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► **To cite this version:**

Marie-Hélène Azam, Benjamin Morille, Jérémy Bernard, Marjorie Musy, Fabrice Rodriguez. A new urban soil model for SOLENE-microclimat: Review, sensitivity analysis and validation on a car park. Urban Climate, 2017, 10.1016/j.uclim.2017.08.010 . hal-01629430v1

HAL Id: hal-01629430

<https://hal.science/hal-01629430v1>

Submitted on 6 Nov 2017 (v1), last revised 1 Jun 2018 (v2)

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Urban soil model under summer conditions: review, sensitivity analysis and validation

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Abstract

The main purpose of this study is to propose a model that well reproduces the heat storage flux into urban ground as well as surface temperature evolution. For that purpose a complete bibliographic review is first achieved. Some lacks are identified and the methodology to define the model in agreement with the conclusions of the literature review is presented as well as the way to assess its performances. Three nodes distributions are proposed regarding ground temperature profiles using an analytic solution. A sensitivity study is achieved on a large number of parameters: the material properties, the size of the layers, the deep boundary condition, and the convective heat transfer coefficient. The model ability to reproduce heat conduction transfer is validated thanks to a measurement campaign realized on a large asphalt

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parking lot during two clear and hot days. The RMSE between estimated and observed surface temperature is $0.75^{\circ}C$. The validation also include comparison with temperature at 4 different depths. The RMSE are $0.73^{\circ}C$, $0.48^{\circ}C$, $0.21^{\circ}C$ and $0.06^{\circ}C$ respectively at 5cm, 10cm, 34cm and 50cm. Performances obtained with the model using different nodes distributions are discussed and compared with results from the literature. The model presents better performances than most of others models applied in quite similar conditions. Finally, the application of the proposed model at a yearly scale demonstrates that the accuracy loss caused by the decrease of the nodes number depends on weather conditions. In particular, the most difficult days to simulate are clear and sunny days.

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

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1 **1. Introduction**

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

10 For that purpose, numerical simulation is a powerful tool. Several mod-
11 els under development simulate the UHI phenomenon and its consequences.
12 Different scales are considered depending on the application intended: for
13 example TEB [2] or ARPS-VUC [3] are more suitable to the city scale ap-
14 plications while models like SOLENE-microclimat [4], Envi-met [5] and En-
15 viBatE [6] are dedicated to the district scale. For a same scale, each tool
16 may have one specific feature among many others : EnviBatE [6] is designed
17 to study the energy demand of a buildings group, SOLENE-microclimat [4]
18 focuses on outdoor comfort and on the impact of urban climate on indoor
19 comfort, and ENVImet [5] is dedicated to outdoor comfort.

20 All those models have in common to represent several physical mecha-
21 nisms : radiative fluxes, thermal fluxes and fluid dynamic. Furthermore the
22 representation of those phenomena is essential to calculate precisely the soil
23 surface temperature, which is the interaction key between the soil and the
24 urban environment (radiative and sensible fluxes). The heat flux stored and
25 released by the urban material respectively during day- and night-time is one
26 of the main causes of UHI development. This heat flux is more important in
27 urban than in rural areas due to the high inertia of the materials used. Thus
28 the simulation of heat transfer in the facades but also in the soil are of the
29 highest importance.

30 The objective of this paper is to propose a model that well reproduces
31 the heat storage flux into urban ground as well as the surface temperature
32 evolution.

33 A literature review on models representing heat transfer into soils permits
34 to identify some lacks as well as to pick up data for the model parametriza-

35 tion.

36 The measurement campaign presented provides input data and validation
37 data for the model. The chosen indicators to assess the model performance
38 are then presented. The calibration of the model is carried out and the
39 different nodes distributions are justified.

40 The results of the study are divided in three parts :

- 41 • sensitivity study on model parameters,
- 42 • model validation using an ideal nodes distribution in order to evaluate
43 the model ability to reproduce the conductive heat transfer into the
44 soil,
- 45 • calculation of the accuracy loss caused by different nodes distributions.

46 Then model performances are compared to the ones of models identified
47 in the literature. Finally the performances are analyzed for a whole year
48 simulation.

49 This exhaustive study provides accurate information on the reliability of
50 SOLENE-microclimat, the tool where the soil model is implemented in.

51 **2. State of the art**

52 *2.1. Existing models*

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

- 55 • Geothermal energy applications,

- 56 • Road applications: pavement sustainability or frost forecasts,
 - 57 • Hydrology and interaction between soil, vegetation and atmosphere.
- 58 Those other domains have the advantage of proposing a different point of
59 view on the way to model heat transfer in the ground. In the Table 1 the
60 articles used for the following bibliographic review are gathered with the
61 characteristics 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, [7])				x	x		x				x	
Best (1998, [8])		x			x		x		x	x		
Best and al. (2005, [9])		x			x		x			x		
Bouyer (2009, [4])				x	x		x		x		x	
Chow and al. (2011, [10])	x				x				x			
Diefenderfer and al. (2006, [11])		x				x				irrelevant		
Gros et al. (2015, [6])				x	x						x	
Herb et al. (2008, [12])			x		x		x		x		x	
Hermansson (2004, [13])		x			x						x	
Ho (1987, [14])			x			x					x	
Jacovides (1996, [15])	x				x		x		x		x	
Lin (1980, [16])			x		x		x				x	
Masson (2000, [2])				x				x				
Milhalakou and al. (1997, [17])	x				x			x		x		
Milhalakou and al. (2002, [18])	x				x		x		x			
Nowamooz and al. (2015, [19])	x				x				x		x	
Ozgener and al. (2013, [20])	x				x		x			x		
Qin and al. (2002, [21])			x		x		x				x	
Saito and Simunek (2009, [22])			x		x		x				x	
Swaaid and Hoffman (1989, [23])			x			x					x	
Yang and al. (2013, [5])				x	x		x		x		x	

Table 1: Models application and type of soil

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

62 Even if the field of application is different, all the articles presented have
63 the common objective of predicting surface temperature, or ground heat
64 flux. Depending on the application, the physical mechanisms modeled are
65 not the same. In addition to the conductive heat flux, the moisture flow
66 is often modeled. This is the case for several applications that use bare-
67 soil and vegetation covers [21, 22, 12, 7]. This is useful to estimate the
68 water availability for vegetation or to adjust the thermal properties of the
69 soil depending on humidity content. Nevertheless, for impervious surfaces,
70 moisture flux are most of the time neglected [12].

71 The soil model presented in this paper is designed for impervious surface
72 in urban environment. Urban grounds are heterogeneous and made of differ-
73 ent layers characterized by large differences regarding their physical proper-
74 ties. Thus the model shall be able to take into account several layers. In the
75 literature, the soil is modeled either by an homogeneous or an heterogeneous
76 column. But for a given area, the size of each layer and its physical properties
77 are not known accurately. By simplification, half of the soil models presented
78 here considers an homogeneous column of soil (Table 1). Nevertheless, in or-
79 der to accurately simulate the conduction flux all along the vertical axis, the
80 soil profile should be consistent with reality, which implies to consider an
81 heterogeneous soil.

