, we evaluate the reliability of the coupled scheme developed by Martin et al. (2015) in estimating urban temperature in a Central European city. For this purpose, we extended the capabilities of the coupled scheme by implementing estimation models of waste heat releases generated by a hydronic heating system, anthropogenic heat created by traffic, and direct normal irradiance received from sun. To evaluate the risk in choosing one method of direct normal irradiance estimation rather than another, we computed the sensitivity of the agreement between measured and estimated urban temperature to variations of direct normal irradiance estimates. Using one of the most accurate direct normal irradiance estimates, we analyzed winter and spring urban temperature assessed by the coupled-scheme in the Sperrstrasse. As main outcome, a better accuracy can be achieved by the coupled scheme in Basel than that obtained by Martin et al. (2015) in Masdar Institute.

2. Coupled scheme

To estimate urban temperature in the Sperrstrasse, we employed a lumped thermal parameter model coupled with an EnergyPlus model. As an extension of the coupled scheme developed by Martin et al. (2015), we included two new elements: anthropogenic heat from cars and waste heat releases from the heating system. Sensible anthropogenic heat from traffic $Q_{traffic}$ is assumed to be schedule dependent, i.e.:

$$Q_{traffic} = I_{traffic} \, F_{traffic}(h) \quad (1)$$

where $I_{traffic}$ is the maximum intensity of the sensible anthropogenic heat from traffic, and $F_{traffic}(h)$ the fraction of $I_{traffic}$ at hour h. We supposed that the behavior of sensible heat released by traffic $F_{traffic}(h)$ in Basel is similar to that reported in Toulouse (Pigeon et al., 2007). Waste heat releases caused by the consumption of heating were computed as:

$$Q_{waste} = \delta_{waste} \, (1 - \eta) \, Q_e \quad (2)$$

where δ_{waste} is the fraction of waste heat going into the urban canyon, η the efficiency of the boiler, and Q_e the amount of fuel used by the HVAC system. To estimate the energy consumption of the heating system Q_e, we designed a real load model for hydronic systems using the EnergyPlus toolkit (cf. baseboard system modeling in EnergyPlus Development Team, 2013). According to Zogg (2002), the energy produced by boilers covers 86% of the heating demand in Switzerland. Sources of energy consumed by boilers are oil (57%), natural gas (26%), and wood (3%). The efficiency of boilers is about 80% on average. The distribution of heat to buildings is broadly done by hydronic systems (i.e. baseboards or radiators).

3. Validation environment

To validate urban temperature calculated by the coupled scheme, we used BUBBLE measurements in the Sperrstrasse. According to Martin et al. (2015), the coupled scheme enables us to estimate the mean urban temperature from urban boundary layer conditions. As mean urban temperature of the Sperrstrasse, we took the average between measurements at 2.6 m. and 13.9 m above street level. As urban boundary layer conditions, we used measurements of dry-bulb temperature at 26 m., relative humidity at 26 m., wind speed at 26.10 m., wind direction at 31.70 m., and pressure at Basel altitude. Direct normal and diffuse horizontal irradiance were estimated employing a method taking global horizontal irradiance at 31.70 m. as input.

Before selecting a suitable model to estimate direct normal and diffuse horizontal irradiance reaching the Sperrstrasse, we tested several methods implemented in the Matlab PV_LIB toolbox[1] on measurements for a Typical Meteorological Year (TMY) in Strasbourg (~ 120 km. from Basel) and Geneva (~ 230 km. from Basel). More precisely, we analyzed the distribution of Root Mean Square Error (RMSE) and Mean Bias Error (MBE) of direct normal irradiance estimates over each day (i.e. 365 samples). Among all methods implemented in the PV_LIB toolbox, the DISC and the DIRINT methods provide the best daily agreements between measured and estimated direct normal irradiance in Strasbourg and Geneva. Both models essentially take as input global horizontal irradiance, the zenith angle, and the day of the year. In addition to these three parameters, the DISC method (Maxwell, 1987) can also consider pressure to improve estimates. Atmospheric pressure is fundamentally considered by the DIRINT model (Ineichen et al., 1992) while dew point temperature can be optionally specified. Fig. 1 shows that there is no significant difference between distributions of the daily RMSE and MBE achieved by the two methods in one location. Nevertheless, their accuracy strongly diverges from one location to another. According to TMY data for Strasbourg, the daily RMSE and MBE of direct normal estimates provided by the two models are below 188 W/m^2 and 70 W/m^2, respectively, in more than 95% of cases. On the other hand, the third quartiles of the daily RMSE and MBE achieved by direct normal estimates in Geneva are around 285 W/m^2 and 143 W/m^2, respectively.

