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# A new urban soil model for SOLENE-microclimat: review, sensitivity analysis and validation on a car park.

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## Abstract

The main purpose of this study is to evaluate an urban soil model that will accurately reproduce the heat flux into urban soil, which has an influence on the urban heat island effect, for typical urban land use such as a car park. After a complete literature review, a sensitivity study is carried out on a large number of parameters: material properties, layer size, deep boundary condition, and convective heat transfer coefficient. The model's ability to reproduce heat conduction transfer is validated via a measurement campaign performed on an asphalt car park during hot days. The mean daily RMSE between estimated and observed surface temperature is 0.86°C, and 0.72°C, 0.58°C, 0.26°C and 0.13°C respectively at 5cm-, 10cm-, 34cm- and 50cm-depths. Performances obtained using different node distributions are

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discussed and compared with results from the literature. The model is more efficient than most of the other models applied under similar conditions. Finally, application of the proposed model on a yearly basis demonstrates that the accuracy loss caused by the decrease in the number of nodes is higher for clear and sunny days.

*Keywords:* Urban soil model, Heat transfer, Soil surface temperature, SOLENE-Microclimat, Urban Heat Island.

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### **Highlights**

- We propose a soil model dedicated to the assessment of climate adaptation strategies.
- Computed surface temperature and temperature at several depths are validated against measurements
- An overall sensitivity analysis of the model parameters is performed
- Different convection flow modes –forced, mixed and natural- are investigated
- The model’s performance with optimized mesh is compared with that of the literature

## 1. Introduction

In conditions of global warming, the development of cities must be carried out considering the urban heat island (UHI) phenomenon [1] as a serious environmental issue. This phenomenon has several consequences on outside comfort and on building energy needs. In order to mitigate the UHI, it is necessary to identify its causes and to quantify the impact of mitigation solutions. Measurements campaigns are useful to evaluate the UHI, but linking it to the influence of modifications in urban form or urban planning choices is quite tricky.

For this purpose, numerical simulation is a powerful tool. Several models under development simulate the UHI phenomenon and its consequences. Different scales are considered, depending on the application intended: for example TEB [2] or ARPS-VUC [3] are more suitable for city-scale applications while models like SOLENE-microclimat [4], Envi-met [5] and EnviBatE [6] are more appropriate for the district scale.

For a given scale, each tool may have one specific feature among many others: EnviBatE [6] is designed to study the energy demand of a group of buildings, SOLENE-microclimat [4] focuses on outdoor comfort and on the impact of urban climate on indoor comfort, and ENVI-met [5] is dedicated to outdoor comfort.

All those models have in common the fact that they represent several physical mechanisms: radiative fluxes, thermal fluxes and fluid dynamics. Furthermore, the representation of these phenomena is essential to accurately calculate the soil surface temperature, which is the key to the interaction between the soil and the urban environment (radiative and sensible fluxes).

26 The heat flux stored and released by urban material respectively during day-  
27 and night-time is one of the main causes of UHI development. This heat flux  
28 is greater in urban than in rural areas due to the high inertia of the materials  
29 used. The simulation of heat transfer in facades and in the soil are therefore  
30 of the highest importance.

31 Consequently, there is a need to enhance the ability of urban soil mod-  
32 els to simulate heat fluxes in complex heterogeneous urban contexts. The  
33 SOLENE-microclimat model (whose efficiency has already been proven) is  
34 being developed and validated to answer this need. It is a complex model  
35 made up of several modules [7], implying that validation should be performed  
36 on each module individually. This article presents one of these validation  
37 steps.

38 The main purpose of this article is to modify and validate the existing  
39 SOLENE-microclimat soil model. The modifications are based on a review  
40 of the literature and on a sensitivity analysis. Validation is performed using  
41 temperature and flux measurement carried out on an open car park.

42 The open space is chosen to get away from the constraints of an urban  
43 environment: diffuse and reflected solar radiation depending on masks, the  
44 albedo of the surrounding surfaces, long-wave radiation exchanges with sur-  
45 rounding surfaces, etc.

46 As the accuracy of the model is often linked to its numerical cost, the  
47 additional aim of this study is to develop optimized discretization in order  
48 to reach a compromise between accuracy loss and computational efficiency.

49 The results of the study are divided into three parts:

- 50 • sensitivity study on model parameters,

- 51     • model validation using a centimetric grid in order to evaluate the
- 52         model's ability to reproduce conductive heat transfer into the soil,
- 53     • calculation of the accuracy loss caused by different node distributions.

54 The model's performance is then compared to that of models identified in the  
55 literature. Finally, performance is analysed for a whole year of simulation.

56 This exhaustive study provides accurate information about the reliability  
57 of the SOLENE-microclimat soil model.

## 58 **2. State of the art**

### 59 *2.1. Existing models*

60 In the literature on microclimate models, soil representation is rarely fully  
61 described. However, soil models are also used in other fields such as:

- 62     • Geothermal energy applications,
- 63     • Road applications: pavement sustainability or frost forecasts,
- 64     • Hydrology and interaction between soil, vegetation, and atmosphere.

65 Those other domains have the advantage of proposing a different point of view  
66 on the way to model heat transfer in the ground. In Table 1 the articles used  
67 for the following literature review are shown together with the characteristics  
68 of the soil models.

Article	Type of application				Surface		Type of coating			Soil column	
	B, GE	Roads	SVA	UM	Previous	Imprevious	Pavement	Bare-soil	Vegetation	Homogeneous	Heterogeneous
Asaeda and Ca (1993,[8])				x	x		x	x			x
Best (1998, [9])		x			x		x	x	x	x	
Best and al. (2005, [10])		x			x			x		x	
Bouyer (2009, [4])				x	x		x	x	x		x
Chow and al. (2011, [11])	x				x				x	irrelevant	
Diefenderfer and al. (2006, [12])		x				x	x			irrelevant	
Gros et al. (2015, [6])				x		x	x				x
Herb et al. (2008, [13])			x		x		x	x	x		x
Hermansson (2004, [14])		x				x	x				x
Ho (1987, [15])			x			x	x	x		x	
Jacovides (1996, [16])	x				x			x	x	x	
Lin (1980, [17])			x		x			x		x	
Masson (2000, [2])				x		x	x				x
Milhalakakou and al. (1997, [18])	x				x			x	x	x	
Milhalakakou and al. (2002, [19])	x				x			x	x	x	
Nowamooz and al. (2015, [20])	x				x				x		x
Ozgener and al. (2013, [21])	x				x			x		x	
Qin and al. (2002, [22])			x		x			x			x
Saito and Simunek (2009, [23])			x		x			x			x
Swaid and Hoffman (1989, [24])			x			x	x				x
Yang and al. (2013, [5])				x	x		x	x	x		x

Table 1: Model application and type of soil

B, GE: Buildings, geothermal energy SVA: Interaction soil, vegetation, atmosphere UM: Urban Microclimate

69 Even though the field of application is different, all the articles presented  
70 have the common objective of predicting surface temperature or ground heat  
71 flux. Depending on the application, the physical mechanisms modelled are  
72 not the same. In addition to conductive heat flux, moisture flow is often  
73 modelled. This is the case for several applications that use bare-soil and  
74 vegetation covers [22, 23, 13, 8]. This is useful to estimate the water avail-  
75 ability for vegetation or to adjust the thermal properties of the soil depending  
76 on humidity content. Nevertheless, for impervious surfaces, moisture flux is  
77 mostly neglected [13].

78 The soil model presented in this paper is designed for an impervious  
79 surface in an urban environment. Urban grounds are heterogeneous and  
80 made up of different layers characterized by large differences in their physical  
81 properties. The model must therefore be able to take several layers into  
82 account. In the literature, soil is modelled by either a homogeneous or a  
83 heterogeneous column. But for a given area, the size of each layer and its  
84 physical properties are not accurately known. By simplification, half of the  
85 soil models presented here consider a homogeneous column of soil (Table 1).  
86 Nevertheless, in order to accurately simulate the conduction flux all along the  
87 vertical axis, the soil profile should be consistent with reality, which implies  
88 considering a heterogeneous soil.

89 Thermal properties are either set to experimental data (i.e.: to better  
90 represent measurements the albedo is defined as the ratio between incident  
91 and reflected solar radiation), or calibrated.

92 However, the impact of thermal properties has rarely been investigated.



93 Best (1998, [9]) and Herb et al. (2008, [13]) studied the influence of mate-  
94 rial characteristics (diffusivity, specific heat, etc.) on surface temperature.  
95 According to Best (1998 [9]) and Herb et al. (2008 [13]), the emissivity and  
96 the thermal conductivity of the pavement have the most influence on sur-  
97 face temperature, while the characteristics of the soil underneath have little  
98 influence.

99 In the case of a homogeneous soil column, there are several possibilities  
100 for obtaining ground temperature variation. Among others, we may cite  
101 analytical solutions (Fourier analysis [10, 11, 15, 16, 18, 19, 21, 24]), the  
102 empirical method [11, 12, 19], or even the force-restore method [17].