82 Thermal properties are either set to experimental data (ie : to better
83 represent measurements albedo is defined as the ratio between incident and
84 reflected solar radiation) or calibrated.

85 However, the impact of the thermal properties is rarely investigated. Best

86 (1998, [8]) and Herb et al. (2008, [12]) studied the influence of the material
87 characteristics (diffusivity, specific heat, etc) on surface temperature. Ac-
88 cording to Best (1998 [8]) and Herb et al. (2008 [12]), the emissivity and
89 the thermal conductivity of the pavement have the most influence on surface
90 temperature, while underneath soil characteristics have few influence.

91 In the case of an homogeneous soil column, there are several possibili-
92 ties to obtain ground temperature variation. Among others, we may cite
93 the analytical solution (Fourier analysis [9, 10, 14, 15, 17, 18, 20, 23]), the
94 empirical method [10, 11, 18], or even the Force-restored method [16]. For
95 an heterogeneous soil column, only the numerical method allows to accu-
96 rately estimate the surface temperature as well as the ground temperature
97 for several depths. Twelve of the models described use finite differences
98 method with an implicit scheme [7, 8, 9, 4, 6, 12, 13, 14, 2, 21, 22, 5] except
99 Nowamooz et al. (2015, [19]) who use an explicit scheme. The soil model
100 presented in this paper is based on an implicit finite differences method. The
101 following section presents in detail all the possible parametrization in the
102 case of finite differences method.

103 *2.2. Parametrization of finite differences models*

104 For a same problem-solving method, different choices can be made re-
105 garding the nodes distribution (discretization), the boundaries and the initial
106 conditions (Table 2).

Article	Upper boundary		Convection coeff.		Lower boundary		Initial conditions
	Temperature	Flux	Forced	Natural	Temperature	Flux	
Asaeda and Ca (1993, [7])	x	x	x		2.5m		EV
Best (1998, [8])	x	x	x		1.15m		Exponential profile
Best and al. (2005, [9])	x	x	EV			x	EV
Bouyer (2009, [4])	x	x	x		2m		Constant value
Gros et al. (2015, [6])	x	x	CFD		0.5m		NI
Herb et al. (2008, [12])	x	x	x	x		10m	NI
Hermansson (2004, [13])	x	x	x	x	5m		NI
Ho (1987, [14])	x	x		x	x		Linear or exponential profile
Masson (2000, [2])	x	x	x			x	NI
Nowamooz and al. (2015, [19])	x		irrelevant		4m		EV
Qin and al. (2002, [21])		x	x		x		EV
Saito and Simunek (2009, [22])		x	x		x		EV
Yang and al. (2013, [5])		x	CFD		2m		EV

Table 2: Parametrization of finite differences models

EV: Experimental values NI: No Informations CFD: Computational fluid dynamics

Vertical Discretization

Depending on the author, different vertical discretizations are used. Ho (1987, [14]) and Qin et al (2002, [21]) propose a uniform layout points, whereas most of the articles present a nodes distribution denser near the surface than deeper in the ground. Saito and Simunek (2009, [22]) use a denser distribution near the surface and also near the interface between two layers. However, the choice of the nodes distribution is rarely clearly justified. Only Best et al. (2005 [9]) studied the behavior and the accuracy of the model for different vertical discretization, comparing the numerical solution with the analytical one. The purpose of the present study is to propose an optimized discretization which is a compromise between accuracy loss and computational efficiency. Few sensitivity studies are made on this point. Asaeda and Ca (1993,[7]) studied the influence of the grid size. As expected, the thinner the resolution of the grid, the more precise the surface temperature. This accuracy gain is yet realized to the detriment of calculation duration. Thus as Best et al. (2005 [9]) suggested, a compromise should be found between accuracy and execution time.

Boundary conditions

To solve one dimension heat conduction equation with the finite differences method, two boundary conditions are required. The bottom condition taken at defined depth, can either be a zero flux or a constant temperature (Table 2). If the simulation concerns a short period and the last point of the grid is below diurnal amortization depth, the type of condition has low influence on the surface temperature [8].

131 As the purpose of most articles is to predict surface temperature, the
132 upper boundary condition is defined by the surface energy balance. This
133 balance is composed of the radiative fluxes, the sensible flux, the latent flux,
134 and the conductive heat flux in the soil. The long and short wave radia-
135 tion fluxes are always calculated, except for the validation process for which
136 measurements are used whenever they are available.

137 As urban soils have a low albedo, temperature gradient between the sur-
138 face and the air can be very important, especially during clear days. This
139 phenomenon leads to natural convection (driven by buoyancy forces). In
140 the surface energy balance, most of the authors only take into account the
141 forced convective mode (driven by the wind forces), whereas Herb (2008,
142 [12]) proposes to consider both forced and natural modes.

143 Both Hermansson (2004, [13]) and Herb et al. (2008, [12]) assumed that
144 the method used to calculate the convective heat transfer coefficient is a crit-
145 ical point. To test this assumption, they both realized a sensitivity study on
146 the coefficients of an empirical formula. Herb et al. (2008, [12]) show that
147 the modification of convection parameters can sometimes have an important
148 impact on surface temperature : for a 10% increase of the convection param-
149 eters, the average surface temperature variation is about $0.24^{\circ}C$. This might
150 be explained by low wind speed and by high temperature gradient between
151 the surface and the air. Hermansson (2004, [13]) dissociates winter and sum-
152 mer periods, since the temperature gradient between the surface and the air
153 is smaller during winter. He proposes to use two sets of parameters regarding
154 solar radiation conditions. Depending on the season, the convection losses

155 and the wind velocity are balanced by coefficients.

156 **Initial conditions**

157 In general, few information is given on the initial conditions (temperature
158 profile) except for the validation process. Most of the authors use exper-
159 imental values (Table 2). When this information is not available, several
160 alternatives are proposed : a constant temperature profile is set ([4, 14]) or
161 an exponential profile between the deep soil and the surface ([8, 14]). How-
162 ever, according to Ho (1987, [14]), this parameter has low impact on the
163 surface temperature

164 **3. Methodology of the study**

165 *3.1. Proposed soil model*

166 The soil model presented in this paper is designed for impervious surface
167 such as pavement coating. Thus, only heat transfer is taken into account
168 (moisture transfer is neglected). The soil model is defined as a one dimension
169 soil column where each layer has its own characteristics. In unsteady state,
170 the temperature fluctuation is calculated from the Equation 1, which is an
171 application of the heat equation for a one-dimensional problem.