[1] https://pvpmc.sandia.gov/resources-for-members/pv_lib-toolbox/

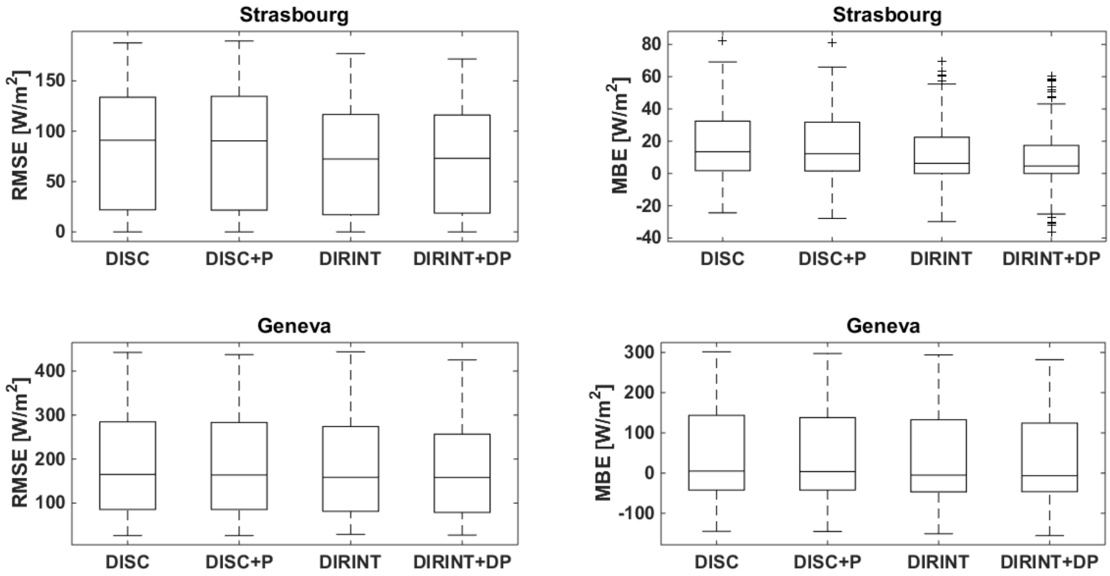

Fig. 1 Distributions of the daily RMSE and MBE acheived by direct normal estimates provided by the DISC method with (DISC+P) and without (DISC) pressure as input, and the DIRINT method with (DIRINT+DP) and without (DIRINT) dew point temperature as input. These distributions were computed from TMY data in Strasbourg and Geneva.

After that, we analyzed the sensitivity of the agreement between measured and estimated urban temperatures to the use of the DISC model rather than the DIRINT model, and vice versa. According to Fig. 2, the choice of model has an insignificant impact on urban temperature estimates. No matter what method of direct normal irradiance estimation we use, the daily RMSE between measured and estimated urban temperatures is below 1.6 K with a probability of 75%. The daily MBE of urban temperature estimates is between -0.36 K and 0.94 K in more than 50% of cases. The average RMSH between urban temperature estimates assessed from direct normal irradiance approximated by the two models is lower than $3 \cdot 10^{-4}$.