103 For a heterogeneous soil column, only the numerical method can be used  
104 to accurately estimate surface temperature and ground temperature for sev-  
105 eral depths. Twelve of the models described use the finite difference method  
106 with an implicit scheme, [8, 9, 10, 4, 6, 13, 14, 15, 2, 22, 23, 5] except  
107 Nowamooz et al. (2015, [20]) who use an explicit scheme. The soil model  
108 presented in this paper is based on an implicit finite difference method. The  
109 following section presents in detail all possible parametrizations in the case  
110 of the finite difference method.

## 111 *2.2. Parametrization of finite difference models*

112 For a given problem-solving method, different choices can be made regard-  
113 ing the node distribution (discretization), boundaries and initial conditions  
114 (Table 2).

Article	Upper boundary		Convection coeff.		Lower boundary		Initial conditions
	Temperature	Flux	Forced	Natural	Temperature	Flux	
Asaeda and Ca (1993,[8])		x	x		2.5m		EV
Best (1998, [9])		x	x		1.15m		Exponential profile
Best and al. (2005, [10])		x	EV			x	EV
Bouyer (2009, [4])		x	x		2m		Constant value
Gros et al. (2015, [6])		x	CFD		0.5m		NI
Herb et al. (2008, [13])		x	x	x		10m	NI
Hermansson (2004, [14])		x	x	x	5m		NI
Ho (1987, [15])		x		x	x		Linear or exponential profile
Masson (2000, [2])		x	x			x	NI
Nowamooz and al. (2015, [20])	x		irrelevant		4m		EV
Qin and al. (2002, [22])		x	x		x		EV
Saito and Simunek (2009, [23])		x	x		x		EV
Yang and al. (2013, [5])		x	CFD		2m		EV

Table 2: Parametrization of finite difference models

EV: Experimental values NI: No Information CFD: Computational Fluid Dynamics

## Vertical discretization

Depending on the author, different vertical discretizations are used. Ho (1987, [15]) and Qin et al. (2002, [22]) propose uniform layout nodes, whereas most of the articles present a denser node distribution near the surface than deeper in the ground. Saito and Simunek (2009, [23]) use a denser distribution near the surface and also near the interface between two layers. However, the choice of node distribution is rarely clearly justified. Only Best et al. (2005 [10]) studied the behaviour and accuracy of the model for different vertical discretizations, comparing the numerical solution with the analytical one. The present study also aims to perform a sensitivity analysis on the discretization in order to know how much accuracy is lost when reducing the number of nodes. Few sensitivity studies have been performed on this point. Asaeda and Ca (1993,[8]) studied the influence of grid size. As expected, the thinner the resolution of the grid, the more precise the surface temperature. But this accuracy gain is obtained to the detriment of calculation duration. So as Best et al. (2005 [10]) suggested, a compromise should be found between accuracy and execution time.

## Boundary conditions

To solve one dimension heat conduction equation with the finite difference method, two boundary conditions are required. The bottom condition taken at a defined depth can either be a zero flux or a constant temperature (Table 2). If the simulation concerns a short period and the last node of the grid is below the diurnal amortization depth, the type of condition has little

140 influence on the surface temperature [9].

141 As the purpose of most articles is to predict surface temperature, the  
142 upper boundary condition is defined by the surface energy balance. This  
143 balance is composed of radiative fluxes, the sensible flux, the latent flux,  
144 and the conductive heat flux into the soil. The long and short-wave radia-  
145 tion fluxes are always calculated, except for the validation process for which  
146 measurements are used whenever they are available.

147 As urban soils have a low albedo, the temperature gradient between the  
148 surface and the air can be very great, especially during clear days. This  
149 phenomenon leads to natural convection (driven by buoyancy forces). Nev-  
150 ertheless, in the surface energy balance, most authors only take into account  
151 the forced convective mode (driven by wind forces), whereas Herb et al.  
152 (2008, [13]) proposes considering both forced and natural modes.

153 Both Hermansson (2004, [14]) and Herb et al. (2008, [13]) assumed that  
154 the method used to calculate the convective heat transfer coefficient is a crit-  
155 ical point. To test this assumption, they both carried out a sensitivity study  
156 on the coefficients of an empirical formula. Herb et al. (2008, [13]) show  
157 that the modification of convection parameters can sometimes have a signif-  
158 icant impact on surface temperature: for a 10% increase in the convection  
159 parameters, the average surface temperature variation is about  $0.24^{\circ}\text{C}$ . This  
160 might be explained by low wind speed and by a high-temperature gradient  
161 between the surface and the air. Hermansson (2004, [14]) dissociates winter  
162 and summer periods since the temperature gradient between the surface and  
163 the air is smaller during winter. He proposes to use two sets of parameters

164 regarding solar radiation conditions. Depending on the season, convection  
165 losses and wind velocity are balanced by coefficients.

## 166 **Initial conditions**

167

168 In general, little information is given on the initial conditions (tempera-  
169 ture profile) except for the validation process. Most authors use experimental  
170 values (Table 2). When this information is not available, several alternatives  
171 are proposed: a constant temperature profile [4, 15] or an exponential profile  
172 between the deep soil and the surface is set [9, 15]. However, according to  
173 (1987, [15]), this parameter has little impact on surface temperature

## 174 **3. Methodology of the study**

### 175 *3.1. Description of the proposed soil model*

176 The soil model presented in this paper is designed for an impervious  
177 surface such as a pavement coating. Only heat transfer is therefore taken  
178 into account (moisture transfer is neglected). The soil model is 1-D, defined  
179 as a one-dimensional soil column where each layer has its own characteristics.  
180 In an unsteady state, temperature fluctuation is calculated from Equation 1,  
181 which is an application of the heat equation for a one-dimensional problem.

$$\frac{\partial T}{\partial t} = \alpha_{soil} \cdot \frac{\partial^2 T}{\partial x^2} \quad (1)$$

182  $\alpha_{soil}$  : thermal diffusivity of the soil [ $m^2 s^{-1}$ ]

183 The problem is solved by a finite difference method using an electrical  
 184 analogy. Heat resistances represent the resistance to heat transfer through a  
 185 ground layer and heat capacities, the heat storage capacity of a ground layer.  
 186 They are defined in Figure 1.

187 The soil model is composed of  $n$  nodes. The energy balance equation is  
 188 calculated at the surface (node  $i = 0$ , Equation 2), and then for each following  
 189 node  $i \in ]0 : n - 1]$  (Equation 3) until the last one which includes the bottom  
 190 boundary condition ( $i = n$ , Equation 4).

$$\frac{T_{surface} - T_{air}}{R_c} + \frac{T_{surface} - T_1}{R_1} + C_e \frac{dT_{surface}}{dt} = R_{net} - LE \quad (2)$$

$$\frac{T_i - T_{i-1}}{R_i} + \frac{T_i - T_{i+1}}{R_{i+1}} + C_i \frac{dT_i}{dt} = 0 \quad (3)$$

$$\frac{T_n - T_{n-1}}{R_{n-1}} + \frac{T_n - T_\infty}{R_n} + C_i \frac{dT_n}{dt} = 0 \quad (4)$$

193  $R_{net}$ : net radiation [ $W.m^{-2}$ ]

194  $LE$ : latent heat flux [ $W.m^{-2}$ ]

195  $H$ : sensible heat flux [ $W.m^{-2}$ ]

196  $C_e$ : heat capacity of the surface layer [ $J.m^{-2}.K^{-1}$ ]

197  $C_i$ : capacity of the layer at the node  $i$  [ $J.m^{-2}.K^{-1}$ ]

198  $R_c$ : convection resistance [ $m^2.K.W^{-1}$ ]

199  $R_i$ : heat resistance of the layer between the node  $i - 1$  and  $i$  [ $m^2.K.W^{-1}$ ]

200  $T_{surface}$ : surface temperature [ $K$ ]

201  $T_{air}$ : air temperature [ $K$ ]

202  $T_i$ : temperature of the node  $i$  [ $K$ ]

203

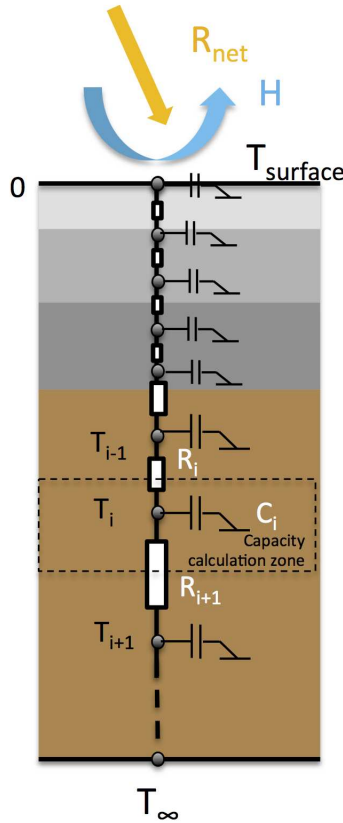


Figure 1: Schematic representation of the soil model: representation of node distribution, heat resistances and capacities, description of a common cross-section of an urban soil column with diffusive material layers in shade of grey and underneath natural soil in brown (*1 column, print in color*)

204 According to this method, any node distribution and any boundary con-  
 205 dition depth may be used. Most of the authors [8, 9, 10, 5] in the literature  
 206 work with a centimetric grid when accuracy is required. A model with one  
 207 node per centimetre is used (see Section 3.1.3).