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

172 α_{soil} : thermal diffusivity of the soil [$m^2 s^{-1}$]

173 The problem is solved by a finite differences method using a nodal dis-
174 cretization and an electrical analogy. Heat resistances represent the resis-
175 tance to heat transfer through a ground layer and heat capacities, the heat
176 storage capacity of a ground layer. They are defined on Figure 1.

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

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

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

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

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

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

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

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

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

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

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

190 $T_{surface}$: surface temperature [K]

191 T_{air} : air temperature [K]

192 T_i : temperature of the node i [K]

193

194 According to this method, any nodes distribution and any boundary con-
 195 dition depth may be used. Most of the authors in the literature work with
 196 centimetric grid when accuracy is required. A model with one node per cen-
 197 timeter is used and defined as the "ideal model" in the following parts. The
 198 top node is located at the ground surface and the deepest one at a depth of

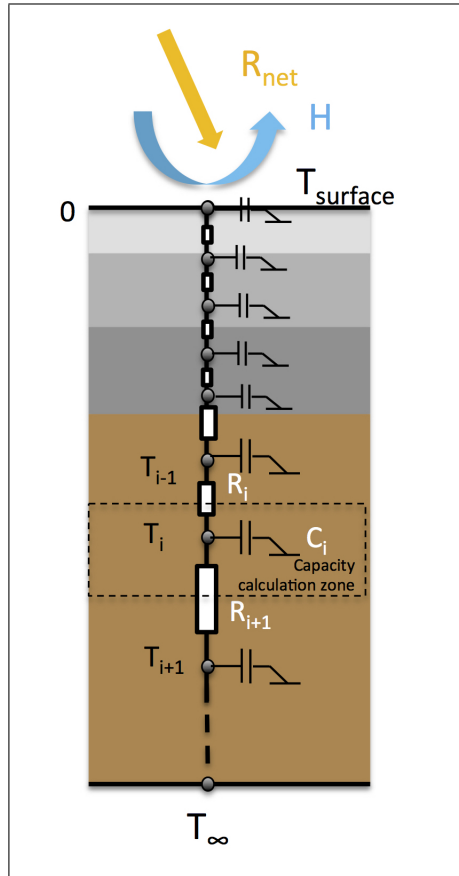


Figure 1: Soil model

199 1m. At this depth, the temperature is supposed to be constant over a day.
 200 A new value will be set for each day. More details are given in Section 3.1.1.

201 Figure 1 illustrates the way thermal properties are defined. Each layer of
 202 material is supposed homogeneous and isotropic and has its own character-
 203 istics which are considered to be constant over time.

204 As the nodes distribution is defined independently from the soil layers and
 205 characteristics, they are not automatically located at the interface between

206 two layers.

207 3.1.1. Deep boundary condition

208 In the deep soil, the temperature is supposed constant over a day. In the
209 case of an homogeneous soil, an analytic solution can be used to calculate
210 the temperature for any depth z and any time t . If the surface temperature
211 is considered to be sinusoidal, the analytic solution follows the Equation 5.

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

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

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

214 zd_a : damping depth with an annual beat [m]

215 w_a : annual beat $w_a = 2 * \pi / 31536000$

216 t_0 : day of the year where the surface temperature was the coldest

217

218 The parameters T_{ma} , A_a and t_0 are respectively the mean, the amplitude
219 and the phase of a day surface temperature signal. As a first approximation,
220 the value for each of those parameters is set according to air temperature sig-
221 nals. The values used, derived from measurements recorded during 4 years in
222 three locations of the city of Nantes (FRANCE). The mean annual temper-
223 ature is $12.50^{\circ}C$, the yearly half amplitude of the daily mean temperature
224 is $11.86^{\circ}C$ and the phase shift 30 days.

225 From a certain depth, the daily signal is completely damped. The damp-
226 ing depth depends on the soil characteristics through the parameter zd_a ,

227 defined by the Equation 6. The depth from where the signal is damped at
228 95 or 99 % can be estimated from Equation 7.

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

229

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

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

231

232 For a range of materials (asphalt, concrete, bare-soil), the most diffusive is
233 the marble. For this material, the depth corresponding to a daily damping of
234 99% is 0.89cm. Beyond a meter, the hypothesis is made that the temperature
235 is constant over the day whatever the type of ground. For this reason, the
236 bottom node is located below this depth.

237 3.1.2. Upper boundary: Heat flux across a ground surface

238 The upper boundary condition is defined from the energy balance at the
239 ground surface (Equation 8).

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

240 with R_{net} , Q_{cond} , H , LE previously defined and $LE=0$ because water fluxes
241 are not considered in this step of the model.

242 Radiative flux

243 The net radiative flux is the balance of all radiative fluxes at the soil
244 surface. It is the sum of short-wave radiation and long-wave radiation. The

245 historical SOLENE radiative model computes radiative transfers, including
246 long-wave radiation, inter-reflexion and shading effects [24]. So this input
247 data doesn't need be calculated in the further model.

248 **Convective heat flux**

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

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

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

252 T_{air} : air temperature [K]

253 $T_{surface}$: surface temperature [K]

254

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

259 The most simple is a linear relation of the wind speed (Equation 10). De-
260 pending on the situation (i.e. surface texture, wind velocity, windward/leeward
261 surface, etc), Palyvos (2008, [25]) suggests around forty combinations for a
262 and b coefficients. For an horizontal surface, with feeble winds ($V_{air} < 5m/s$),
263 several coefficients are proposed (Table 3).

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

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

265

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

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

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

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

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

269

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

270 Re : Reynolds number

271 Gr : Grashof number

272 Nu : Nusselt number

273 L_c : characteristic length [m]

274 λ_{fluid} : thermal conductivity of the fluid [$W.m^{-1}.K$]

275

276 This type of correlation allows to define a convective heat transfer coef-
277 ficient as a function of the flow modes:

- 278 • Natural or free convection: air flow driven by buoyancy forces,
- 279 • Forced convection: air flow driven by wind forces,
- 280 • Mixed convection: when the air flow is created by both wind and buoy-
281 ancy forces.

282 In the case of urban applications, wind speed is often feeble and the
283 temperature gradient important. Then free convection may become predom-
284 inant. A comparison between the MacAdams formula and the correlation
285 method is performed in order to choose the most suitable method for urban
286 climate application (Section 4.1.1).

287 *3.2. Presentation of the measurement campaign*

288 The measurement campaign provided data that are used either as model
289 inputs or as validation data to evaluate the model performance and its accu-
290 racy.

