

A new Building Energy Model coupled with an Urban Canopy Parameterization for urban climate simulations—part II. Validation with one dimension off-line simulations

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Abstract Recent studies show that the fluxes exchanged between buildings and the atmosphere play an important role in the urban climate. These fluxes are taken into account in mesoscale models considering new and more complex Urban Canopy Parameterizations (UCP). A standard methodology to test an UCP is to use one-dimensional (1D) off-line simulations. In this contribution, an UCP with and without a Building Energy Model (BEM) is run 1D off-line and the results are compared against the experimental data obtained in the BUBBLE measuring campaign over Basel (Switzerland) in 2002. The advantage of BEM is that it computes the evolution of the indoor building temperature as a function of energy production and consumption in the building, the radiation coming through the windows, and the fluxes of heat exchanged through the walls and roofs as well as the impact of the air conditioning system. This evaluation exercise is particularly significant since, for the period simulated, indoor temperatures were recorded. Different statistical parameters have been calculated over the entire simulated episode in order to compare the two versions of the UCP against measurements. In conclusion, with this work, we want to study the effect of BEM on the different turbulent fluxes and exploit the new possibilities that the UCP–BEM offers us, like

the impact of the air conditioning systems and the evaluation of their energy consumption.

1 Introduction

The Urban Canopy Parameterization (UCP) of Martilli et al. (2002) simulates the impact of urban buildings on airflow in mesoscale atmospheric models. This scheme takes into account the impact of the urban surfaces on wind, temperature, and turbulent kinetic energy (TKE), but does not explicitly resolve the generation of energy within the buildings and its transfer to the atmosphere. Since this effect can significantly modify the urban energy budget, Salamanca et al. (2009) developed a Building Energy Model (BEM) that was implemented in the urban parameterization (UCP–BEM) of Martilli. Thanks to this improvement, a detailed study of the impact of cities on the urban climatology can be conducted. However, this parameterization needs to be validated against meteorological observations in order to judge the reliability of the results and its predictions. In the last years, several measurement campaigns have been carried out to evaluate different urban schemes; see Masson et al. (2002) and Best et al. (2006) for example. These necessary campaigns help us to understand the physical processes that take place in the urban atmosphere and to validate the accuracy of our schemes. All the experience and knowledge acquired with these studies could be applied to evaluate new strategies of city development to minimize the intensity of the Urban Heat Island phenomenon (UHI). Following this idea, the goal of the present work is twofold: on the one hand, the recent UCP–BEM scheme is evaluated against the surface energy balance fluxes measured in the BUBBLE (<http://www.unibas.ch/geo/mcr/Projects/BUBBLE/>) experi-

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ment and compared with the results obtained with the previous version of UCP of Martilli; on the other hand, the new possibilities that the UCP–BEM scheme offers are evaluated. In particular, with this new scheme, the impact of the air conditioning systems on the atmosphere can be evaluated, and the energy consumption can be calculated for different situations. The UCP–BEM parameterization has been coupled to the mesoscale model (FVM, Clappier et al. 1996), and for this work, the 1D off-line version (see Section 3.1 for details) is used.

In Section 2, a short description of the theoretical context is explained. In Section 3, the 1D off-line configuration and the fundamental characteristics of the simulated urban area are described. In Section 4, results obtained with the two schemes are compared. And finally, in Section 5, the heat emission and the energy consumption of the air conditioning systems in different situations are analyzed. Conclusions and future research are given in Section 6.

2 Approach

The urban surface energy balance, defined by (Oke 1988), plays a fundamental role in this work. Assuming no horizontal advection, the relevant energetic exchange processes can be written as:

$$Q_{\text{net}} = Q_{\text{H}} + Q_{\text{LE}} + Q_{\text{stor}} \quad (1)$$

where the term Q_{net} is the net all wave radiation, Q_{H} the sensible heat flux, Q_{LE} the latent heat flux, and finally Q_{stor} the net heat stored in the urban area. It is important to mention that in an urban area the heat fluxes (Q_{H} and Q_{LE}) are not only the result of the partitioning of the net radiation, as it happens for natural surfaces, but they have a component due to human activities (anthropogenic heat). In the UCP of Martilli et al. (2002), this was not considered¹, while in the new UCP–BEM scheme, a fraction of the total anthropogenic heat is taken into account (the heat released by the traffic and industry are not considered in the new UCP–BEM scheme). The latent and sensible anthropogenic heat is considered in this new UCP–BEM separately (more details in Salamanca et al. 2009), and includes all additional energy produced by human activities within the buildings; the latent heat generated by people, the sensible heat generated by machines and people, and the heat generated by the air conditioning systems (this last heat is injected directly into the atmosphere, while the other fluxes are released

within the buildings due to human presence). In the model, the anthropogenic latent heat interacts with the outdoor air through the natural ventilation of the buildings, while the sensible heat is exchanged with the atmosphere through natural ventilation and by heat diffusion through the walls. In the model, all these anthropogenic heats (jointly with the heat generated by the air conditioning systems) are added to the terms Q_{LE} and Q_{H} of the Eq. (1). In the two urban schemes, the different urban fluxes can be addressed independently, and the heat stored in the urban fabric is calculated using the energy balance equation,

$$Q_{\text{stor}} = Q_{\text{net}} - Q_{\text{H}} - Q_{\text{LE}} \quad (2)$$

A standard way to validate an urban parameterization is to compute the different fluxes at different heights and to compare them with the measurements. An example is sketched in Fig. 1.