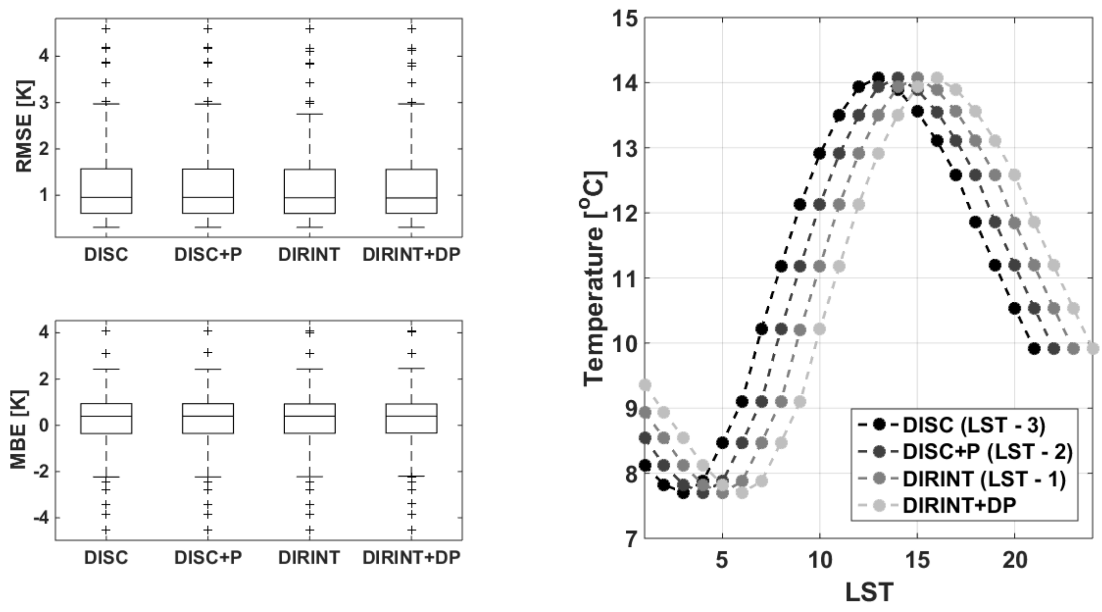

Fig. 2 Distributions of the daily RMSE and MBE achieved by urban temperature estimates using the DISC method with (DISC+P) and without (DISC) pressure as input, and the DIRINT method with (DIRINT+DP) and without (DIRINT) dew point temperature as input. The average diurnal cycle of urban temperature estimates is also illustrated. To make all average diurnal cycles visible, we introduced a different delay for each of them.

Table 1 Configuration of the coupled scheme for urban temperature estimation in the Sperrstrasse

Parameters	**Value**	**Reference**
Simulation time-step [*step/hour*]	1	
Simulation period	12/5 (2001) – 07/14 (2002)	
Street		
width [*m*]	15	Hamdi and Masson (2008)
anthropogenic intensity from traffic [*W/m²*]	8	Bueno Unzeta (2012)
waste heat fraction [%]	30	
Paved surface (84%)		Hamdi and Masson (2008)
depth [*m*]	0.25	Bueno Unzeta (2012)
volumetric specific heat [*MJ/(m³ K)*]	1.4	Bueno Unzeta (2012)
albedo [-]	0.08	Hamdi and Masson (2008)
emissivity [-]	0.94	Hamdi and Masson (2008)
Unpaved surface (Sandy loam)		
depth [*m*]	0.1	
volumetric specific heat [*MJ/(m³ K)*]	1.1	
albedo [-]	0.15	
emissivity [-]	0.8	
vegetation-to-soil ratio [%]	70	
vegetation albedo [-]	0.17	
Reference building		
height [*m*]	14.6	Hamdi and Masson (2008)
length [*m*]	13.5	Dorer et al. (2013)
width [*m*]	110.5	Dorer et al. (2013)
orientation [º]	70	
people density [people/m²]	0.08	
internal gain intensity [W/m²]	5.8	Bueno Unzeta (2012)
infiltration [*ac/h*]	0.5	Bueno Unzeta (2012)
thermal set points [*ºC*]	19 – No max.	Bueno Unzeta (2012)
Walls		
albedo [-]	0.14	Hamdi and Masson (2008)
U-value [*W/(m² K)*]	0.6	Bueno Unzeta (2012)
Roof		
albedo [-]	0.14	Hamdi and Masson (2008)
U-value [*W/(m² K)*]	0.3	Bueno Unzeta (2012)
Windows (30%)		
albedo [-]	0.08	
U-value [*W/(m² K)*]	2.4	Bueno Unzeta (2012)
Heating system		
outdoor air flow rate [*L/(m² s)*]	0.3	
boiler efficiency [*W/W*]	0.8	Zogg (2002)