208 The top node is located at the ground surface and the deepest one at a  
 209 depth of 1m. At this depth, the temperature is supposed to be constant over

210 a day. A new value will be set for each day. More details are given in Section  
211 3.1.1.

212 Figure 1 illustrates the way thermal properties are defined. Each layer  
213 of material is assumed to be homogeneous and isotropic and has its own  
214 characteristics which are considered to be constant over time.

215 As the node distribution is defined aside from the soil layers and char-  
216 acteristics, the nodes are not automatically located at the interface between  
217 two layers.

### 218 3.1.1. *Deep boundary condition*

219 In deep soil, the temperature is taken to be constant over a day. In the  
220 case of homogeneous soil, an analytic solution can be used to calculate the  
221 temperature for any depth  $z$  and any time step  $t$ . If the surface temperature  
222 is considered to be sinusoidal, the analytic solution follows Equation 5. The  
223 parameters  $T_{ma}$ ,  $A_a$  and  $t_0$  are respectively the mean, the amplitude, and the  
224 phase of a day surface temperature signal.

$$T(z, t) = T_{ma} + A_a \cdot \exp\left(-\frac{z}{zd_a}\right) \sin\left(w_a(t - t_0) - \frac{z}{zd_a}\right) \quad (5)$$

225  $T_{ma}$ : mean annual temperature [ $^{\circ}\text{C}$ ]

226  $A_a$ : annual half amplitude of the climatic thermal wave at the surface [ $^{\circ}\text{C}$ ]

227  $zd_a$ : damping depth with an annual beat [ $m$ ]

228  $w_a$ : annual beat  $w_a = 2 * \pi / 31536000$  [ $rad.s^{-1}$ ]

229  $t_0$ : day of the year where the surface temperature was the coldest

230



231 From a certain depth, the daily signal is completely damped. The damp-  
 232 ing depth depends on the soil characteristics through the parameter  $z_{da}$ ,  
 233 defined by Equation 6. The depth from where the signal is damped at 95 or  
 234 99 % can be estimated from Equation 7.

$$z_{da} = \sqrt{\frac{2 \cdot \alpha_{sol}}{w_a}} \quad (6)$$

235

$$A(z) = A_j \cdot \exp\left(\frac{-z}{z_{da}}\right) \quad (7)$$

236  $A_j$ : half daily amplitude of the climatic thermal wave at the surface [ $^{\circ}\text{C}$ ]

237

238 For a range of materials (asphalt, concrete, bare-soil), the most diffusive  
 239 is marble. For this material, the depth corresponding to a daily damping of  
 240 99% is 0.89cm. Beyond a meter in depth, the temperature is assumed to be  
 241 constant throughout the day whatever the type of ground. For this reason,  
 242 the bottom node is located below this depth.

### 243 3.1.2. Upper boundary: Heat flux across a ground surface

244 The upper boundary condition is defined by the energy balance at the  
 245 ground surface (Equation 8).

$$R_{net} = Q_{cond} + H + LE \quad (8)$$

246 with  $R_{net}$ ,  $Q_{cond}$ ,  $H$ ,  $LE$  previously defined.

## 247 Radiative flux

248 The net radiative flux is the balance of all radiative fluxes at the soil  
249 surface. It is the sum of short-wave radiation and long-wave radiation. The  
250 historical SOLENE radiative model computes radiative transfers, including  
251 long-wave radiation, inter-reflexion and shading effects [7]. So this input data  
252 does not need to be calculated in future simulations.

### 253 **Convective heat flux**

254 The heat flux exchanged between the surface and a moving fluid can be  
255 expressed with the Equation 9:

$$H = h_c(T_{air} - T_{surface}) \quad (9)$$

256  $h_c$ : convective heat transfer coefficient [ $W.m^{-2}.K^{-1}$ ]

257  $T_{air}$ : air temperature [ $K$ ]

258  $T_{surface}$ : surface temperature [ $K$ ]

259

260 In order to calculate this flux, the convective heat transfer coefficient is  
261 required. In the literature, this coefficient is always a function of wind speed.  
262 Linear or power law functions are used, or correlations using dimensionless  
263 numbers ([25], [26]). For urban applications, the first solution is often used.

264 The simplest is a linear relation of the wind speed (Equation 9). Depend-  
265 ing on the situation (i.e. surface texture, wind velocity, windward/leeward  
266 surface, etc.), Palyvos (2008, [25]) suggests around forty combinations for  $a$   
267 and  $b$  coefficients. For a horizontal surface, with low winds ( $V_{air} < 5m/s$ ),  
268 several coefficients are proposed (Table 3).

$$h_c = a + b * V_{air} \quad (10)$$

269  $V_{air}$ : wind speed [ $m.s^{-1}$ ]

270

Reference	a	b
McAdams (1954, [27])	5.7	3.8
ASHRAE (1993)	5.62	3.9
Cristofari et al. (2006)	5.67	3.86

Table 3: Coefficients  $a$  and  $b$  for a flat surface low wind speed

271 Methods based on correlations that use dimensionless numbers (Reynolds,  
 272 Grashof, and Nusselt) also exist. For flat surfaces Morille (2012, [28]) presents  
 273 coefficients depending on the flow regime (Table 4).

Convection mode	Flow regime	$a$	$b$	$c$	$d$	$e$	$f$
Free	laminar	0	0	0.49	1/4	1	1
	turbulent	0	0	0.13	1/3	1	1
Mixed	laminar	1	3/2	0,57	3/5	0,68	1/3
	turbulent	1	12/5	12,1	1	0,03	1/3
Forced	laminar	0,56	1/2	0	0	1	1
	turbulent	0,03	4/5	0	0	1	1

Table 4: Coefficients as a function of the convection mode for a flat surface

$$Nu = e(aRe^b + cGr^d)^f \quad (11)$$

274

$$Nu = \frac{h_c \cdot L_c}{\lambda_{fluid}} \quad (12)$$

275 *Re*: Reynolds number

276 *Gr*: Grashof number

277 *Nu*: Nusselt number

278  $L_c$  : characteristic length [*m*]

279  $\lambda_{fluid}$ : thermal conductivity of the fluid [*W.m<sup>-1</sup>.K*]

280

281 This type of correlation can be used to define a convective heat transfer  
282 coefficient as a function of the flow modes:

- 283 • Natural or free convection: air flow driven by buoyancy forces,
- 284 • Forced convection: air flow driven by wind forces,
- 285 • Mixed convection: when the air flow is created by both wind and buoy-  
286 ancy forces.

287 In the case of urban applications, wind speed is often low and the tem-  
288 perature gradient great. Free convection may then become predominant.  
289 A comparison between the MacAdams formula and the correlation method  
290 is made in order to choose the most suitable method for an urban climate  
291 application (Section 4.1.1).

### 292 3.1.3. Node distribution

293 Authors in the literature work with centimetric grid when accuracy is  
294 required ([8, 9, 10, 5]). In order to gauge the accuracy of the proposed grid

295 different grid sizes are compared to the analytic solution (Equation 5) for a  
296 homogeneous soil of asphalt-concrete ( $\alpha = 1.04 * 10^{-6} m^2.s^{-1}$ ).

297 The analytic solution is compared to a finite difference model with a  
298 sinusoidal temperature signal imposed at the surface (Equation 13). The  
299 bottom boundary condition is taken as a fixed temperature equal to the  
300 mean annual temperature. The model is initialized with a temperature profile  
301 calculated by the analytic solution. The simulation is run for 6 days with a  
302 time step of 900 seconds.

$$T_s(t) = T_{ma} + A_a \cdot \sin(w_a(t - t_0)) \quad (13)$$

303 Different grid sizes are tested from 0.0025m to 0.025m with steps of  
304 0.0025m. For each grid size, the RMSE is calculated at the last time step,  
between the analytic solution and the finite difference model.