3 Applied framework

3.1 The 1D off-line configuration

A peculiarity of the UCP used in this study is that it is multilayered. To run it off-line, then the simulation is

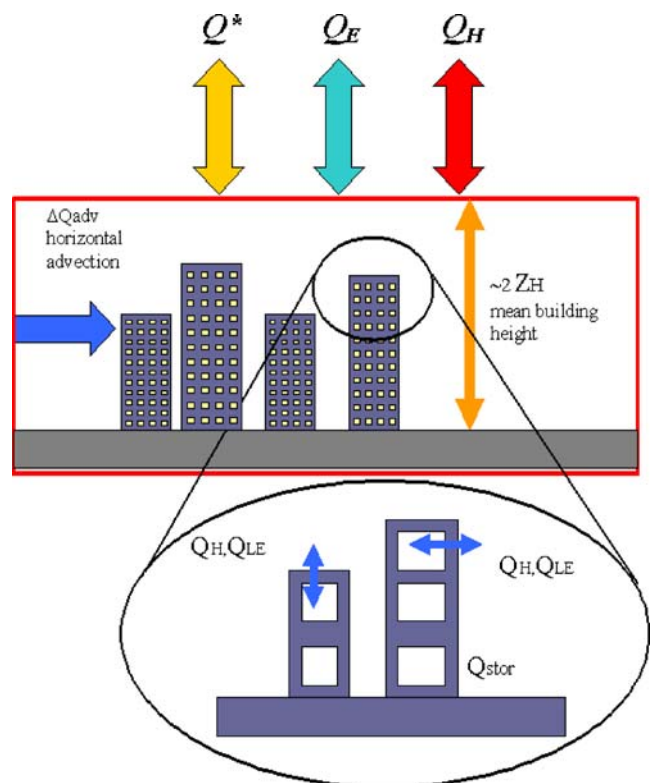


Fig. 1 Schematic picture of the heat fluxes considered in an urban environment

¹ To be precise, in the UCP of Martilli, it is possible to fix the internal building temperature, which accounts in some indirect and very rough way for the anthropogenic heat. But this technique is not precise, and does not allow any estimation of energy consumption.

performed on a vertical column (1D), ranging from street level to the height of the forcing (32 m in this case), with a vertical resolution of 2 m. The model calculates the vertical profile of several variables (temperature, wind, humidity, TKE) and turbulent fluxes from the forced altitude down to ground. The model uses a *k-l* turbulence closure scheme, hence the vertical turbulent fluxes $\overline{w'\xi'}$ (ξ stands for any scalar variable) are computed using the *K*-theory, as,

$$\overline{w'\xi'} = -K \frac{\partial \bar{\xi}}{\partial z}. \tag{3}$$

The computation of the turbulent transfer coefficients *K* leads to the calculation of a prognostic equation for the TKE (Bougeault and Lacarrère 1989), as it is explained in Martilli et al. (2002). The only difference, compared to the formulation presented in Martilli et al. (2002), is in the estimation of the length scales. Since it is impossible to estimate the values of *l_{up}* because the whole planetary boundary layer (PBL) is not resolved, it is assumed that the relevant length scale is the height above ground.

The forcing was applied to air temperature, humidity, pressure, wind components, long-wave downward radiation, and solar radiation.

In summary, the sensible and latent heat fluxes are estimated at different heights from (details of the symbols in Appendix)

$$Q_H = \bar{\rho} C_P \overline{w'\theta'} = -\bar{\rho} C_P K \frac{\partial \bar{\theta}}{\partial z} \tag{4}$$

$$Q_{LE} = \bar{\rho} L_V \overline{w'q'} = -\bar{\rho} L_V K \frac{\partial \bar{q}}{\partial z}, \tag{5}$$

while the net radiation *Q_{net}* is a weighted average of the net radiation at each surface (walls, roof, street, and vegetated part).

It should not be forgotten that the energy balance (Eq. 1), which represents a budget of the different fluxes representative of an urban zone, never describes local values.

3.2 Urban area characteristics and measurements

The data used in this work were collected at the main urban surface site of the BUBBLE experiment (Sperrstrasse). It is located in a heavily built-up part of the city of Basel, Switzerland (European urban, mainly residential three- to four-story buildings in blocks, flat commercial and light industrial buildings in the backyards). The parameters of the city surface are summarized in Table 1 (more details in Christen 2005) and the thermal properties of the materials in Table 2. The measurement setup consists of a tower (see Fig. 2) inside a street canyon reaching up to 32 m (approximately 2.2 times the mean roof height of the urban

Table 1 Morphometric parameters and surface characteristics of the city surface of the city of Basel for a circle of 250 m around the tower at Basel-Sperrstrasse

Mean building height	<i>Z_H</i>	14.6m
Population density	ρ_{inhab}	Between 200 and 300 inhabitants/ha
Frontal aspect ratio	λ_F	0.37
Plan aspect ratio of buildings	λ_p	0.54
Plan aspect ratio of vegetation	λ_V	0.16
Complete aspect ratio ^a	λ_C	1.92
Plan area ratio of impervious non-building surfaces	λ_I	0.30
Roof materials	–	45% tiles, 50% gravel, 5% corrugated iron
Building materials	–	Plaster, concrete, brick

^a This term is the total surface of a building in contact with the outdoor air divided by the area of a unit urban cell

surface). The intensive operation period (IOP) analyzed was between June 10th and July 10th 2002. The overall framework and the experimental activities during BUBBLE are documented in Rotach et al. (2005). Measurements were taken at different heights in and above the street canyon with a 10-min average time resolution.