4. Winter and spring urban temperature estimates

When we analyzed urban temperature assessed by the coupled scheme, we clearly observed different characteristics between winter (i.e. December 21st 2001 to March 21st 2002) and spring (i.e. March 21st 2002 to June 21st 2002) estimates. According to Fig. 3, the coupled scheme underestimates winter urban temperature measurements on average. Although the coupled scheme underestimates winter urban temperature with an MBE of -0.43 K (cf. Table 2), the K-S distance and RMSH of urban temperature estimates are 2.5 and 5 times, respectively, lower than those achieved by Martin et al. (2015) in the best case. In contrast with winter urban estimates, the coupled scheme tends to overestimate spring urban temperature measurements in the Sperrstrasse. Spring overestimations are slightly higher than winter underestimations with a MBE of 0.8 K. On the other hand, the RMSE between measured and estimated spring urban temperatures is 0.25 K lower than that between measurements and estimates of winter urban temperature. As for the winter urban temperature estimates, the fidelity between measurements and estimates of spring urban temperature in terms of K-S distance and RMSH is better than that observed in Masdar Institute by Martin et al. (2015).

Table 2 Agreement between measured and estimated urban temperature in the Sperrstrasse.

	Winter	Spring
K-S distance [-]	8.47	11.03
RMSH [-]	0.04	0.07
RMSE [K]	1.51	1.26
MBE [K]	-0.43	0.8

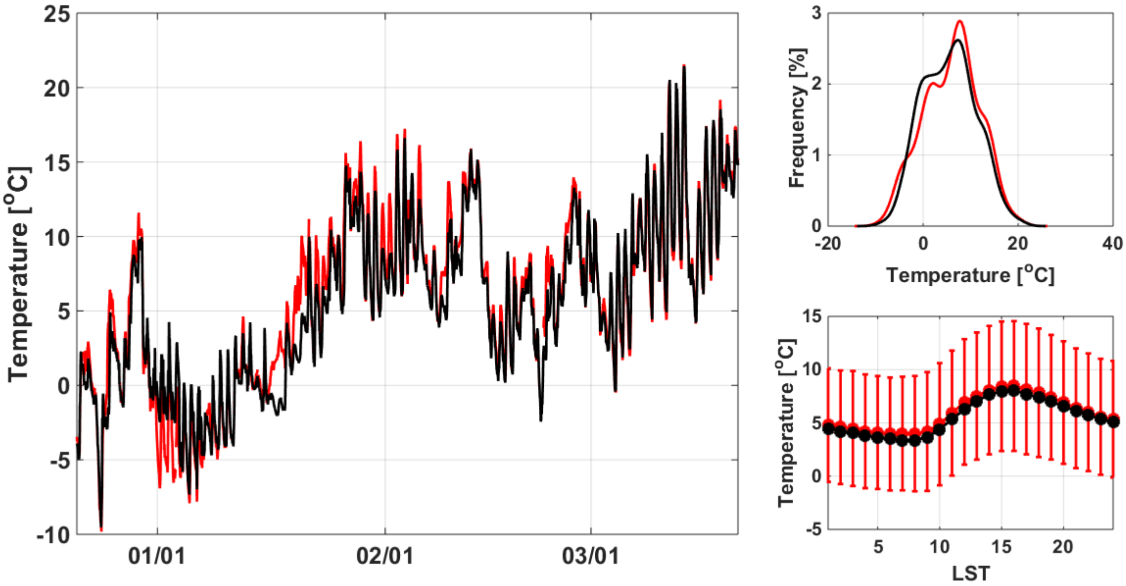

Fig. 3 Measured (red) and estimated (black) winter urban temperature in the Sperrstrasse.