291 Data from the ROSURE/HydroVille project are used. This project was
292 leaded by IFSTTAR and funded by the National Institute for Earth sciences
293 and Astronomy (INSU) of the *Centre National de la recherche scientifique*

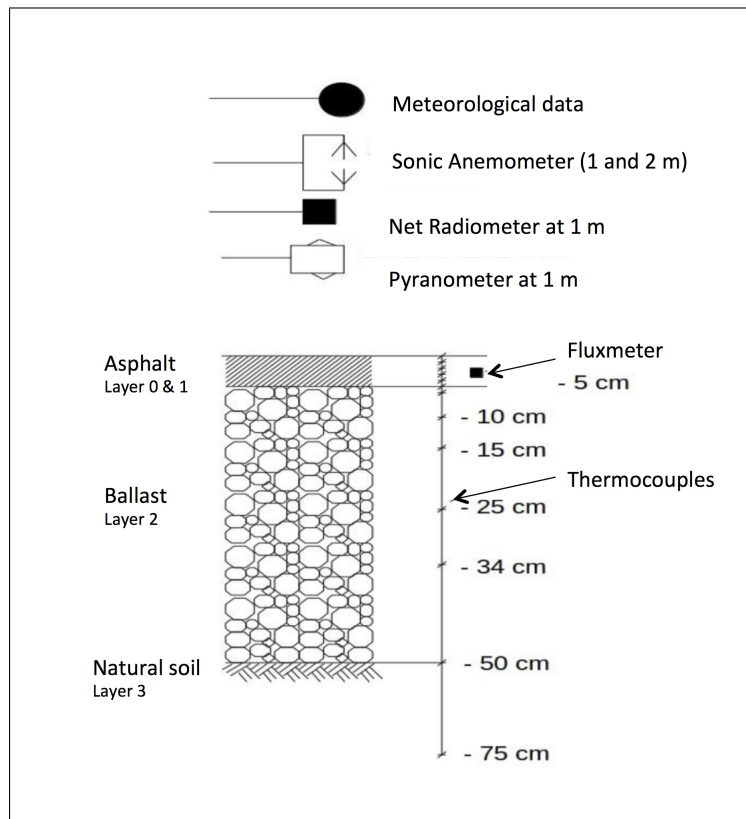


Figure 2: Drawing of the measurement campaign

294 (CNRS). A campaign devoted to the documentation of energy and water
 295 budgets of an asphalt parking lot was carried out in the month of June,
 296 2004. This campaign especially focused on surface and air temperatures and
 297 on heat flux measurements during a warm summer period. Artificial rain
 298 events were performed during the campaign but the present study only focus
 299 on dry weather periods.

300 The experiment site is located near Nantes (France) within the IFSTTAR
 301 center of Bouguenais, and consisted in an asphalt parking lot of 2500 square
 302 meters. The soil structure is composed of a 5cm- asphalt layer, a 45cm-

303 ballast layer and natural soil underneath. Along the observations available
304 for this campaign, this study focused on the following variables, all observed
305 in the middle of the parking lot (Figure 2):

- 306 • surface and ground temperatures; a vertical profile was placed with
307 type T thermocouples (diameter $120\mu m$) located at 0, 1, 2, 3, 4, 5, 6,
308 10, 15, 24, 34, 50 and 75 cm depth.
- 309 • wind speed and direction (Young Campbell (05103) monitor);
- 310 • humidity and air temperature at 1 and 2m above ground; HMP45C
311 TRH probes (Campbell) with Vaisala HR HUMICAP for humidity and
312 PT1000 for temperature.
- 313 • convective heat fluxes at 1 and 2m height; sonic anemometer USA1
314 (Metek)
- 315 • radiation components, thanks to 4 pyranometers and a radiometer at a
316 height of 1m; 2 pyranometers CM6B (Kipp & Zonen), 2 pyranometers
317 CGR3 (Kipp & Zonen) and a net radiometer NRLite (Kipp & Zonen).

318 The data were collected with a 1 min time step except for the sonic
319 anemometer (0,1 s). The final data are averaged to 15 min time steps. From
320 the whole measurement period, two consecutive days are selected with dif-
321 ferent meteorological conditions: one cloudy sky day (5th of june) and one
322 clear sky day (6th of june). The clear sky day will be used to calibrate the
323 model while the cloudy day will be used to evaluate the model.

324 *3.3. Model performance assessment*

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

329 In this article, the indicator chosen is the RMSE (Root Mean Square
330 Error). As most of the authors used it, it will be easier to compare the
331 model accuracy. In order to evaluate if the dynamic of heat storage is well
332 reproduced, the RMSE will be calculated at the surface and at several depths.

333 *3.4. Calibration of the materials' properties*

334 As seen before, the thermal characteristics of the soil are often unknown
335 and must be adjusted to well represent fluxes and temperatures variations.
336 The characteristics of the soil layers are calibrated according to the observed
337 soil profile, reducing the difference between the measured and simulated sur-
338 face temperature. Data acquired on the 6th of June are used for calibration.

339 Temperature gradient is initialized from ground temperatures measured
340 on 5th of June at midnight. The deep boundary condition, corresponding
341 to the ground temperature at 75 cm depth is set according to experimental
342 data.

343 Albedo and emissivity of the surface are calculated from short and long
344 wave radiations measured during the period of interest. For the albedo, the
345 mean diurnal value is 0.173 (for reflected short-wave radiation flux $K_{up} >$
346 $20W/m^2$), and the mean emissivity value over the period is 0.965.

347 The thermal characteristics (Figure 2) are adjusted by an iterative pro-
 348 cedure reducing the difference between the measured and simulated temper-
 349 ature at the surface and various depths. The thermal characteristics values
 350 are considered acceptable when the RMSE on each ground temperature has
 351 the same level of magnitude than the uncertainty of the sensor ($0.3K$).

352 Yang et al. (2013, [5]) noticed that thermal characteristics of the asphalt
 353 layer may vary with depth. Due to the asphalt compaction, the layer density
 354 and the asphalt proportion are not constant along depth, altering the thermal
 355 properties. Yang et al. (2013, [5]) made the choice to divide the asphalt
 356 layer into several layers to which different properties were attributed. The
 357 same phenomena is observed through the analyze of the temperature signal
 358 within the asphalt layer. For this reason, the asphalt layer is divided in two
 359 layers (respectively one of 1cm, and one of 4cm). The calibrated material
 360 characteristics are summarized in the Table 5.

Layer	Depth	Thermal conductivity	Volumetric heat capacity
Number	m	$W/(m.K)$	$J/(m^3.K)$
0	0.01	2.5	2.3
1	0.05	2.5	2.1
2	0.5	1.8	2.3
3	1	1.3	2.1

Table 5: Calibrated characteristics of the soil

361 *3.5. Methodology of nodes distribution definition*

362 Optimization of the nodes distribution is one of the major modeling chal-
 363 lenge. The principle consists in reducing the number of nodes up to a situa-
 364 tion where calculation time and lack of accuracy are minimal.