4 Results

During the IOP, the mean air temperature was 20°C and the mean precipitation was 65 mm (more details in Christen 2005). The simulations were carried out during the overall

Table 2 Thermal properties of the building materials for roofs, walls, and roads used in the simulations corresponding to the Basel-Sperrstrasse site

	1	2	3	4
Roof layer				
<i>d</i>	0.02	0.02	0.02	0.04
<i>C</i>	1.128	0.276	0.382	1.745
λ	0.614	0.129	0.090	0.984
Road layer				
<i>d</i>	0.010	0.040	0.025	0.975
<i>C</i>	1.940	1.940	1.550	1.350
λ	0.750	0.750	0.934	0.275
Wall layer				
<i>d</i>	0.01	0.03	0.08	0.02
<i>C</i>	1.778	1.780	1.764	1.779
λ	1.070	1.076	1.071	0.651

Layer sequence: 1 is nearest to the surface. Here, *d* is the thickness of layer (m), *C* is the heat capacity of the layer (MJ m⁻³ K⁻¹), and λ is the thermal conductivity (W m⁻¹ K⁻¹)



Fig. 2 The street canyon from above (Sperrstrasse). The tower reaches approximately 2.2 times the mean roof height of the urban surface (photography obtained from the internet page of the BUBBLE experiment)

IOP with four different setups. In the first one, only the UCP of Martilli (ucp case) was considered. The second simulation was carried out considering the UCP–BEM scheme (ucp–bem case), but without considering the effects of the air conditioning systems (they were turned off in the model). Finally, the last two simulations were carried out using the same UCP–BEM parameterization but with the air conditioning systems running in two different ways; for the first one, the air conditioning was working 24 h a day (ucp–bemac case), while for the second one, air conditioning was working from 8:30 to 18:30 h every day (ucp–

bemac* case). A mathematical description of the modeling of the air conditioning systems is explained in Salamanca et al. (2009). During the IOP, sensors of temperature were installed in the stairwells of some buildings. These measurements suggest that the target temperature of the air conditioning systems was close to 24°C (Voogt, personal communication). A detailed summary of the setting used in the four simulations is described in Table 3.

The heat production by an adult when he is resting is about 70 W, when working (office work) is about 110 W, and when occupied (walking, driving, domestic work, etc.) is about 300 W (Oke 1987). Averaging these quantities and assuming 8 h daily for each activity gives a heat production per person of 160 W. Furthermore, the water lost by evaporation during a day by an adult is about 0.8 kg. This quantity corresponds to approximately 22.7 W of latent heat per person. Using these values and the fact that in Basel-Sperrstrasse the population density is about 250 inhabitants/ha (Christen 2005), it is possible to estimate the total sensible and latent human heat generated in this zone. In the simulations, a constant ratio of occupants of 0.0116 persons/m² of floor and a sensible heat flux from equipment of 7.4 W/m² of floor were considered. The values of sensible heat flux from equipment were chosen to be coherent with the estimation of an anthropogenic heat emission of 20 W/m² of land for the Basel-Sperrstrasse site (Christen 2005).

4.1 Sensible heat

Two periods are analyzed in this section. The first period goes from 14th of June 2002 (165 Julian day) to 23 rd of June 2002 (174 Julian day), both inclusive, and the second one from 30th of June (181 Julian day) to 14th of July 2002 (195 Julian day). Most of the days in the first period were sunny, and in some days the temperature reached up to 35°C. In the second period, cloudy skies and lower temperatures were more frequent. In Fig. 3, one can see the results obtained for the sensible heat flux ($w'\theta'$

Table 3 Input parameters and variables considered in the four different simulations that were carried out

Case	ucp	ucp–bem	ucp–bemac	ucp–bemac*
Z_0 (m) ^a	0.0005	0.0005	0.0005	0.0005
Indoor surface wall temperature fixed	20°C	Not fixed	Not fixed	Not fixed
Natural ventilation	No	Yes	No	No
Number of floors considered in a building	–	4	4	4
Coefficient of performance (COP) ^b	–	–	3.5	3.5
Target temperature of room cooling	–	–	23.5°C	23.5°C
Comfort range of temperature	–	–	±0.5°C	±0.5°C
Sensible heat generated by a person	–	160 W	160 W	160 W
Latent heat generated by a person	–	22.7 W	22.7 W	22.7 W

^a In the Urban Canopy Model, the roughness of the roofs and the streets is taken into account to compute the exchange of the heat fluxes between the surfaces and the atmosphere

^b Typical air conditioning systems for office buildings have values of COP between 2 and 5; see Ashie et al. (1999)

kinematic heat flux) calculated in the four different cases against the measurements at different heights (to facilitate the clarity in the plots and to avoid noise induced by the intermittent presence of clouds, only three selected days for the first period and two selected days for the second are shown, and hourly mean values are used). Above the roofs, the ucp-bem's cases show better fits than the ucp case (Fig. 3c–d). In the IOP, the air conditioning systems were

working (this can be deduced from the indoor air temperature measurements showing a little variation of temperature during the day) and these systems produce an increase of sensible heat fluxes into the atmosphere. To quantify the differences between the simulation and the measurements, we computed the root mean square error (RMSE) for the sensible heat flux Q_H for the four cases during the two periods of simulation (hourly mean values