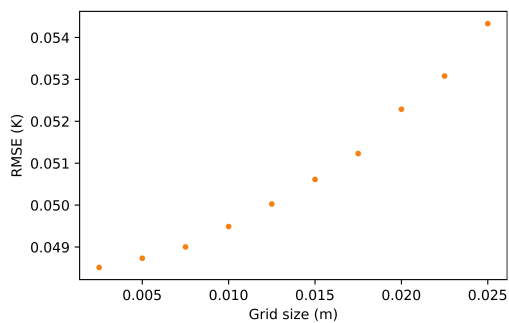


Figure 2: Changes in RMSE for different grid sizes(1 column, print in color)

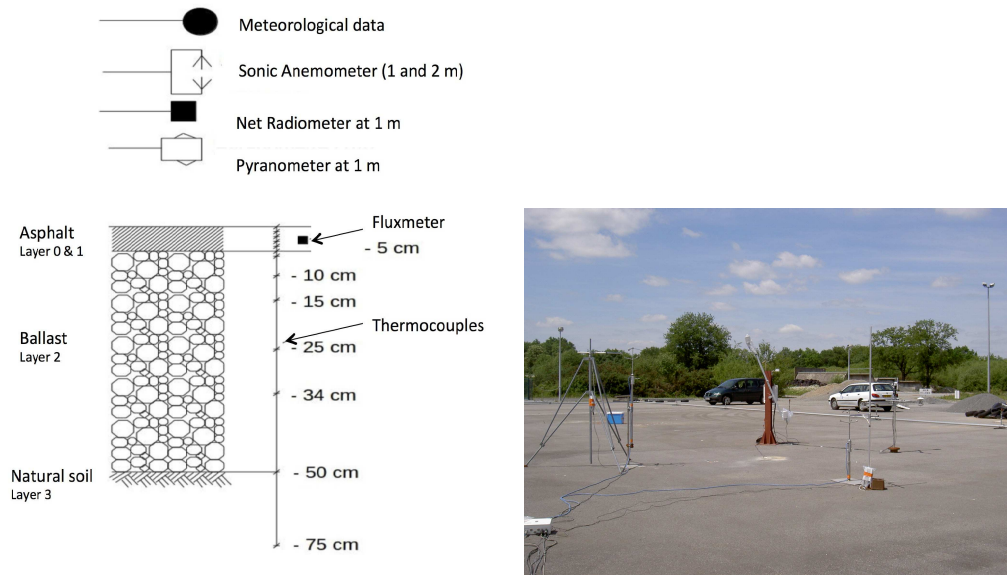
305

306 Figure 2 shows changes in the RMSE for different grid sizes(from 0.0025 to  
307 0.025m). As expected, the RMSE increases when the grid size increases. The

308 benefits of increasing the grid from  $0.005m$  to  $0.01m$  improved the RMSE by  
 309 only  $0.0009^{\circ}C$ . A model with one node per centimetre is used as a reference.

310 *3.2. Presentation of the measurement campaign*

311 The measurement campaign provided data that are used either as model  
 312 inputs or as validation data to evaluate the performance of the model and  
 313 its accuracy.



(a) Drawing of the instruments used during the campaign (see Table 5 for a description of the instruments) and cross-section of the soil composition (see Table 6 for the material properties) (b) View of the experimental site (a 2,500m<sup>2</sup> asphalt car park) with the instruments

Figure 3: Illustration of the ROSURE measurement campaign

314 Data from the ROSURE/HydroVille project are used [29]. This project  
315 was led by IFSTTAR and funded by the National Institute for Earth Sciences  
316 and Astronomy (INSU) of the *Centre National de la recherche scientifique*  
317 (CNRS). A campaign devoted to the documentation of energy and water  
318 budgets of an asphalt car park was carried out in the month of June 2004.  
319 This campaign especially focused on surface and air temperatures and on  
320 heat flux measurements during a warm summer period. Artificial rain events  
321 were created during the campaign but the present study focuses only on dry  
322 weather periods.

323 The experiment site is located near Nantes (France) within the IFSTTAR  
324 center of Bouguenais, and consisted of a  $2,500m^2$  asphalt car park (Figure  
325 3(b)). The soil structure is composed of a 5cm- asphalt layer, a 45cm- ballast  
326 layer and an altered mica-schist natural soil underneath. Throughout the  
327 observations available for this campaign, this study focuses on the following  
328 variables, all observed in the middle of the car park described in the Table 5  
329 and in Figure 3(a):

- 330 ● surface and ground temperatures: vertical profile at depths of 0, 1, 10,  
331 3, 4, 5, 6, 10, 15, 104, 34, 50 and 75 cm;
- 332 ● wind speed and direction;
- 333 ● humidity and air temperature;
- 334 ● convective heat fluxes;
- 335 ● radiation components.

Physical quantity	Instrument type	Height (m)	Measured variable
Temperature profile	thermocouples type T (diameter $120\mu m$ )	0 to -0.75	$T(z)$
Wind speed and direction	Young Campbell (05103) monitor	1.5	$v$
Humidity and air temperature	HMP45C TRH probes (Campbell) with Vaisala HR HUMICAP	1 and 2	$T, H_R$
Soil heat flux	Fluxmeter HFP01 Huskflux	-0.03	$G$
Short wave radiation	2 pyranometers CM6B (Kipp & Zonen)	1	$R_s \downarrow, R_s \uparrow$
Long wave radiation	2 pyranometers CGR3 (Kipp & Zonen)	1	$R_{IR} \downarrow$ $, R_{IR} \uparrow$
Net radiation	Radiometer NRLite (Kipp & Zonen)	1	$R_n$
Convective heat flux	Sonic Anemometer USA1 (Metek)	1 and 2	H

Table 5: Captor used and the corresponding measures



336 The data were collected with a 1 min time step except for the sonic  
 337 anemometer (0.1 s). The final data were averaged to 15 min time steps. From  
 338 the whole measurement period, only days without artificial precipitation were  
 339 used. Four days were selected with different meteorological conditions: three  
 340 sunny days with scattered clouds (June 5<sup>th</sup>, 12<sup>th</sup>, 13<sup>th</sup>) and one clear sky day  
 341 (6<sup>th</sup> of June). The clear sky day was used to calibrate the model (6<sup>th</sup> of June)  
 342 while the other days were used to evaluate the model (June 5<sup>th</sup>, 12<sup>th</sup>, 13<sup>th</sup>).  
 343 The meteorological conditions are presented in Figure 4 and Figure 5 .

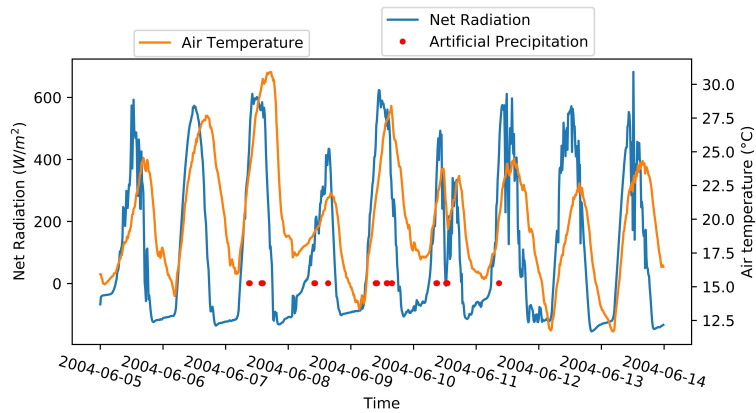


Figure 4: Net Radiation measured at a height of 1m and Air Temperature measured at a height of 2m from June 5<sup>th</sup> to 14<sup>th</sup> (2 columns, print in color)

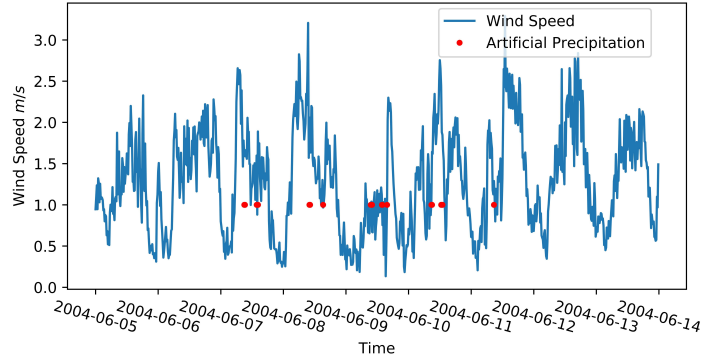


Figure 5: Wind speed measured at a height of 1.5m from June 5<sup>th</sup> to 14<sup>th</sup> of June (2 columns, print in color)

344 *3.3. Soil model setup*

345 In order to model the car park described above, the model parameters  
 346 need to be set for the current situation.

347 *3.3.1. Deep boundary condition*

348 The deep boundary condition is calculated from Equation 5. The value  
 349 for each of the parameters ( $T_{ma}$ ,  $A_a$  and  $t_0$ ) is set according to air temperature  
 350 signals. The values used, derived from measurements recorded over 4 years in  
 351 three locations of the city of Nantes (France). The mean annual temperature  
 352 is  $T_{ma} = 2.50^\circ\text{C}$ , the yearly half amplitude of the daily mean temperature is  
 353  $A_a = 1.86^\circ\text{C}$  and the phase shift  $t_0 = 0$  days.

354 *3.3.2. Upper boundary condition*

355 The measurement campaign provided data that are used as model inputs  
 356 for the calculation of the surface energy balance on the upper boundary  
 357 condition (Equation 8).

358 The sensible heat flux is calculated from the measured air temperature.  
359 For the radiative budget measurements are used. Latent heat flux is not  
360 considered for now, as in this step of the model only dry days are modeled.  
361 In Equation 8,  $LE = 0$ .

### 362 3.3.3. Calibration of the material' properties

363 As seen before, the thermal characteristics of the soil are often unknown  
364 and must be adjusted to properly represent fluxes and temperatures varia-  
365 tions. The characteristics of the soil layers are calibrated according to the  
366 observed soil profile, reducing the difference between the measured and simu-  
367 lated surface temperature, with the centimetric grid. Data acquired on June  
368 6<sup>th</sup> are used for calibration.