Zone	Depth of the part [m]	Criterion
1	0.08	Amortization depth for the material with the highest diffusivity and three hourly pulsation
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 6: Criterion for the choice of each zone's size

365 For the grid optimization, the choice was made to work with annual
 366 simulation. First, an analytic solution is used to better understand ground
 367 temperature dynamic. In this way, two sinusoidal temperature signals are
 368 applied to the surface: a three hours period (corresponding to weather change
 369 or shadow created by building during a day) and a day period (corresponding
 370 to the day-night cycle). Closer we get to the deep condition, more linear
 371 the profile. With finite differences method, more linear is the profile, less
 372 dense the distribution of node needs to be. According to this result, nodes
 373 distribution is different in the three zones : the criteria used to identify each
 374 of them are given in Table 6.

375 Then, three nodes distributions are proposed to better represent those
 376 ground temperature profiles (Figure 3). The final distribution profiles are
 377 consistent with those proposed in the literature: the nodes density is higher
 378 in the upper layer of the ground than in the lower layers.

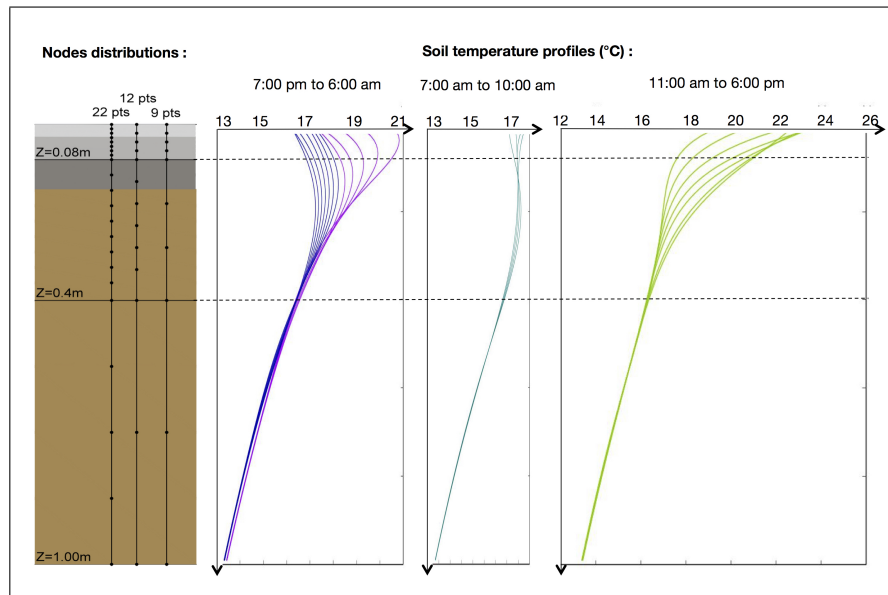


Figure 3: 3 nodes distributions proposal

379 4. Results

380 4.1. Sensitivity study

381 Some assumptions made for the model parametrization can affect the sur-
 382 face temperature calculation. Some authors realized a sensitivity study on
 383 the surface and material parameters, on the convective heat transfer coeffi-
 384 cient or on the grid size. However, none of those studies has compared the
 385 relative influence of all the affecting parameters. In the following section, a

386 model sensitivity study is performed on the surface temperature. Two kinds
387 of parameters are used for this study : those used for the calibration step (soil
388 thermal characteristics and the convective heat transfer coefficient) and two
389 additional parameters which have been identified to be relevant: the deep
390 boundary conditions and the size of the layers. The parameters sensitivity is
391 studied regarding the order of magnitude of its uncertainty.

392 *4.1.1. Convective heat transfer coefficient*

393 Several methods are presented to estimate the convective heat transfer
394 coefficient h in Section 3.1.2. Two methods are first compared to select the
395 most suitable one:

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

400 The Figure 4 illustrates the comparison. For the correlation method, after
401 calculation of the dimensionless coefficients, the convection mode varies over
402 time: it is mostly mixed during the night and forced during the day. The
403 free convection is not represented with the first formula whereas it is not
404 integrated in the MacAdams formula. The correlation method is closer to
405 the measured heat flux all over the comparison period.

406 The correlation method used to calculate the convective heat transfer co-
407 efficient (Section 3.1.2), is based on results obtained by Tain and Petit (1989,

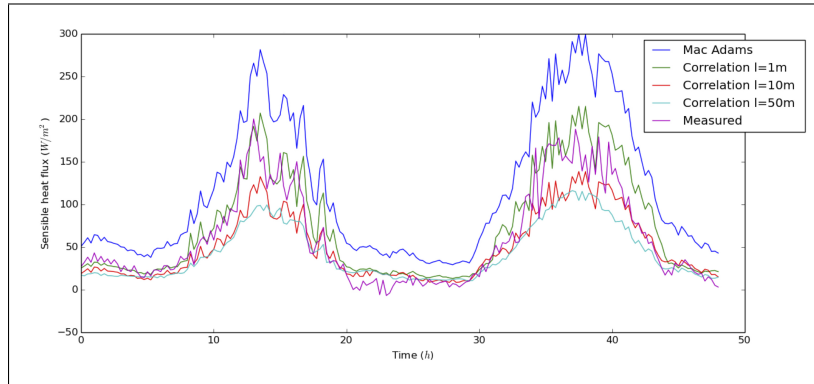


Figure 4: Comparison of sensible heat fluxes (*print in color*)

408 [29]) applied for an horizontal flat plate. In order to apply the similitude theory, a characteristic length should be set which is most of the time defined
 409 as the distance from the leading edge. Applied to our case, this characteristic length is difficult to define. The influence of several lengths (1, 10 and
 410 50 m) is tested (Figure 4). Among the tree values tested, it appears that
 411 the 1m- characteristic length correlation method produces the lowest RMSE
 412 (24.27W/m²).
 413
 414

415 For each value, the correlation method remains better than the MacAdams
 416 method. As a result, for the following sub-sections, the correlation method
 417 is chosen with a characteristic length of 1m.

418 In order to see the influence of the characteristic length value on the
 419 sensible heat flux, the RMSE calculated with the 1m- characteristic length
 420 is compared to the daily mean sensible heat flux (61W/m²). The RMSE
 421 represents 40% of the mean experimental value.

422 According to those levels of magnitude, we realize the sensitivity study

423 varying the convective heat transfer coefficient up to 40% of its initial value.
 424 The aim is here to quantify the influence of this coefficient on the surface
 temperature. The results are presented on the Table 7.

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

Table 7: Influence of the convective heat transfer coefficient on the surface temperature (5th and 6th of june)

425

426 4.1.2. Sensitivity of the layer definition

427 Modification of soil thermal conductivity, soil density and the thickness
 428 of the layers is performed one by one for each layer. The magnitude of the
 429 modifications and the layers concerned by the modification are described in
 430 the Table 8. The surface temperature modification caused by each material
 431 property change is also presented in this Table.

432 The height of each soil layer is not constant over the depth. Each height
 433 is then roughly estimated. To evaluate this lack of accuracy, the influence of
 434 the biggest layers (1 and 2) is investigated (Table 8).