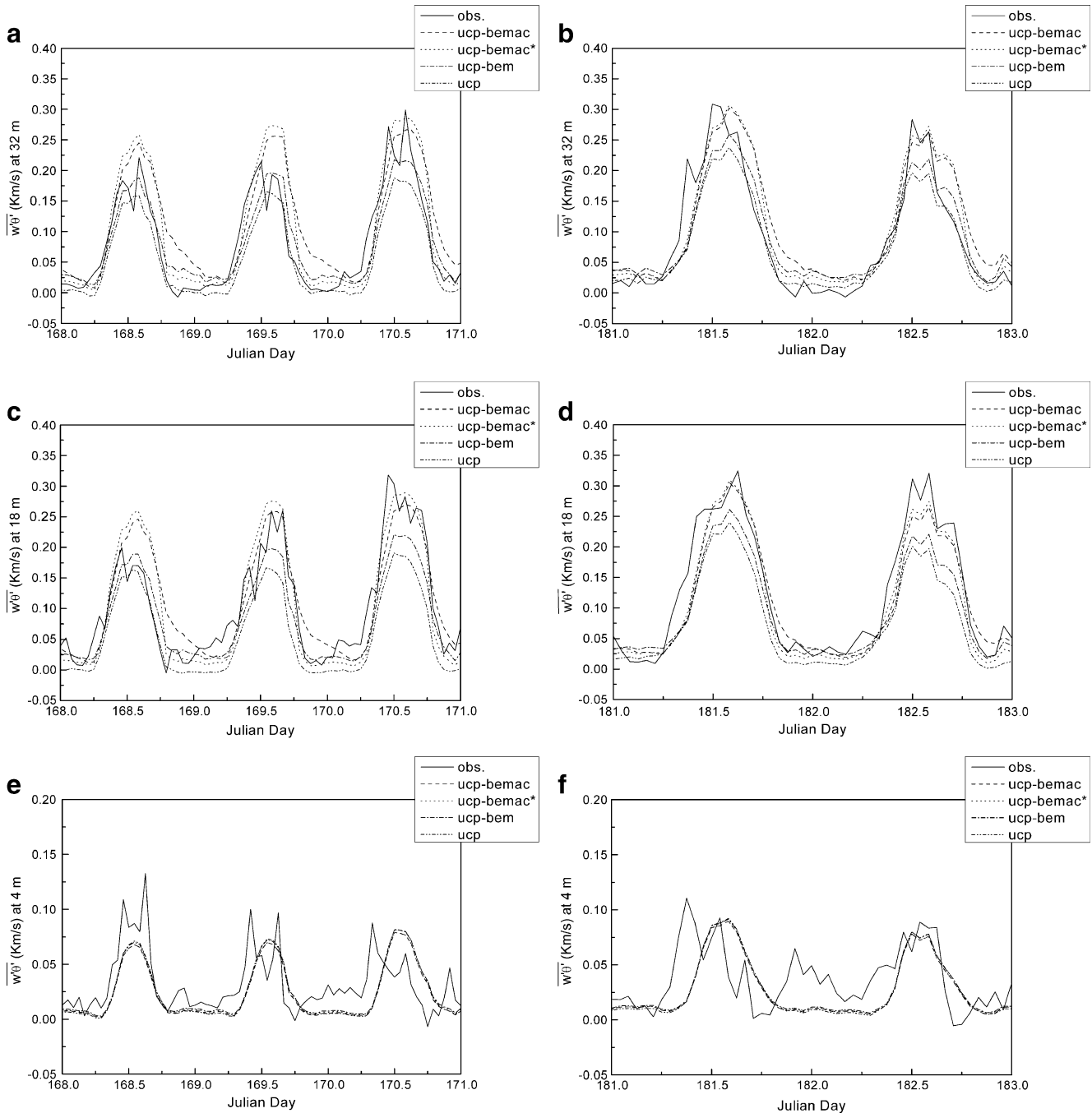


Fig. 3 Sensible heat fluxes obtained with the two parameterizations (UCP and UCP-BEM) in four different situations against the measurements for the two periods analyzed: **a–b** at 32 m, **c–d** at 18 m, and **e–f** at 4 m from the ground

Table 4 Performance statistics (RMSE) for sensible heat fluxes (W/m^2) at different heights for the four cases simulated at the Basel-Sperrstrasse site (first period)

Case	Days	165–174		
		ucp–bemac	ucp–bemac*	ucp–bem
Q_H (32 m)	59.71	55.66	39.20	46.35
Q_H (night-time) (32 m)	46.69	16.42	23.24	20.77
Q_H (daytime) (32 m)	68.61	73.71	48.58	59.71
Q_H (18 m)	53.30	53.62	56.62	77.94
Q_H (night-time) (18 m)	35.75	37.38	29.19	51.85
Q_H (daytime) (18 m)	64.28	64.00	71.76	94.19
Q_H (4 m)	30.94	30.80	30.78	31.53
Q_H (night-time) (4 m)	16.85	16.21	15.55	17.32
Q_H (daytime) (4 m)	38.90	38.92	39.12	39.58

were considered). Moreover, night-time and daytime values were also calculated. A value was considered a night-time value when the observed net radiation was negative. Otherwise, the value was considered a daytime value. Here, the RMSE is defined as:

$$\text{RMSE} = \left[\frac{1}{N} \sum_{j=1}^N (V_j - V_0)^2 \right]^{\frac{1}{2}} \quad (6)$$

where V_j and V_0 are simulated and observed values, respectively.

4.1.1 First period

RMSE results (see Table 4 and Fig. 3a) at 32 m show that the inclusion of BEM improves the results compared to the standard ucp. For the first period, the best result is obtained in the ucp–bem (no air conditioning) case when entire days (day and night-time) are considered. During the night, the best fit (RMSE night-time) is obtained when the air conditioning is used only during daytime (ucp–bemac* case), while for the ucp–bem simulation (no air condition-

ing), we observed the best RMSE during daytime. In fact, during the day, when the air conditioning is in use, the sensible heat is slightly overestimated at this height. As indicated in Fig. 3c, larger differences are observed 18 m above the ground (the mean building height was 14.6 m). Here, the best RMSE result (considering all the days) is obtained in the ucp–bemac case, the second better in the ucp–bemac*, the third in the ucp–bem, and the worst fit is generated by the ucp simulation.