369 The temperature profile is initialized from ground temperatures measured  
370 on June 6<sup>th</sup> at midnight. The deep boundary condition, corresponding to  
371 the ground temperature at a depth of 75 cm is set according to experimental  
372 data. At the surface, the boundary condition is calculated from the energy  
373 balance with the measured radiative heat flux and calculated convective heat  
374 flux (with correlation method formula and a characteristic length of 1m, see:  
375 Section 4.1.1 and Figure 8).

376 Albedo and emissivity of the surface are calculated from short and long  
377 wave radiations measured during the period of interest. For the albedo, the  
378 mean diurnal value is 0.173 (for reflected short-wave radiation flux  $K_{up} >$   
379  $20W.m^{-2}$ ), and the mean emissivity value over the period is 0.965.

380 Soil composition and thermal properties are not known with any accu-  
381 racy. Their values were not measured during the campaign. As a result,  
382 only approximate soil composition was available. Cohard et al. (2017, [29])  
383 tried to estimate the first layers characteristics from the temperature and the  
384 ground heat flux measurement. They obtained the following thermal diffusiv-  
385 ity  $\alpha = 1.04 * 10^{-6} m^2.s^{-1}$  for a fixed capacity (with  $\rho = 920 kg.m^{-3}$  and  $Cp =$   
386  $2050 J.kg^{-1}.K^{-1}$ ). The resulting thermal conductivity is  $1.96 W.m^{-1}.K^{-1}$ .

387 From the measured temperature gradient, changes in the soil thermal  
388 properties within the first layer were identified (0-1cm, 1-5cm). The total  
389 capacity of the first layer was then estimated with the surface energy bud-  
390 get measured, the ground heat flux measured at 3.5cm and the temperature  
391 gradient. The thermal characteristics were then adjusted by an iterative  
392 procedure reducing the difference between the measured and the simulated  
393 temperature at the surface and various depths. The thermal characteristics  
394 values were considered acceptable when the RMSE on each ground tempera-  
395 ture had the same level of magnitude as the uncertainty of the sensor ( $0.2^{\circ}C$ ).

396 The calibrated material characteristics are summarized in Table 6.

397 As the material properties were calibrated with the calculated convective  
398 heat flux, the proposed thermal properties compensate for the error between  
399 the calculation and measurement of the convective heat flux. For this reason  
400 the thermal conductivity proposed ( $2.5 W.m^{-1}.K^{-1}$ ) is greater than that es-  
401 timated from Cohard et al. (2017, [29]). However, Xu et al. (2010, [30]) point  
402 out that the thermal conductivity of asphalt concrete can vary from 0.74 to

Layer	Material	Depth	Thermal conductivity	Volumetric heat capacity
Number	Characteristics	m	$W.m^{-1}.K^{-1}$	$10^6 J.m^{-3}.K^{-1}$
0	Asphalt Concrete	0.01	2.5	2.3
1	Asphalt Concrete	0.05	2.5	2.1
2	Old Filled Ballast	0.5	1.8	2.3
3	Altered Mica-schist Natural Soil	1	1.3	2.1

Table 6: Calibrated characteristics of the soil

403  $2.88W.m^{-1}.K^{-1}$ , diffusivity ranges from  $4.4 * 10^{-7}$  to  $14.4 * 10^{-7}m^2.s^{-1}$ , and  
404 specific heat from 879 to  $1364J.kg^{-1}.K^{-1}$ .

405 Yang et al. (2013, [5]) noticed that thermal characteristics of the asphalt  
406 layer may vary with depth. Due to asphalt compaction, the layer density  
407 and the asphalt proportion are not constant along the depth, altering the  
408 thermal properties. Yang et al. (2013, [5]) chose to divide the asphalt layer  
409 into several layers to which different properties were attributed. The same  
410 phenomenon is observed through analysis of the temperature signal within  
411 the asphalt layer. For this reason, the asphalt layer is divided into two layers  
412 (of 1cm and 4cm respectively).

413 After calibration, the model correctly reproduces the conducted heat flux  
414 into the different layers of the soil as shown in Figure 6.

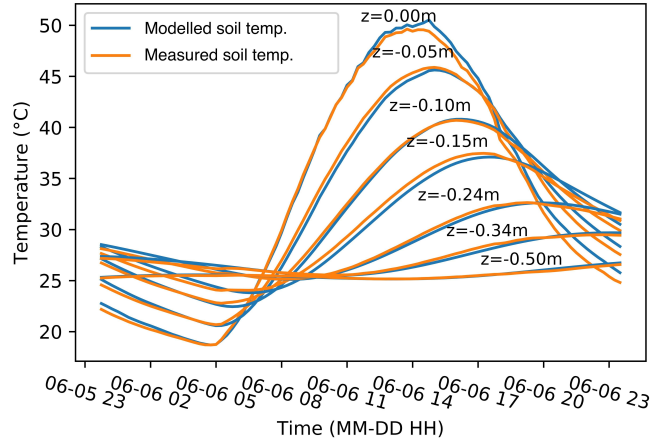


Figure 6: Comparison of simulated and measured temperatures at the surface and at several depths on June 6<sup>th</sup> (1 column, print in color)

#### 415 3.4. Model performance assessment

416 Several indicators may be used to evaluate the performance of a soil  
 417 model. Most authors focus on the ability of their model to estimate surface  
 418 temperature. Only a few of them go further in the analysis evaluating the  
 419 heat flux calculation or the ground temperature at different depths.

420 In this article, the indicator chosen is the RMSE (Root Mean Square  
 421 Error). As the authors used this, it will be easier to compare model accuracy.  
 422 In order to determine whether the dynamics of heat storage are properly  
 423 reproduced, the RMSE will be calculated at the surface and at several depths.

#### 424 3.5. Node distribution definition methodology

425 Optimization of the node distribution represents a major challenge. The  
 426 principle consists in reducing the number of nodes until a situation is reached  
 427 where calculation time and lack of accuracy are minimal.

<b>Zone</b>	<b>Depth of the part [m]</b>	<b>Criterion</b>
1	0.08	Amortization depth for the material with the highest diffusivity and three hourly pulsations
2	0.4	Amortization at 95% of the daily signal for the most common material for this part ( soil, concrete, stone)
3	1.0	Amortization at 95% of the daily signal for the material with the highest diffusivity

Table 7: Criterion for the choice of size for each zone

428 For grid optimization, the choice was made to work with annual simula-  
429 tion. First, an analytic solution is used to better understand ground temper-  
430 ature dynamics. In this way, two sinusoidal temperature signals are applied  
431 to the surface: a three-hour period (corresponding to weather change or shad-  
432 ows created by buildings during a day) and a day period (corresponding to  
433 the day-night cycle). The profiles obtained from the analytical solution are  
434 presented on the right-hand side of Figure 7. The closer we get to the deep  
435 condition, the more linear the profile. With the finite difference method, the  
436 more linear the profile, the less dense the distribution of nodes needs to be.  
437 According to this result, node distribution is different in the three zones: the  
438 criteria used to identify each of them are given in Table 7.

439 Three node distributions are then proposed to better represent these  
440 ground temperature profiles (Figure 7). The final distribution profiles are

441 consistent with those proposed in the literature: the node density is higher  
442 in the upper layer of the ground than in the lower layers.

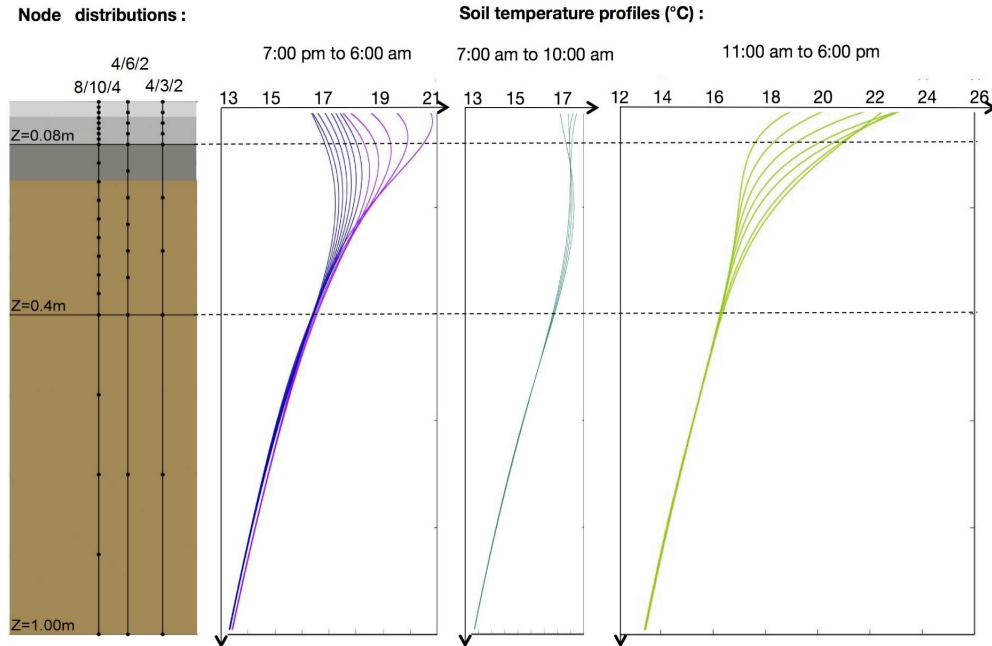


Figure 7: Three proposed node distributions (On the left-hand side the three node distributions, and on the right-hand side the temperature profiles obtained from the analytic solution.) (2 columns, print in color)

## 443 4. Results

### 444 4.1. Sensitivity study

445 Some assumptions made for the model parametrization may affect the sur-  
446 face temperature calculation. Some authors carried out a sensitivity study



447 on the surface and material parameters, on the convective heat transfer coef-  
448 ficient or on the grid size. However, none of these studies has compared the  
449 relative influence of all the affecting parameters.