435 The temperature change associated to layer size modification has the
 436 same magnitude as the one associated to soil property modification of the
 437 layers 0 and 3. However, it is negligible compared to temperature change
 438 associated to soil property modification of the layers 1 and 2.

Parameter	Modified layer	Maximum difference at the surface ($^{\circ}C$)
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 8: Influence of the soil characteristics (5th and 6th of june)

439 *4.1.3. Deep boundary condition*

440 The temperature imposed as deep boundary condition can have an influ-
441 ence on the surface temperature. If the deep temperature is overestimated
442 by one degree, the difference on surface temperature is only of $0.05^{\circ}C$.

443 Finally, the convective heat transfer coefficient is the most influent pa-
444 rameter , followed by the material characteristics, the layer size and the deep
445 boundary condition.

446 4.2. Model ability to reproduce heat conduction transfer: Validation

447 The ability of the model to well reproduce the physical phenomenon is
448 evaluated in this part. In order to quantify the uncertainty due to the model
449 itself (i.e. the accuracy of the physical phenomenon representation), the
450 model is first evaluated comparing temperature estimation to experimental
451 data. As it was noticed in Section 3.3, the evaluation of a soil model per-
452 formance only based on surface temperature comparison is one of the lack
453 identified in the literature. In this study, the comparison of the results is
454 realized on the basis of the temperature at the surface and at several depths
455 in the soil.

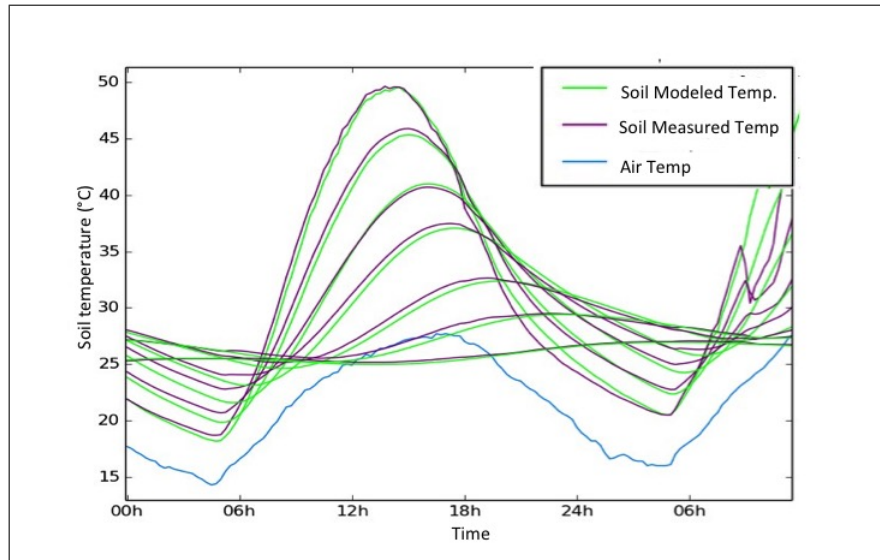


Figure 5: Comparison of simulated and measured temperatures at the surface and at several depths (*print in color*)

456 The model is evaluated during the 5th and the 6th of June. The model
457 reproduces correctly the heat flux conducted into the different layers of the

458 soil as shown in the Figure 5. The maximum difference between the measured
 459 and simulated temperature at the surface is $1.91^{\circ}C$ and the RMSE $0.75^{\circ}C$.

460 To quantify the accuracy of the model to reproduce the temperature vari-
 461 ation at several depths, Qin (2002, [21]) divide the RMSE per the amplitude
 462 of the signal. In fact as the amplitude decreases, the relative error increased.
 463 To avoid this bias, the standard deviation of the experimental data is used
 464 instead of the amplitude. This is a more robust indicator against outliers
 465 (Table 9). Going deeper in the ground the amplitude decreased with the
 466 RMSE but in proportion this error is increasing. In fact, at the surface, the
 467 RMSE only represents 8% of the signal standard deviation when at a depth
 468 of 34 cm and 50cm it represents respectively 16% and 12%. The error stays
 469 under the uncertainty of the temperature measurement.

Depth	Maximum absolute error ($^{\circ}C$)	RMSE ($^{\circ}C$)	RMSE/standard deviation
Surface	1.61	0.75	0.08
5 cm	1.42	0.73	0.09
10 cm	0.83	0.48	0.09
34 cm	0.52	0.21	0.16
50 cm	0.13	0.06	0.12

Table 9: Evaluation of the ideal model according to the experimental data (5th and 6th of june)

470 *4.3. Influence of the nodes distribution*

471 The ability of the model to reproduce the physical phenomenon (ideal
 472 model compared to the experimental data) is compared to the accuracy loss
 473 due to the reduction of the number of nodes. Table 10 presents the total
 474 error due to the model and the nodes distribution (first line) and the part of
 475 the error which is due to the nodes reduction (2nd line).

Model	1pt/cm	8/10/4	4/6/2	4/3/2
Root mean square error with ex- perimental data ($^{\circ}C$)	0.75	1.12	1.23	1.56
Root mean square error with ideal model ($^{\circ}C$)	-	0.28	0.75	1.36

Table 10: Evaluation of the model with reduced numbers of points (5^{th} and 6^{th} of june)

476 For the 8/10/4 points model, the reduction of the number of points has a
 477 negligible influence compared to the uncertainty of the temperature measure-
 478 ment. Even if the total error of this model with experimental data ($1.12^{\circ}C$)
 479 increases, this justifies that a higher number of points could not be so rele-
 480 vant since the uncertainty do not permits to say if the model precision would
 481 be higher or not. In all cases, number of nodes is not the main cause of the
 482 error.

483 For the 4/6/2 points model, the RMSE is the same if the model is com-
 484 pared with the experimental data or with the ideal model. This means that
 485 the reduction of the model remains acceptable.

486 Finally for the 4/3/2 model, the accuracy loss due to the reduction of the
487 number of nodes becomes dominant.

488 For all models, non-cumulative errors are observed. For instance, the
489 4/3/2 model accuracy (1.56°C) remains lower than the loss of accuracy due
490 to the node number reduction (1.36°C) added to the error between measure-
491 ments and the ideal model (0.75°C).