During daytime, the best fit is obtained with the ucp–bemac* scheme and during night-time with the ucp–bem. Figure 3e indicates that near the ground the effect of the air conditioning systems is negligible. The RMSE parameters confirm this hypothesis (there are no important differences between the four cases simulated). In fact, in the model, the heat is released into the atmosphere by an air conditioning system located on the roof of the buildings, which might explain the small difference obtained near the ground within the urban canopy. It could be interesting to study the effect of air conditioning systems located at different heights on the facade of buildings. In fact, in that case, heat would be directly released within the urban canyons.

Table 5 Performance statistics (RMSE) for sensible heat fluxes (W/m^2) at different heights for the four cases simulated at the Basel-Sperrstrasse site (second period)

Case	Days	181–195		
		ucp–bemac	ucp–bemac*	ucp–bem
Q_H (32 m)	44.63	39.64	35.35	36.09
Q_H (night-time) (32 m)	37.43	21.84	25.80	14.73
Q_H (daytime) (32 m)	49.92	49.97	41.75	47.12
Q_H (18 m)	37.65	34.99	41.15	54.17
Q_H (night-time) (18 m)	25.88	23.96	19.56	30.77
Q_H (daytime) (18 m)	45.28	42.12	52.94	67.94
Q_H (4 m)	27.41	27.33	27.15	27.87
Q_H (night-time) (4 m)	15.62	15.32	14.91	16.34
Q_H (daytime) (4 m)	34.36	34.36	34.24	34.75

4.1.2 Second period

For this period (see Table 5 and Fig. 3b), the best fit at 32 m is obtained again in the ucp–bem case when complete days are considered. Values close to ucp–bem are generated by the ucp and ucp–bemac* cases. Unexpectedly, the best night-time value is obtained with the ucp scheme, and finally, during daytime the lower RMSE is computed with the ucp–bem (no air conditioning) case. At 18 m (Fig. 3d), the best results are obtained when the air conditioning systems are in use (ucp–bemac and ucp–bemac* cases), with a large difference between the new schemes and the traditional ucp. During night-time, the best fit is obtained in the ucp–bem case, followed closely by the ucp–bemac* one. During daytime, the best adjustment is generated with the ucp–bemac* scheme. Finally, at 4 m above the ground (Fig. 4f), there are no important differences between the four cases simulated.

In the above comparison between modeled and measured sensible heat fluxes, the following points must be taken into account:

- There is a general tendency for the ucp–bemac and ucp–bemac* simulations to have worse RMSE than ucp at 32 m, but better at 18 m. Since there are no sources or sinks of energy between 18 and 32 m in the model, the computed values are similar at the two heights. The difference should therefore derive from the measurements. To confirm this hypothesis, the difference between the sensible heat fluxes measured at 32 and 18 m have been plotted (Fig. 4). As one can see, differences in the measured values between the two heights are around 50–100 W/m², and may be due to some horizontal advection effect. Since in the model horizontal advection is not taken into account, we think

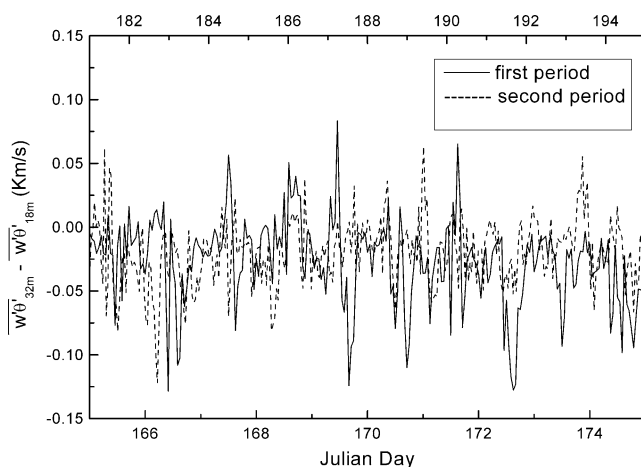


Fig. 4 Sensible heat flux at 32 m minus sensible heat flux at 18 m of height. The lower axis corresponds to the first period and the upper axis to the second period

that the 18 m measurements are more significant for the validation of the model.

- The ucp (old version) maintains the internal temperature inside the building constant, but does not take into account the energy consumption needed to keep it constant. Therefore, this model cannot reproduce the complete impact generated by anthropogenic heating. The fluxes computed by ucp, then, do not result from a complete representation of the physics of the system.
- The ucp–bem without air conditioning does not control the temperature inside the building. The variation of the internal temperature modeled by ucp–bem is much higher than the measured variation (close to 1°C around 24°C). So, even if the RMSE of the sensible heat flux at 18 m is comparable to those computed by ucp–bemac and ucp–bemac*, the sensible heat fluxes computed by ucp–bem are not a complete representation of the physics of the system.
- It is interesting to observe (Fig. 3) that, at 18 m during night-time, ucp has the lowest sensible heat flux, close to zero, while ucp–bem, ucp–bemac, and ucp–bemac* all have a clear positive sensible heat flux, in agreement with the measurements. The nocturnal positive sensible heat flux is a crucial feature to model the nocturnal Urban Heat Island.

In conclusion, it is possible to say that the fact of considering the generation of heat within the buildings, and in particular the effect of the air conditioning, improves the estimation of the sensible heat fluxes in the city, not only because the statistical parameters are better than those of the old ucp but also because the physics of the system is better represented. This is a very important point since it increases the confidence in the predictive capability of the model.

