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

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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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**Contents**

## 1. Introduction

In global warming circumstances, the development of cities requires to be carried out considering the urban heat islands (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 its mitigation solutions. Measurements campaigns are useful to evaluate the UHI but then, linking it to the influence of urban form modifications or urban planning choices is quite tricky.

For that 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 to the city scale applications while models like SOLENE-microclimat [4], Envi-met [5] and EnviBatE [6] are dedicated to the district scale. For a same scale, each tool may have one specific feature among many others : EnviBatE [6] is designed to study the energy demand of a buildings group, SOLENE-microclimat [4] focuses on outdoor comfort and on the impact of urban climate on indoor comfort, and ENVImet [5] is dedicated to outdoor comfort.

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

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

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

tion.

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

The results of the study are divided in three parts :

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

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

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

## 2. State of the art

### *2.1. Existing models*

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

- Geothermal energy applications,

- Road applications: pavement sustainability or frost forecasts,
- Hydrology and interaction between soil, vegetation and atmosphere.

Those other domains have the advantage of proposing a different point of view on the way to model heat transfer in the ground. In the Table 1 the articles used for the following bibliographic review are gathered with the 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 | | | x |
| Best (1998, [8]) | | x | | | x | | x | x | x | x | |
| Best and al. (2005, [9]) | | x | | | x | | | x | | x | |
| Bouyer (2009, [4]) | | | | x | x | | x | x | x | | x |
| Chow and al. (2011, [10]) | x | | | | x | | | | x | irrelevant | |
| Diefenderfer and al. (2006, [11]) | | x | | | | x | x | | | irrelevant | |
| Gros et al. (2015, [6]) | | | | x | | x | x | | | | x |
| Herb et al. (2008, [12]) | | | x | | x | | x | x | x | | x |
| Hermansson (2004, [13]) | | x | | | | x | x | | | | x |
| Ho (1987, [14]) | | | x | | | x | x | x | | x | |
| Jacovides (1996, [15]) | x | | | | x | | | x | x | x | |
| Lin (1980, [16]) | | | x | | x | | | x | | x | |
| Masson (2000, [2]) | | | | x | | x | x | | | | x |
| Milhalakakou and al. (1997, [17]) | x | | | | x | | | x | x | x | |
| Milhalakakou and al. (2002, [18]) | x | | | | 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 |
| Swaid and Hoffman (1989, [23]) | | | x | | | x | x | | | | x |
| Yang and al. (2013, [5]) | | | | x | 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

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

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

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

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

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

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

### *2.2. Parametrization of finite differences models*

For a same problem-solving method, different choices can be made regarding the nodes distribution (discretization), the boundaries and the initial 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 | | 2.5m | | EV |
| Best (1998, [8]) | | x | x | | 1.15m | | Exponential profile |
| Best and al. (2005, [9]) | | 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, [12]) | | x | x | x | | 10m | NI |
| Hermansson (2004, [13]) | | x | x | x | 5m | | NI |
| Ho (1987, [14]) | | x | | x | x | | Linear or exponential profile |
| Masson (2000, [2]) | | 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].

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

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

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

and the wind velocity are balanced by coefficients.

**Initial conditions**

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

## 3. Methodology of the study

### *3.1. Proposed soil model*

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

$$\frac{\delta T}{\delta t} = \alpha_{soil} . \frac{\delta^2 T}{\delta t^2} \tag{1}$$

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

The problem is solved by a finite differences method using a nodal discretization and an electrical analogy. Heat resistances represent the resistance to heat transfer through a ground layer and heat capacities, the heat storage capacity of a ground layer. They are defined on Figure 1.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

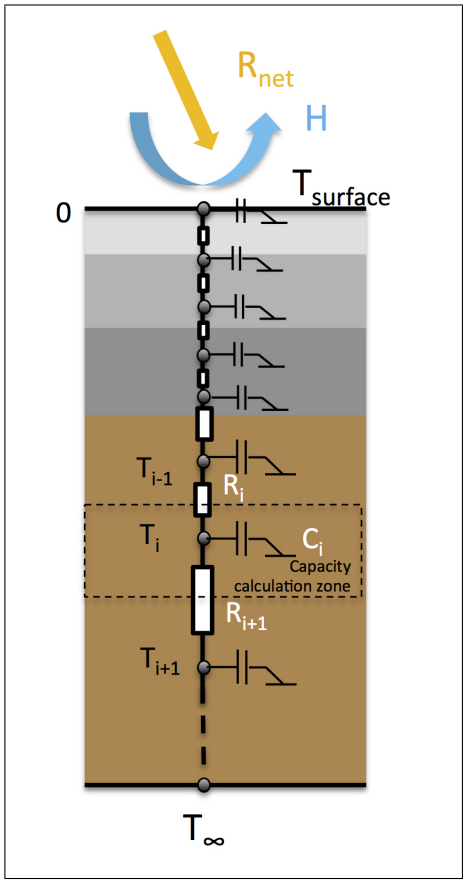


Figure 1: Soil model

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

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

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

two layers.

### *3.1.1. Deep boundary condition*

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

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

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

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

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

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

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

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

From a certain depth, the daily signal is completely damped. The damping depth depends on the soil characteristics through the parameter $z_{da}$,

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

$$z_{da} = \sqrt{\frac{2.\alpha_{sol}}{w_a}} \tag{6}$$

$$A(z) = A_j . \exp(\frac{-z}{z_{da}}) \tag{7}$$

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

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

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

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

$$R_{net} = Q_{cond} + H + LE \tag{8}$$

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

**Radiative flux**

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

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

**Convective heat flux**

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

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

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

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

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

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

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

$$h_c = a + b * V_{air} \tag{10}$$

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

| **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

Methods based on correlations that use dimensionless numbers (Reynolds, Grashof, and Nusselt) also exist. For flat surfaces Morille (2012, [28]) presents 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

$$h_c = e(aRe^b + cGr^d) \tag{11}$$

$$Nu = \frac{h_c.L_c}{\lambda_{fluid}} \tag{12}$$

$Re$: Reynolds number

$Gr$: Grashof number

$Nu$: Nusselt number

$L_c$ : characteristic length $[m]$

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

This type of correlation allows to define a convective heat transfer coefficient as a function of the flow modes:

- Natural or free convection: air flow driven by buoyancy forces,
- Forced convection: air flow driven by wind forces,
- Mixed convection: when the air flow is created by both wind and buoyancy forces.