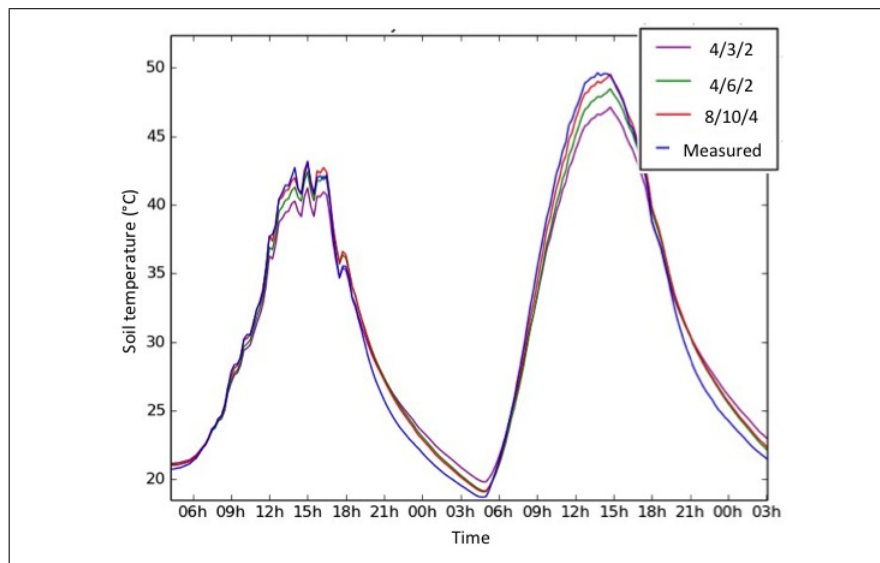


Figure 6: Surface temperature calculated with the different numbers of nodes compared to measured one. (*print in color*)

492 Figure 6 compares the surface temperature evolution of the different mod-
493 els with the measured one. Firstly, all the models represent well the time
494 evolution of the surface temperature. Nevertheless, the daily maximum and
495 minimum peak are underestimated. This is due to the nodes number re-
496 duction that leads to worsen the representation of the heat transfer into the

497 floor. In fact, this induces a time shift of the heat conduction whose the main
498 influence of which appears when its sign changes.

499 Finally, the lower number of points for the model, the higher the under-
500 estimation of the daily maximum and minimum peak. Indeed the reduction
501 of the number of points has consequences on the reproduction of the daily
502 peaks. As a conclusion, this confirms that the correct representation of the
503 surface temperature requires to correctly represent heat flux transfer into the
504 soil.

505 **5. Discussion**

506 This part is devoted to discuss the overall accuracy of the model. The
507 results are firstly compared to those presented in the literature. Then the
508 accuracy of the model according to meteorological data is evaluated with an
509 annual simulation.

510 *5.1. Comparison with other model accuracy*

511 The performance of the models presented above may be compared to the
512 performance of others models. Among literature the results of the following
513 authors are chosen: Yang et al. (2013 [5]), Herb et al. (2008 [12]), Best
514 (1998 [8]) , Malys, (2012 [30, 24]). Note that Malys, (2015, [30, 24]) applied
515 the model proposed by Bouyer (2009, [4]). Those models are chosen because
516 their simulation conditions (weather conditions, nodal distribution, type of
517 ground surface, indicator calculated for performance evaluation) are the clos-
518 est to those of the present study. Conditions of simulation and results are
519 summarized in Table 11.

520 Three of the four articles ([5, 8, 12]) have in common the type of surface
521 studied and a gradual distribution of nodes: thinner at the surface than
522 bellow. The last one, Malys (2012, [30, 24]) evaluated SOLENE-microclimat
523 previous soil model with a grass surface and a nodal distribution of only 4
524 nodes.

525 Simulations are run during summer period for clear and hot days. Indeed
526 the surface temperature rise from $41^{\circ}C$ to $70^{\circ}C$, except for Best (1998, [8]),
527 who worked with lower temperature.

528 According to the results presented in Table 11, the ideal model is more
529 accurate than the four other models from the literature. This is a logical
530 result as this ideal model use an high number of nodes.

531 Best model (1998, [8]) accuracy ($1.2^{\circ}C$) is similar to the 8/10/4 points
532 model. Nevertheless, as it is applied for winter conditions, the solicitations
533 are softer (amplitude of $18^{\circ}C$) than the ones of this study.

534 Using a 15 nodes model, Herb et al. (2008 [12]) obtained lower perfor-
535 mances ($1.58^{\circ}C$) than the 8/10/4 points model ($1.12^{\circ}C$) and the 4/6/2 points
536 model ($1.23^{\circ}C$) but similar performances than the 4/3/2 model ($1.56^{\circ}C$).
537 The application conditions being similar, it can be affirmed that our model
538 is at least as accurate model as Herb et al. (2008 [12]) model but with a
539 more optimized discretization. The difference of performance can mainly be
540 explained by a thinner discretization near the surface.

Article	Surface type	Meteorological conditions	Maximum surface temperature C	Amplitude	Numerical discretization	RMSE °C
Best (1998, [8])	Asphalt	Winter conditions	-	-	20 nodes	1.08
	Concrete		12	18		1.2
Herb and al. (2008, [12])	Asphalt	Hot and Dry (July)	55	30	15 nodes	1.58
Malys (2012, [30])	Grass	Hot and Dry (May)	41	19	4 nodes	2.3
	Tiles, concrete,					
Yang and al. (2013, [5])	asphalt, paved,	Hot and Dry (August)	70	40	14 nodes	1.98
	grass					
Presented here	Asphalt	Heat wave conditions	50	30	100 nodes	0.75
					8/10/4	1.12
					4/6/2	1.23
					4/3/2	1.56

Table 11: Comparison with the other models: simulation conditions

541 Yang et al. (2013, [5]) presented a 14 layers model with $1.98^{\circ}C$ accuracy
542 which is lower than all the models evaluated in this paper. Nevertheless, it
543 is applied to extremes conditions : maximum surface temperature can reach
544 $70^{\circ}C$ with a daily variation whose amplitude reaches $40^{\circ}C$.

545 Our 8/10/4 points model has the same accuracy than Best model (1998,
546 [8]) but under disadvantageous conditions : surface temperature amplitude
547 is much higher in the present study ($31^{\circ}C$) than the one used by Best (1998,
548 [8]) ($18^{\circ}C$). For similar surface temperature amplitude (respectively $< 30^{\circ}C$
549 and $40^{\circ}C$), Herb et al. (2008 [12]) and Yang et al. (2013, [5]) obtained a
550 RMSE of $1.58^{\circ}C$ and $1.98^{\circ}C$.

551 The model presented by Malys (2012, [30]) has only four nodes whereas
552 the other models have more than 14 nodes. Consequently, it is the least ac-
553 curate one even if the model is applied with fair solicitations : low amplitude
554 of the surface temperature variation ($19^{\circ}C$) and low maximum temperature
555 ($41^{\circ}C$) . Using a higher number of nodes with good distribution seems to
556 be essential to obtain good performances. However, caution should be taken
557 with this result since Malys (2012, [30]) does not use the same ground surface
558 type than the other authors.