4.2 Net radiation

The differences between the four simulations for the net radiation (Fig. 5 and Table 6) are small when the complete days are considered. However, for the first period, it is interesting to observe that during night-time the best results are obtained with the ucp–bem schemes, and the simulation that matches the measurements most closely is the ucp–bemac*. During daytime, the best fit is obtained in the ucp case in the two periods followed closely by the ucp–bemac schemes.

The underestimation of the net radiation during daytime for the two periods (Fig. 5) could be a consequence of overestimating the upward long-wave radiation in the four schemes which, in turn, might be caused by an overestimation of the roof surface temperature. The roof surface

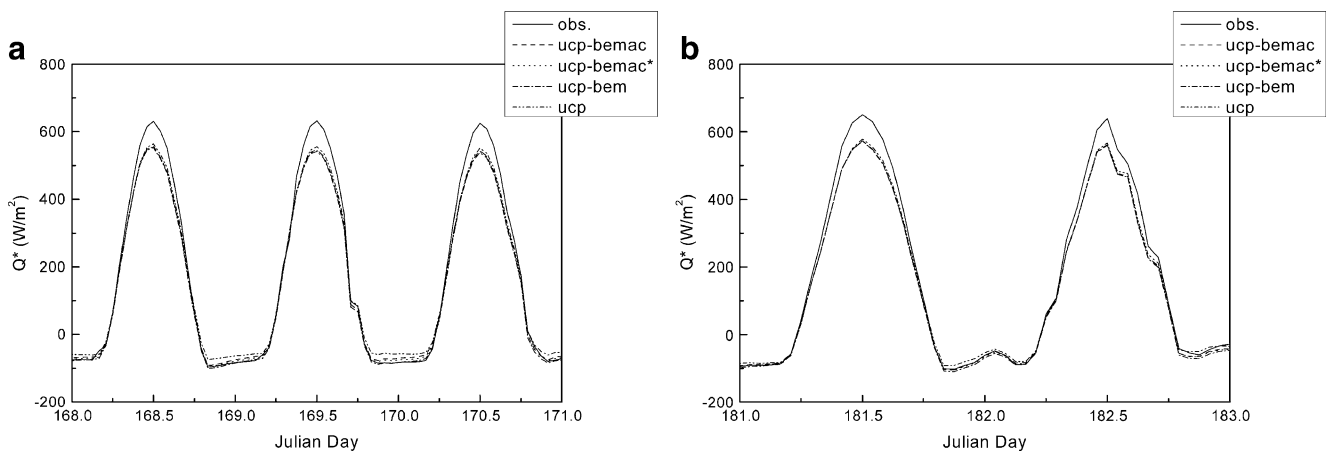


Fig. 5 Net radiation for the four different schemes against measurements: **a** 3 days are shown for the first period, and **b** two selected days are shown for the second period

temperature is very sensitive to the roof's roughness length, a parameter for which there is little information.

4.3 Latent heat

The RMSE (Table 6) for the latent heat shows that in the two periods there are no significant differences between the four schemes when complete days are considered. It was not necessary to evaluate the daytime and night-time RMSE parameters because the plots (not shown) do not reveal significant differences.

5 Waste heat emission and energy consumption

In this last section, the waste heat emission of the air conditioning systems and the energy consumption are evaluated. The sensible heat ΔH_s (W) (in the Q_H term)

Table 6 Performance statistics (RMSE) for different heat fluxes (W/m^2) at 32 m of height for the four cases simulated at the Basel-Sperrstrasse site

Case	ucp-bemac	ucp-bemac*	ucp-bem	ucp
Days 165–174 (first period)				
Q_{net}	36.95	37.79	39.94	34.42
Q_{net} (night-time)	7.02	5.09	6.62	15.89
Q_{net} (daytime)	49.51	50.85	53.63	44.21
Q_{LE}	25.29	25.26	25.46	25.35
Days 181–195 (second period)				
Q_{net}	36.00	36.26	37.47	33.32
Q_{net} (night-time)	12.22	12.73	14.92	10.71
Q_{net} (daytime)	47.61	47.85	49.03	44.19
Q_{LE}	23.67	23.61	23.82	23.82

ejected into the atmosphere by an air conditioning system is calculated as (more details about the symbols in Appendix):

$$\Delta H_s = \frac{COP + 1}{COP} (H_{sout} + H_{lout}). \quad (7)$$

If we sum the heat fluxes of all the buildings in the grid cell and divide by the corresponding area, we obtain the heat flux ejected into the atmosphere per unit of land area. Ten simulations are presented in this section, which were carried out considering only the cases with air conditioning systems:

- To evaluate the sensitivity of the model to the target temperature imposed inside the buildings, we carried out two simulations with the target temperature decreased by 1°C (bemac -1in and bemac* -1in cases), and two with the target temperature increased by 1°C (bemac +1in and bemac* +1in).
- To study the impact of the air conditioning system on the outdoor temperature, and consequently the corresponding increase in energy consumption, two simulations were carried out increasing the outdoor temperature by 1°C (bemac +1out and bemac* +1out cases) at the forcing height.
- Finally, two more simulations (bemac-insulating and bemac*-insulating) were considered by increasing the thickness of the insulating material (thermal conductivity $\lambda = 0.09$ W/m K) at the roof of the buildings from 2 to 6 cm.