450 In the following section, a model sensitivity study is performed on the  
451 surface temperature on June 5<sup>th</sup> and 6<sup>th</sup>. Two kinds of parameters are used  
452 for this study: those used for the calibration step (soil thermal characteristics  
453 and the convective heat transfer coefficient) and two additional parameters  
454 which have been identified to be relevant: the deep boundary conditions and  
455 the size of the layers. Parameter sensitivity is studied regarding the order of  
456 magnitude of its uncertainty.

457 The sensitivity study is presented from the most influential parameter to  
458 the least influential: the convective heat transfer coefficient, followed by the  
459 material characteristics, the layer size, and the deep boundary condition.

#### 460 *4.1.1. Convective heat transfer coefficient*

461 Several methods are presented to estimate the convective heat transfer  
462 coefficient  $h$  in Section 3.1.2. Two methods are first compared to select the  
463 most suitable:

- 464 • MacAdams (1954, [27]) formula: linear function of the wind speed  
465 (coefficients  $a$  and  $b$  equal to 3.8 and 5.7 respectively).
- 466 • Correlation equation with dimensionless numbers and different charac-  
467 teristics length (1, 10, 50 m).

468 Figure 8 illustrates the comparison. For the correlation method, after cal-  
469 culating the dimensionless coefficients, the convection mode varies over time:

470 it is mostly mixed during the night and forced during the day. Free convec-  
 471 tion is not represented by the first formula, whereas it is not integrated into  
 472 the MacAdams formula. The correlation method is closer to the measured  
 473 heat flux throughout the comparison period.

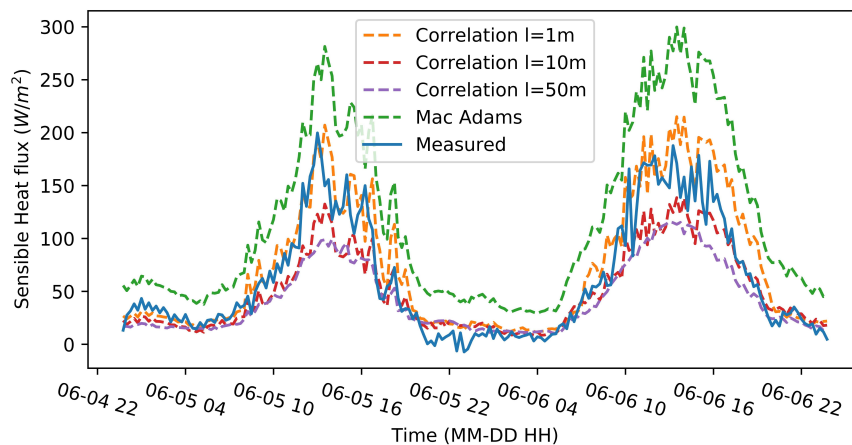


Figure 8: Comparison between the measured sensible heat fluxes at a height of 2m and two calculation methods: the correlation method and the Mac Adams formula. (2 columns, print in color)

474 The correlation method used to calculate the convective heat transfer co-  
 475 efficient (Section 3.1.2), is based on results obtained by Tain and Petit (1989,  
 476 [31]) applied for a horizontal flat plate. In order to apply the similitude the-  
 477 ory, a characteristic length should be set which is most of the time defined  
 478 as the distance from the leading edge. Applied to our case, this character-  
 479 istic length is difficult to define. The influence of several lengths (1, 10 and  
 480 50 m) is tested (Figure 8). Among the three values tested, it appears that  
 481 the 1m- characteristic length correlation method produces the lowest RMSE  
 482 ( $24.27W.m^{-2}$ ).

483 For each value, the correlation method remains better than the MacAdams  
 484 method. As a result, for the following sub-sections, the correlation method  
 485 is chosen with a characteristic length of 1m. The resulting convective heat  
 486 transfer coefficient varies from 2.6 to 12.6  $W.m^{-2}.K^{-1}$ .

487 In order to see the influence of the characteristic length value on the  
 488 sensible heat flux, the RMSE calculated with the 1m- characteristic length  
 489 is compared to the daily mean sensible heat flux (  $61W.m^{-2}$ ). The RMSE  
 490 represents 40% of the mean experimental value.

491 According to these levels of magnitude, we performed the sensitivity study  
 492 varying the convective heat transfer coefficient up to 40% of its initial value.  
 493 The aim is here to quantify the influence of this coefficient on the surface  
 temperature. The results are presented in Table 8.

<b>Indicator</b>	$h + 40\%$	$h - 40\%$
Maximum error ( $^{\circ}C$ )	3.70	5.46
Mean error ( $^{\circ}C$ )	1.89	2.78
RMSE ( $^{\circ}C$ )	2.12	3.14

Table 8: Influence of the convective heat transfer coefficient on the surface temperature  
 (June 5<sup>th</sup> and 6<sup>th</sup>)

494

#### 495 4.1.2. Sensitivity of the layer definition

496 Modification of soil thermal conductivity, soil density and the thickness  
 497 of the layers is performed one by one for each layer. The magnitude of the  
 498 modifications and the layers concerned by the modification are described

499 in Table 9. The surface temperature modification caused by each material  
 500 property change is also presented in this table.

<b>Parameter</b>	<b>Modified layer</b>	<b>Maximum difference at the surface (°C)</b>
Thermal conductivity	0	< 0,1
$\lambda + -10\%$	1	< 0,7
	2	< 0,7
	3	< 0,1
Density	0	< 0,07
$\rho + -5\%$	1	< 0,3
	2	< 0,3
	3	< 0,07
Size of the layer	1	< 0,04
$e + -0,01m$	2	< 0,15

Table 9: Influence of soil characteristics (June 5<sup>th</sup> and 6<sup>th</sup>)

501 The height of each soil layer is not constant over the depth. Each height is  
 502 therefore roughly estimated. To evaluate this lack of accuracy, the influence  
 503 of the biggest layers (1 and 2) is investigated (Table 9).

504 The temperature change associated with layer size modification has the  
 505 same magnitude as that associated with soil property modification of lay-  
 506 ers 0 and 3. However, it is negligible compared to the temperature change  
 507 associated with soil property modification of layers 1 and 2.

508 *4.1.3. Deep boundary condition*

509 The temperature imposed as a deep boundary condition may have an in-  
510 fluence on the surface temperature. If the deep temperature is overestimated  
511 by one degree, the surface temperature increases by only 0.05°C.

512 *4.2. Model ability to reproduce heat conduction transfer: validation*

513 The ability of the model to properly reproduce the physical phenomenon  
514 is evaluated in this section. In order to quantify the uncertainty due to the  
515 model itself (i.e. the accuracy of the physical phenomenon representation),  
516 the model is first evaluated comparing temperature estimation to experimen-  
517 tal data. For this purpose, the model with a centimetric grid is used. As was  
518 noticed in Section 3.4, the evaluation of soil model performance based only  
519 on surface temperature comparison is one of the lacks identified in the liter-  
520 ature. In this study, results are compared on the basis of the temperature at  
521 the surface and at several depths in the soil.

522 The model was evaluated during June 5<sup>th</sup>, 12<sup>th</sup>, and 13<sup>th</sup>. The model cor-  
523 rectly reproduces the heat flux conducted into the different layers of the soil  
524 as shown in Figures 9 and 10. The maximum difference between the mea-  
525 sured and simulated temperature at the surface is 1.67°C, with an RMSE  
526 of 0.71°C for June 5<sup>th</sup>; 1.16°C with an RMSE of 0.60°C for June 12<sup>th</sup> and  
527 2.45°C with an RMSE of 1.28°C for June 13<sup>th</sup>. The mean daily RMSE be-  
528 tween the estimated and the observed surface temperature is 0.86°C, and  
529 0.72°C, 0.58°C, 0.26°C and 0.13°C at 5cm-, 10cm-, 34cm- and 50cm-depths  
530 respectively (June 5<sup>th</sup>, 12<sup>th</sup> and 13<sup>th</sup>).