559 Two of the authors highlight that the high amplitude of surface tem-
560 perature recorded during the day is harder to represent than the surface
561 temperature during the night. Yang et al.(2013, [5]) described the fact that
562 the model fits well with the measurement at night time and in the morning,
563 but when the temperature rises during the afternoon, the model underesti-
564 mates the temperature with an average of $3.5^{\circ}C$. Best (1998, [8]) also has

565 best results during the night (RMSE $0.83^{\circ}C$) than during the day (RMSE
566 $1.26^{\circ}C$). This analysis is consistent with the assumption made previously:
567 clear and hot days, characterized by high surface temperature amplitude, are
568 the most difficult days to simulate.

569 In general, one needs to be careful considering the results of this compar-
570 ison for several other reasons :

- 571 • surface temperature used as the reference temperature for each study
572 comes from surface temperature measurement. Uncertainty on such
573 measurement might be the same magnitude than the RMSE observed,
574 which makes comparison between models difficult.
- 575 • The comparison of the models performance is given for study in similar
576 conditions. Nevertheless they cannot be exactly the same. Localization
577 is not the same, weather conditions differ, surface type or at least soil
578 composition is not exactly the same.

579 If we concluded that the models proposed in this paper seem to present a
580 better performance than those of the literature, the difference must be put
581 into perspective with application conditions. All those models should be
582 applied to a single case study.

583 *5.2. Performance according to meteorological data*

584 The accuracy of a nodes distribution according to meteorological data
585 is evaluated comparing numerical profile of an annual simulation (hourly
586 time step) for each nodes distribution (8/10/4, 4/6/2, 4/3/2). For those

587 simulations, meteorological data recorded during one year (2010) at the Pin
 588 Sec station of the city of Nantes are used. Those data were collected by the
 589 ONEVU (Observatoire Nantais des EnVironnements Urbains) : observatory
 590 of the urban environment of theIRSTV (Mestayer et al. 2011 [31]). Among
 591 the available observations, the following data are used as input in the model:
 592 air temperature, pressure and humidity; global and IR radiative flux; wind
 593 velocity and direction.

	8/10/4	4/6/2	4/3/2
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 ideal model over a year ($^{\circ}C$)	0,58	1,35	2,18
Yearly mean absolute difference with the ideal model ($^{\circ}C$)	0,1	0,2	0,33

Table 12: Distribution of the points and precision

594 Table 12 presents the results of the comparison between the surface tem-
 595 perature model for each of the nodes distribution compared to the ideal

596 model. In the case of the 8/10/4 points model, the maximum absolute dif-
 597 ference is $0.58^{\circ}C$ and for the 4/3/2 points model $2.18^{\circ}C$. The mean absolute
 598 difference for the first node distribution is only $0.1^{\circ}C$ whereas the one of the
 599 4/3/2 distribution is $0.33^{\circ}C$, which remains in the order of magnitude of the
 600 measurement uncertainty.

601 For each case, the appearing frequency of the mean daily error between
 602 the ideal and the reduced model is calculated. Every day is classified in a
 603 different class of performance to illustrate the differences between the nodes
 604 distributions (Table 13).

Mean daily error	Low : $E < 0.2$	Medium: $0.2 < E < 0.5$	High $E > 0.5$
8/10/4	363	2	0
4/6/2	212	150	3
4/3/2	82	224	59

Table 13: Number of days for which each class of error occurs.(error calculated compared the ideal model)

605 The 8/10/4 points model does not have any day having a mean error
 606 higher than $0.5^{\circ}C$ and has only two days with a mean error higher than
 607 $0.2^{\circ}C$. The 4/6/2 points model has almost as many days represented with a
 608 high or a medium performance. Finally most of the days represented by the
 609 4/3/2 points model have medium performance. More detailed investigation
 610 of the days with high mean daily error shows that these days were clear
 611 and sunny ones. This confirms the fact that clear day are more difficult to
 612 simulate than cloudy days.

613 **6. Conclusion**

614 The main purpose of this study is to propose a model that well repro-
615 duces the heat storage flux into urban ground as well as surface temperature
616 evolution.

617 Some lacks were identified in the literature review pointing up the need:

- 618 • to perform overall sensitivity analysis,
- 619 • to investigate the interest of using different convection flow modes
620 (forced, mixed, natural)
- 621 • to justify the choice of nodal distribution,
- 622 • to assess models not only for surface temperature calculation.

623 To test the robustness of our model regarding its parameters, a complete
624 sensitivity study was achieved on the model parameters: all have a negligible
625 impact except the convective heat transfer coefficient.

626 Special attention has been paid to the way to calculate the convective
627 heat transfer coefficient. The chosen method permits to take into account
628 the different kind of convection flow modes which is necessary for urban
629 application. Nevertheless, the sensible heat flux can vary of 40%, leading to
630 an uncertainty up to $3.14^{\circ}C$ on the surface temperature RMSE.

631 After the calibration of the different parameters, the soil model (using an
632 "ideal" node distribution - 1 node/cm) accuracy is evaluated according to a
633 measurement campaign that is realized on a large asphalt parking lot during

634 two clear and sunny days. The RMSE between estimated and observed
635 temperature is calculated for surface temperature and ground temperature at
636 several depths. Surface temperature RMSE is $0.75^{\circ}C$, RMSE for temperature
637 at 34cm of depth is $0.21^{\circ}C$. The results validate the ability of the model to
638 well reproduce the heat storage into the ground.

639 Three nodes distributions are proposed on the base of the analyze of the
640 different temperature profiles along the depth. They all are dedicated to
641 any kind of urban impervious surfaces. However, for less diffusive soils, the
642 user is free to define other distributions in order to adapt the model to his
643 application. The accuracy of the models varies from $1.12^{\circ}C$ to $1.56^{\circ}C$. These
644 performances are better than those of models from the literature applied
645 under quite similar conditions.

646 Finally, the application of the models all over a year shows that only few
647 days are represented with an accuracy worse than $0.5^{\circ}C$. Most of the days
648 are even reproduced with an accuracy better than $0.2^{\circ}C$. The investigation
649 demonstrates that the surface temperature during clear and sunny days are
650 the most difficult to reproduce.

651 This paper provides a complete overview of a soil model performance,
652 comparing it with experimental data, ideal model and literature results. Be-
653 cause of the measurement uncertainty, better performances would be difficult
654 to obtain and especially to assess. Nevertheless, the comparison of the model
655 performances with results from literature would require a benchmark. The
656 presented model, now validated is now ready to include the moisture trans-
657 fers and in particular the evaporation of water at the soil surface so that to

658 help to assess properly the effect on local climate and outdoor comfort of
659 moistening techniques.

660 **Acknowledgements**

661 This research work was carried out within the scope of the EVA Project,
662 funded by the ADEME (French Environment and Energy Management Agency)
663 under Contract No. 1216C0037. The authors are grateful to the ADEME and
664 Véolia for their financial support of this study, as well as to the IFSTTAR,
665 the LHEEA and the ONEVU for providing us the experimental data.

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