All these simulations were performed for the two entire periods (from 165 to 174 Julian days for the first period and from 181 to 195 Julian days for the second period). In Figs. 6 and 7, one can see the heat ejected into the atmosphere (only the results for the three above selected days are plotted for the first period and the two selected days for the second). The time average $\langle \Delta H_s \rangle$ during 10 days (first period) and during 15 days (second period) (10-min time resolution) gives, in the bemac cases (see Tables 7 and 8), heat fluxes near to 100 (W/m^2) and to 50

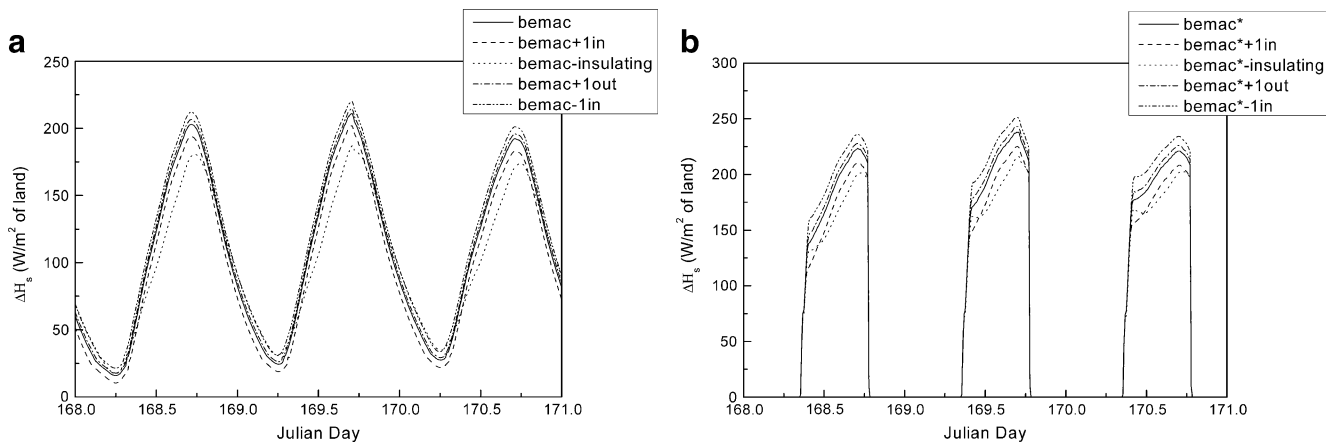


Fig. 6 Sensible heat ejected into the atmosphere by the air conditioning systems corresponding to the first period (only 3 days are shown): **a** bamac cases and **b** bamac* cases

(W/m²) of land, respectively. On the other hand, we obtained close to 160 (W/m²) for the first period and to 90 (W/m²) of land for the second in the bamac* schemes (for the bamac* cases, the average was computed considering only the working time by day). Observe that the waste heat released into the atmosphere when the target temperature is lowered by 1°C is higher compared to when the outdoor temperature is increased by 1°C (similar differences are observed in the two periods). On the other hand, the heat ejected into the air is decreased considerably when the thickness of the insulating material is increased, and an energy saving of 7–11% was observed.

The cooling energy consumption E_C (W) for an air conditioning system and the total consumption ΔE_C (J) for a period of time can be calculated as:

$$E_C = \frac{1}{COP} (H_{sout} + H_{lout}), \quad (8)$$

and

$$\Delta E_C = \int_{\substack{\text{Period} \\ \text{of} \\ \text{simulation}}} E_C dt. \quad (9)$$

It is also interesting to estimate the total consumption between the different simulations. One can see in Tables 7 and 8 the results for the total consumption by square kilometer of city and by day (here 1 kWh=3.6×10⁶J). The saving in energy consumption due to an increased thickness of the insulation material approaches 7–11% for both periods. In contrast, when the target temperature was decreased by 1°C, we observed an increase (negative values in Tables 7 and 8 indicate an increase in energy consumption) in the consumption of nearly 9% for the first period and 14% for the second. Eventually, the consumption increased by 3% in

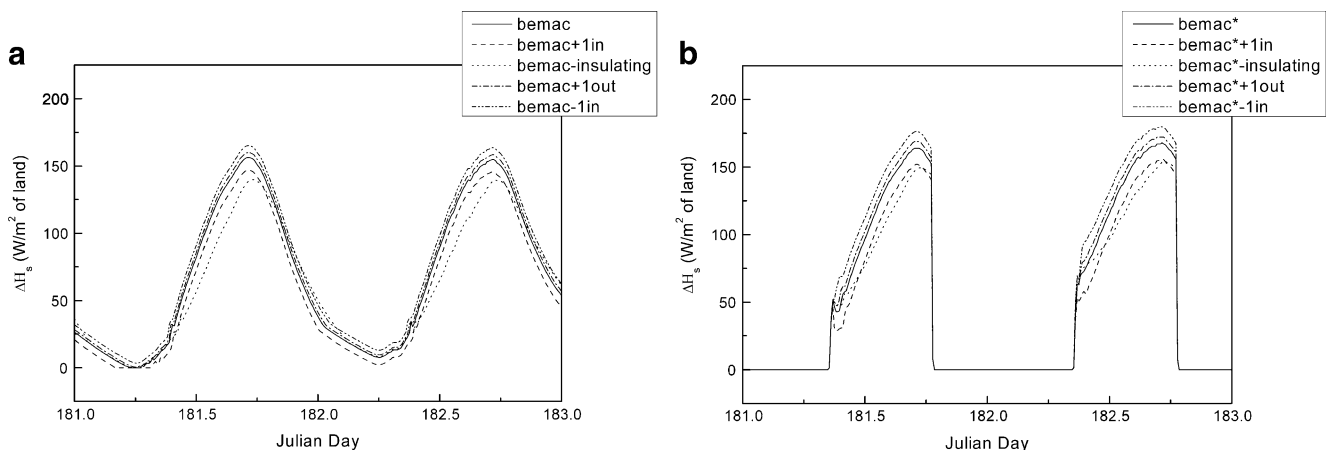


Fig. 7 Sensible heat ejected into the atmosphere by the air conditioning systems corresponding to the second period (only 2 days are shown): **a** bamac cases and **b** bamac* cases