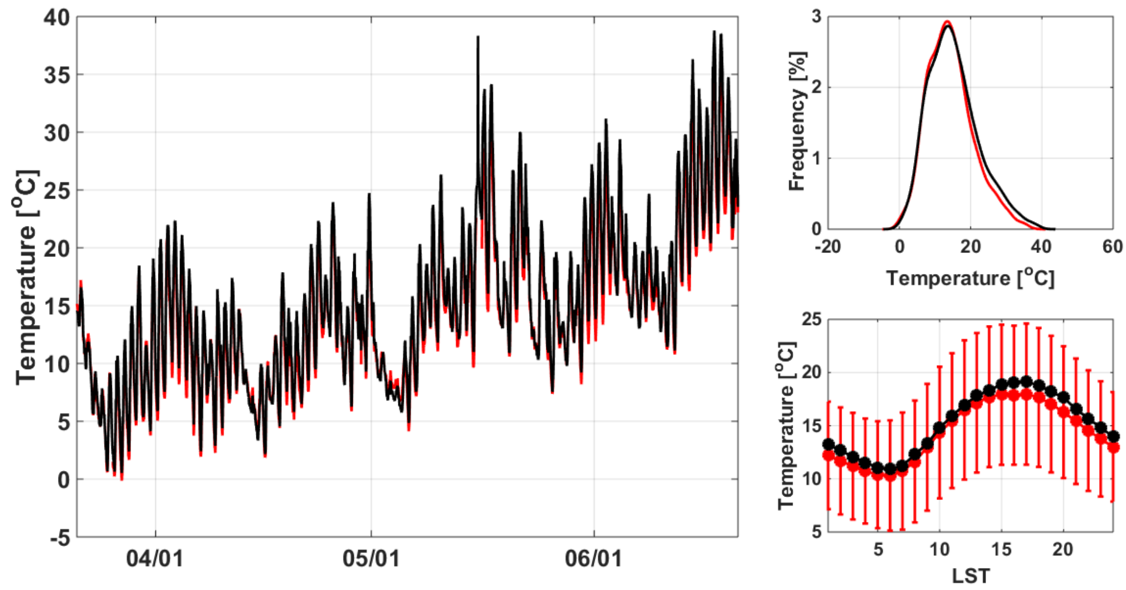

Fig. 4 Measured (red) and estimated (black) spring urban temperature in the Sperrstrasse.

5. Conclusion

In this paper, we introduced an extended version of the lumped thermal parameter model coupled with an EnergyPlus model we used to estimate urban temperature in a dense Central European city. To do so, we included models to approximate anthropogenic heat gains created from traffic, waste heat releases generated from a hydronic heating system, and direct normal irradiance received from sun. For validation purposes, we employed BUBBLE measurements collected between December 5th 2001 and July 14th 2002.

Based on information reported in the literature, we designed a coupled scheme model for the Sperrstrasse (Basel, Switzerland). Employing TMY data for Strasbourg and Geneva, we tested all methods of direct normal irradiance estimation implemented in the Matlab PV_LIB toolbox. Among all of them, the DISC model (with and without pressure as input), and the DIRINT model (with and without dew point temperature as input) achieved the best fidelity with measurements. However, urban temperature estimates provided by the coupled scheme are insignificantly sensitive to the choice of these two models. After that, we analyzed the accuracy achieved by winter and spring urban temperature estimates in the Sperrstrasse. In both winter and spring conditions, urban temperature estimates in the Sperrstrasse achieved a better accuracy in terms of K-S distance and RMSH than that observed in Masar Institute by Martin et al. (2015). While winter urban temperature measurements are underestimated by the coupled scheme with a MBE of -0.4, urban temperature measurements are overestimated with a MBE of 0.8 in spring. Finally, we noticed that the RMSE achieved by spring urban temperature estimates is lower than that obtained by winter estimates.

From this study, several future works can be planned. First of all, more accurate direct normal irradiance estimation models taking global horizontal irradiance as input could be developed. In addition to this, it would be interesting to evaluate how close the coupled scheme can approximate specific humidity in the Sperrstrasse. Even though humidity represents a key element in the outdoor/indoor comfort, it is often neglected during the validation process of an urban micro climate.

Acknowledgment

This work was funded under the Cooperative Agreement between the Masdar Institute of Science and Technology, Abu Dhabi, UAE and the Massachusetts Institute of Technology, Cambridge, MA, USA, Reference Number 02/MI/MIT/CP/11/07633/GEN/G/00. We also wish to acknowledge Andreas Christen from the University of British Columbia (andreas.christen@ubc.ca) for helping us to obtain BUBBLE measurements.

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