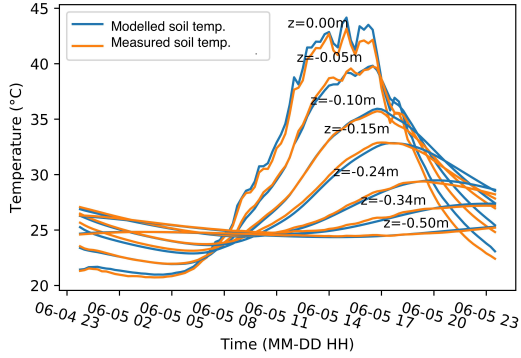


Figure 9: Comparison of simulated and measured temperatures at the surface and at several depths, June 5<sup>th</sup> (1 column, print in color)

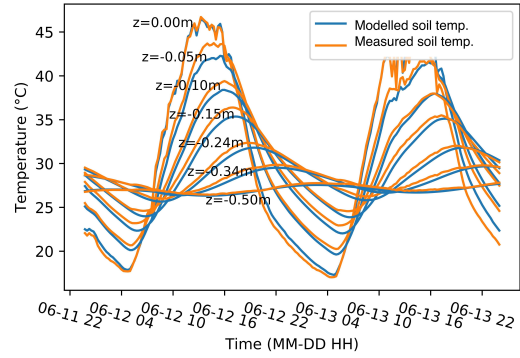


Figure 10: Comparison of simulated and measured temperatures at the surface and at several depths, on June 12<sup>th</sup>, and 13<sup>th</sup> (1 column, print in color)

531 To quantify the accuracy of the model in reproducing the temperature  
 532 variation at several depths, Qin (2002, [22]) divide the RMSE by the am-  
 533 plitude of the signal. In fact, as the amplitude decreased, the relative error  
 534 increased. Going deeper in the ground the amplitude decreased with the  
 535 RMSE but in proportion this error increased. In fact, at the surface, the  
 536 RMSE represents only between 10% to 4.7% of the amplitude, while at a  
 537 depth of 34 cm and 50cm it represents between 6% to 11.7% and between  
 538 8.9% to 104.7% respectively. The error remains under the uncertainty of the  
 539 temperature measurement.

#### 540 4.3. Influence of node distribution

541 The ability of the model to reproduce the physical phenomenon (centi-  
 542 metric grid model compared to the experimental data) is compared to the  
 543 accuracy loss due to the reduction of the number of nodes. Table 11 presents

Date	Depth	Maximum		
		absolute error (°C)	RMSE (°C)	RMSE/amplitude
June 5 <sup>th</sup>	Surface	1.67	0.71	0.032
	5 cm	0.93	0.43	0.024
	10 cm	0.69	0.36	0.028
	34 cm	0.35	0.15	0.060
	50 cm	0.14	0.07	0.089
June 12 <sup>th</sup>	Surface	1.16	0.60	0.020
	5 cm	1.91	0.94	0.040
	10 cm	1.01	0.73	0.045
	34 cm	0.58	0.317	0.095
	50 cm	0.20	0.11	0.1
June 13 <sup>th</sup>	Surface	2.45	1.28	0.047
	5 cm	1.42	0.79	0.024
	10 cm	1.00	0.66	0.028
	34 cm	0.57	0.33	0.117
	50 cm	0.3	0.22	0.247

Table 10: Evaluation of the centimetric grid model according to the experimental data

544 the total error due to the model and node distribution (first and third line)  
545 and the part of the error which is due to the reduction in the number of  
546 nodes (second and fourth line).

<b>Date</b>	<b>Model</b>	<b>1pt/cm</b>	<b>8/10/4</b>	<b>4/6/2</b>	<b>4/3/2</b>
June 5 <sup>th</sup>	RMSE with experimental data (°C)	0.71	0.71	0.65	0.65
	RMSE with centimetric grid (°C)	-	0.03	0.13	0.36
June 12 <sup>th</sup>	Root mean square error with experimental data (°C)	0.60	0.62	0.65	0.85
	RMSE with centimetric grid (°C)	-	0.03	0.15	0.42
June 13 <sup>th</sup>	RMSE with experimental data (°C)	1.28	1.30	1.10	1.26
	RMSE with centimetric grid (°C)	-	0.03	0.44	0.60

Table 11: Evaluation of the model with a reduced numbers of nodes

547 For the 8/10/4 node model, the reduction in the number of nodes has  
548 a very negligible influence. Even though the total error of this model with  
549 experimental data (0.62°C or 1.30°C) increases, this demonstrates that a  
550 higher number of nodes might not be so relevant, since the uncertainty does  
551 not make it possible to say whether model accuracy would be higher or not.  
552 In all cases, the number of nodes is not the main cause of the error.

553 Figure 11 and 12 compare the surface temperature changes of the different  
554 models with that measured. Firstly, all the models properly represent the  
555 change of surface temperature with time. Nevertheless, the daily maximum



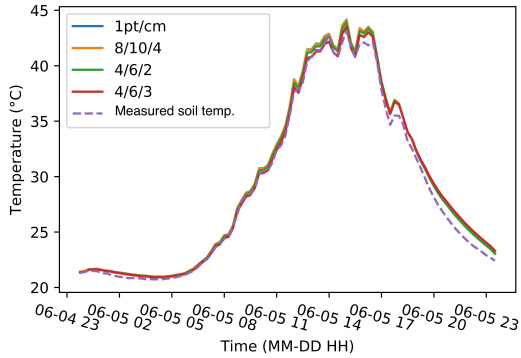


Figure 11: Surface temperature calculated with the different grids compared to that measured (June 5<sup>th</sup>). (1 column, print in color)

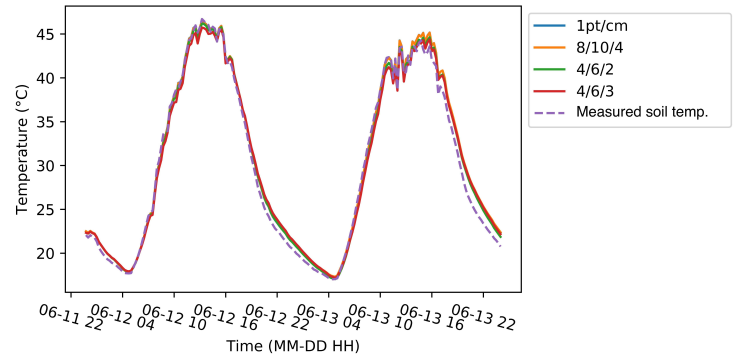


Figure 12: Surface temperature calculated with the different grids compared to that measured (June 12<sup>th</sup> and 13<sup>th</sup>). (1 column, print in color)

556 and minimum peak are slightly underestimated.

557 The underestimated daily maximum peak and minimum trough are due  
 558 to the reduction in the number of nodes that worsens the representation of  
 559 the heat transfer into the ground. In fact, this induces a time shift of heat  
 560 conduction, the main influence of which appears when its sign changes.

561 For the 4/6/2 and for the 4/3/2 node model, the accuracy loss due to  
 562 the reduction in the number of nodes remains lower than the model accuracy  
 563 (centimetric grid RMSE). The absolute error of the model is sometimes lower  
 564 using these node distributions than the centimetric distribution. The reason  
 565 is that the model itself overestimates the surface temperature whereas as a  
 566 lower number of nodes underestimates it (Figures 11 and 12 ).

567 Finally, the reduction of the number of nodes has consequences on the  
 568 reproduction of the daily peaks. This confirms that the correct representation

569 of the surface temperature requires that the heat flux transfer into the soil  
570 be correctly represented.

## 571 **5. Discussion**

572 This part is devoted to discussing the overall accuracy of the model.  
573 The results are firstly compared to those presented in the literature. The  
574 accuracy of the model according to meteorological data is then evaluated  
575 with an annual simulation.

### 576 *5.1. Comparison with other models accuracy*

577 The performance of the models presented above may be compared to  
578 the performance of other models. From the literature the results of the  
579 following authors are chosen: Yang et al. (2013 [5]), Herb et al. (2008 [13]),  
580 Best (1998 [9]) , Malys, (2012 [32, 7]). Note that Malys, (2015, [32, 7])  
581 applied the model proposed by Bouyer (2009, [4]). Those models are chosen  
582 because their simulation conditions (weather conditions, node distribution,  
583 type of ground surface, indicator calculated for performance evaluation) are  
584 the closest to those of the present study. Conditions of simulation and results  
585 are summarized in Table 12.

586 Three of the four articles ([5, 9, 13]) have in common the type of surface  
587 studied and a gradual distribution of nodes: thinner at the surface than  
588 bellow. The last one, Malys (2012, [32, 7]), evaluated the previous SOLENE-  
589 microclimat soil model with a grass surface and a mesh with only 4 nodes.

590 Simulations are run during the summer period during sunny days with  
591 scattered clouds. The surface temperature rises from 41°C to 70°C, except  
592 for Best (1998, [9]), who worked with a lower temperature.

593 According to the results presented in Table 12, the centimetric grid model  
594 is more accurate than the other models from the literature. This is a logical  
595 result as the centimetric model uses a high number of nodes.

596 Using a grid with 15 nodes, Herb et al. (2008 [13]) obtained lower perfor-  
597 mances (1.58°C) than our model. The application conditions being similar,  
598 it can be affirmed that our model is at least as accurate as that of Herb  
599 et al. (2008 [13]) but with more optimized discretization. The difference  
600 in performance can mainly be explained by thinner discretization near the  
601 surface.