Table 7 Results of the energy consumption and the heat ejected into the atmosphere corresponding to the ten cases simulated at the Basel-Sperstrasse site (first period)

Case	bemac +lin	bemac +Iout	bemac- insulating	bemac -lin	bemac* +lin	bemac* +Iout	bemac*- insulating	bemac* +Iout	bemac* -lin
Days 165–174									
$\langle \Delta H_s \rangle$ (W/m ²) of – land	92.63	84.20	86.40	101.17	161.00	147.00	144.19	165.00	173.94
ΔE_C (10 ⁵ kWh/km ² day) of – land	4.95	4.51	4.61	5.40	3.69	3.38	3.31	3.80	3.99
Saving energetic (%)	–	8.87	6.91	–9.12	–	8.45	10.19	–3.08	–8.34
$\langle \Delta H_s \rangle$ (W/m ²) of – land									
ΔE_C (10 ⁵ kWh/km ² day) of – land									
Saving energetic (%)									

Table 8 Results of the energy consumption and the heat ejected into the atmosphere corresponding to the ten cases simulated at the Basel-Sperstrasse site (second period)

Case	bemac +lin	bemac +Iout	bemac- insulating	bemac -lin	bemac* +lin	bemac* +Iout	bemac*- insulating	bemac* +Iout	bemac* -lin
Days 181–195									
$\langle \Delta H_s \rangle$ (W/m ²) of – land	50.18	42.92	46.16	57.79	89.60	76.20	79.97	94.80	103.15
ΔE_C (10 ⁵ kWh/km ² day) of – land	2.81	2.47	2.51	3.17	2.06	1.76	1.84	2.18	2.37
Saving energetic (%)	–	11.88	10.64	–13.03	–	14.76	10.76	–5.70	–15.00
$\langle \Delta H_s \rangle$ (W/m ²) of – land									
ΔE_C (10 ⁵ kWh/km ² day) of – land									
Saving energetic (%)									

the first period, and by almost 5% in the second, when the outdoor temperature was increased by 1°C.

6 Conclusions

In this work, an urban canopy parameterization (ucp–bem(ac)) coupled with a building energy model has been compared with its counterpart without the building energy model (ucp) and evaluated against measurements obtained in the BUBBLE campaign. This work shows that the new scheme ucp–bem(ac) is able to reproduce satisfactorily the urban fluxes, and that it reproduces the physics of the system better than ucp. Since phenomena like the Urban Heat Island, and in general the structure of the Urban Boundary Layer, are dependent on the urban fluxes, it is expected that the inclusion of this scheme in a mesoscale model will improve the capability of that model to reproduce these phenomena.

Moreover, and most important, the scheme is able to compute the heat ejected into the atmosphere by the air conditioning systems and in general the energy consumption linked to meteorological variables. Although further tests in 2D and 3D are needed, it is possible to say that the impact of the air conditioning systems is not negligible and should be taken into account in the mesoscale models to determine the outdoor temperature in big cities in summer conditions. The heat flux due to air conditioning, in fact, can be between 50 and 160 W/m² in average (with peaks of up to 250 W/m² in the hottest hours of the day) depending on meteorological conditions and time of use of the system.

Furthermore, the scheme has been used to test the sensitivity of the energy consumption to different parameters. An increase in the thickness of the insulation materials could reduce the consumption by about 10%. On the other hand, the reduction in the target temperature by 1°C increases the consumption by nearly 10–15%. Finally, an increase in outdoor temperature by 1°C increases the consumption by 3% to 5%. This relationship between air temperature and energy consumption (similar to what was found by Kikegawa et al. 2003, by analyzing the correlation between data on energy consumption and measured air temperature for Tokyo) highlights the importance of using a coupled system. In fact, the feedbacks between the following three points must be considered:

- the air temperature in a city depends on the sensible heat fluxes released into the atmosphere,
- part of the sensible heat fluxes depend on the energy consumption,
- energy consumption depends on the air temperature.

Due to these feedbacks, the estimation of the impact of a change on the target temperature, or the insulation,

mentioned above, may also be underestimated. The inclusion of ucp–bem(ac) in a mesoscale model will allow to account for all these feedbacks.

It is also interesting to mention that a variation in sensible heat fluxes of the order of those estimated in this work due to the air conditioning (50–160 W/m²) may have a significant impact on the pollutant dispersion and also on cloud formation. Potentially a further feedback can exist, since short- and long-wave radiations are affected by aerosols and clouds. Again, having the scheme implemented in a mesoscale model will allow us to account for this impact.

Although these last considerations are not conclusive (more realistic simulations are needed), we can say that the new scheme is able to estimate the urban fluxes, it is a good tool to test new energy consumption reduction strategies, and it can help to better understand the Urban Heat Island phenomenon in big cities.

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Appendix

List of symbols

C_p (Jkg ⁻¹ K ⁻¹)	specific heat of the air at constant pressure
COP	energy efficiency (coefficient of performance)
H_{sout} (W)	sensible heat pumped out for cooling per building
H_{lout} (W)	latent heat pumped out per building
L_v (Jkg ⁻¹)	latent heat of vaporization
q (kgkg ⁻¹)	specific humidity
w (ms ⁻¹)	vertical component of the wind speed
θ (K)	potential temperature
ρ (kgm ⁻³)	density of the air

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