Article	Surface type	Meteorological conditions	Maximum surface temperature °C	Amplitude	Numerical discretization	RMSE °C
Best (1998, [9])	Asphalt	Winter conditions	-	-	20 nodes	1.08
	Concrete		12	18		1.2
Herb and al. (2008, [13])	Asphalt	Hot and Dry (July)	55	< 30	15 nodes	1.58
Malys (2012, [32])	Grass	Hot and Dry (May)	41	19	4 nodes	2.3
Yang and al. (2013, [5])	Tiles, concrete,	Hot and Dry (August)	70	40	14 nodes	1.98
	asphalt, paved, grass					
Presented here	Asphalt	Heat wave conditions	50	30	100 nodes	0.86
					8/10/4: 22 nodes	0.87
					4/6/2: 12 nodes	0.80
					4/3/2: 9 nodes	0.92

Table 12: Comparison with the other models: simulation conditions

602 Yang et al. (2013, [5]) presented a 14-layer model with 1.98°C accuracy  
603 which is lower than all the models evaluated in this paper. Nevertheless, it is  
604 applied to extreme conditions: the maximum surface temperature may reach  
605 70°C with a daily variation whose amplitude reaches 40°C.

606 For similar surface temperature amplitudes ( $< 30^\circ\text{C}$  and  $40^\circ\text{C}$  respectively  
607 ), Herb et al. (2008 [13]) and Yang et al. (2013, [5]) obtained an RMSE of  
608 1.58°C and 1.98°C respectively.

609 The model presented by Malys (2012, [32]) has only 4 nodes whereas  
610 the other models have more than 14 nodes. Consequently, it is the least  
611 accurate one, even though the model is applied with fair solicitations: a  
612 low amplitude of surface temperature variation ( $19^\circ\text{C}$ ) and low maximum  
613 temperature ( $41^\circ\text{C}$ ). Using a higher number of nodes with good distribution  
614 seems to be essential to obtain good performance. However, this result should  
615 be treated with caution since Malys (2012, [32]) does not use the same ground  
616 surface type as the other authors.

617 Two of the authors highlight that the high amplitude of surface tem-  
618 perature recorded during the day is harder to represent than the surface  
619 temperature during the night. Yang et al.(2013, [5]) described the fact that  
620 the model fits well with the measurement at night time and in the morning,  
621 but when the temperature rises during the afternoon the model underes-  
622 timates the temperature with an average  $0.5^\circ\text{C}$ . Best (1998, [9]) also has  
623 better results during the night (RMSE  $0.83^\circ\text{C}$ ) than during the day (RMSE  
624  $1.26^\circ\text{C}$ ). This analysis is consistent with the assumption made previously:  
625 clear, hot days, characterized by high surface temperature amplitude, are

626 the most difficult days to simulate.

627 In general, one needs to exercise care in considering the results of this  
628 comparison for several other reasons:

- 629 • the surface temperature used as the reference temperature for each  
630 study comes from surface temperature measurement. Uncertainty on  
631 such measurement might be of the same magnitude as the RMSE ob-  
632 served, which makes comparisons between models difficult.
- 633 • the comparison of the model's performance is given for studies in sim-  
634 ilar conditions. Nevertheless, they cannot be exactly the same. The  
635 location is not the same, the weather conditions differ, and the surface  
636 type or at least the soil composition is not exactly the same.

637 Even though we conclude that the models proposed in this paper seem to  
638 present better performance than those of the literature, the difference must  
639 be put into perspective with application conditions. All those models should  
640 be applied to a single case study.

## 641 *5.2. Performance according to meteorological data*

642 The accuracy of the different grids according to meteorological data is  
643 evaluated comparing numerical profile of an annual simulation (hourly time  
644 step) for each node distribution (8/10/4, 4/6/2, 4/3/2). For those simula-  
645 tions, meteorological data recorded during one year (2010) at the Pin Sec  
646 station in the city of Nantes are used. These data were collected by the

647 ONEVU (Observatoire Nantais des EnVironnements Urbains - urban envi-  
 648 ronment observatory of the IRSTV [33]). Among the available observations,  
 649 the following data are used as input in the model: air temperature, pressure  
 650 and humidity, global and IR radiative flux, and wind velocity and direction.

	<b>8/10/4</b>	<b>4/6/2</b>	<b>4/3/2</b>
Part 1	1pt/cm	1pt/2cm	1pt/2cm
Part 2	1pt/3.5cm	1pt/5cm	1pt/10cm
Part 3	1pt/15cm	1pt/30cm	1pt/30cm
Total number of points	22	12	9
Maximum absolute difference with the centimetric grid model over a year ( $^{\circ}C$ )	0,58	1,35	2,18
Yearly mean absolute difference with the centimetric grid model ( $^{\circ}C$ )	0,1	0,2	0,33

Table 13: Distribution of the nodes and accuracy

651 Table 13 presents the results of the comparison between the surface tem-  
 652 perature model for each of the node distribution compared to the centimetric  
 653 grid model. In the case of the 8/10/4 nodes model, the maximum absolute

654 difference is  $0.58^{\circ}\text{C}$  and for the 4/3/2 node model,  $2.18^{\circ}\text{C}$ . The mean abso-  
 655 lute difference for the first node distribution is only  $0.1^{\circ}\text{C}$  whereas that of  
 656 the 4/3/2 distribution is  $0.33^{\circ}\text{C}$ , which remains in the order of magnitude of  
 657 the measurement uncertainty.

658 For each case, the frequency of appearance of the mean daily error be-  
 659 tween the centimetric grid and the reduced grid model is calculated. Each  
 660 day is ranked in a different performance class to illustrate the differences  
 661 between the node distribution (Table 14).

<b>Mean daily error</b>	<b>Low : <math>E &lt; 0.2</math></b>	<b>Medium: <math>0.2 &lt; E &lt; 0.5</math></b>	<b>High <math>E &gt; 0.5</math></b>
8/10/4	363	2	0
4/6/2	212	150	3
4/3/2	82	224	59

Table 14: Number of days for which each class of error occurs (error calculated compared the centimetric grid model)

662 The 8/10/4 node model does not have any day with a mean error higher  
 663 than  $0.5^{\circ}\text{C}$  and has only two days with a mean error higher than  $0.2^{\circ}\text{C}$ .  
 664 The 4/6/2 node model has almost as many days represented with high or  
 665 medium performance. Finally, most of the days represented by the 4/3/2  
 666 node model have medium performance. More detailed investigation of the  
 667 days with high mean daily error shows that these days were clear and sunny  
 668 ones. This confirms the fact that clear days are more difficult to simulate  
 669 than cloudy days.



670 **6. Conclusion**

671 The main purpose of this study is to propose a model that accurately  
672 reproduces the heat storage flux into urban ground as well as changes in  
673 surface temperature.

674 Some failings were identified in the literature review, pointing up the  
675 need:

- 676 • to perform an overall sensitivity analysis,
- 677 • to investigate the advantage of using different convection flow modes  
678 (forced, mixed, natural)
- 679 • to justify the chosen mesh,
- 680 • to assess models not only for surface temperature calculation.

681 To test the robustness of our model regarding its parameters, a com-  
682 plete sensitivity study was carried out on the model parameters: all have a  
683 negligible impact except the convective heat transfer coefficient.

684 Special attention has been paid to how the convective heat transfer coeffi-  
685 cient is calculated. The chosen method makes it possible to take into account  
686 the different kinds of convection flow modes which is necessary for an urban  
687 application. Nevertheless, the sensitive heat flux can vary by 40%, leading  
688 to an uncertainty up to 3.14°C on the surface temperature RMSE.

689 After calibration of the different parameters, soil model (using a centimet-  
690 ric grid) accuracy is evaluated according to a measurement campaign carried

691 out in a large asphalt car park during three sunny days with scattered clouds.  
692 The RMSE between estimated and observed temperatures is calculated for  
693 surface temperature and ground temperature at several depths. Surface tem-  
694 perature RMSE is  $0.86^{\circ}\text{C}$ ; RMSE for temperature at 34cm of depth is  $0.26^{\circ}\text{C}$ .  
695 The results validate the ability of the model to reproduce heat storage into  
696 the ground.

697 Three node distributions are proposed on the basis of the analysis of the  
698 different temperature profiles throughout the depth. They all are dedicated  
699 to any kind of impervious urban surfaces. However, for less diffusive soils,  
700 the user is free to define other distributions in order to adapt the model to his  
701 application. The accuracy of the models varies from  $0.62^{\circ}\text{C}$  to  $1.30^{\circ}\text{C}$ . These  
702 performances are better than those of models from the literature applied  
703 under quite similar conditions.

704 Finally, application of the models over a whole year shows that only  
705 a few days are represented with an accuracy worse than  $0.5^{\circ}\text{C}$ . Most days  
706 are even reproduced with an accuracy better than  $0.2^{\circ}\text{C}$ . The investigation  
707 demonstrates that surface temperatures during clear and sunny days are the  
708 most difficult to reproduce.

709 This paper provides a complete overview of soil model performance, com-  
710 paring it with experimental data, centimetric grid model, and literature re-  
711 sults. Because of measurement uncertainty, better performances would be  
712 difficult to obtain and especially to assess. Nevertheless, comparison of the  
713 model performances with results from the literature would require a bench-  
714 mark. The model presented, now validated, is ready to include moisture

715 transfer and in particular the evaporation of water at the soil surface, to  
716 help to properly assess the effect on local climate and outdoor comfort of  
717 moistening techniques.

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