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

### *3.2. Presentation of the measurement campaign*

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

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

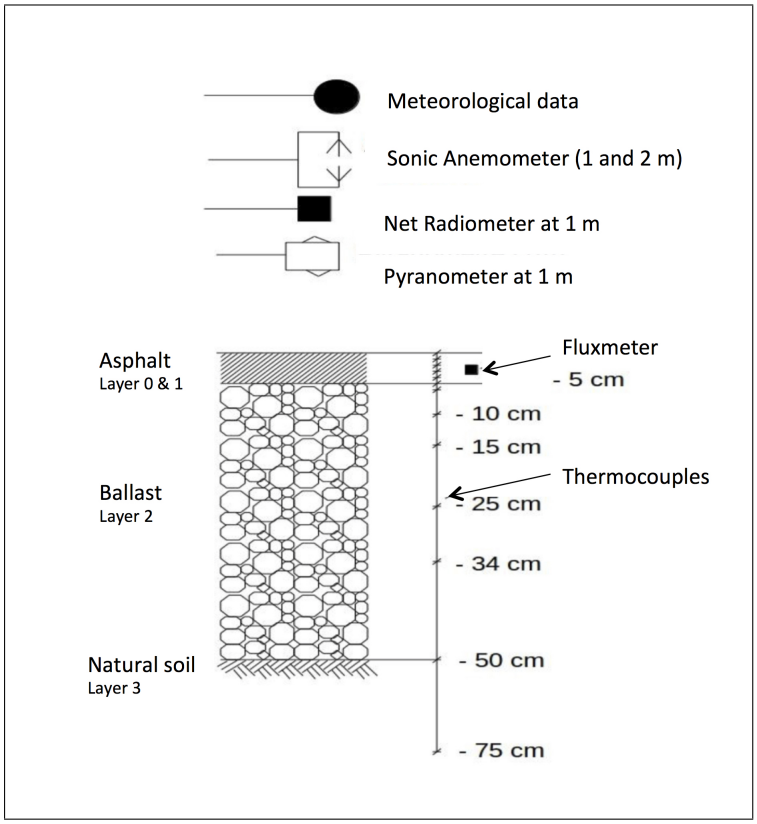


Figure 2: Drawing of the measurement campaign

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

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

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

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

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

### *3.3. Model performance assessment*

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

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

### *3.4. Calibration of the materials' properties*

As seen before, the thermal characteristics of the soil are often unknown and must be adjusted to well represent fluxes and temperatures variations. The characteristics of the soil layers are calibrated according to the observed soil profile, reducing the difference between the measured and simulated surface temperature. Data acquired on the $6^{th}$ of June are used for calibration.

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

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

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

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

### *3.5. Methodology of nodes distribution definition*

Optimization of the nodes distribution is one of the major modeling challenge. The principle consists in reducing the number of nodes up to a situation 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

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

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

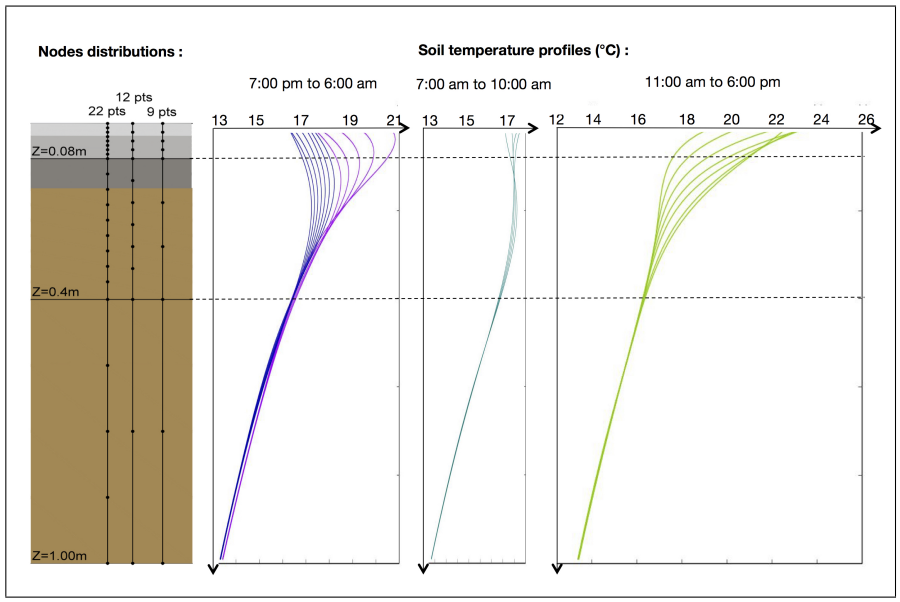


Figure 3: 3 nodes distributions proposal

## 4. Results

### *4.1. Sensitivity study*

Some assumptions made for the model parametrization can affect the surface temperature calculation. Some authors realized a sensitivity study on the surface and material parameters, on the convective heat transfer coefficient or on the grid size. However, none of those studies has compared the relative influence of all the affecting parameters. In the following section, a

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

*4.1.1. Convective heat transfer coefficient*

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

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

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

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

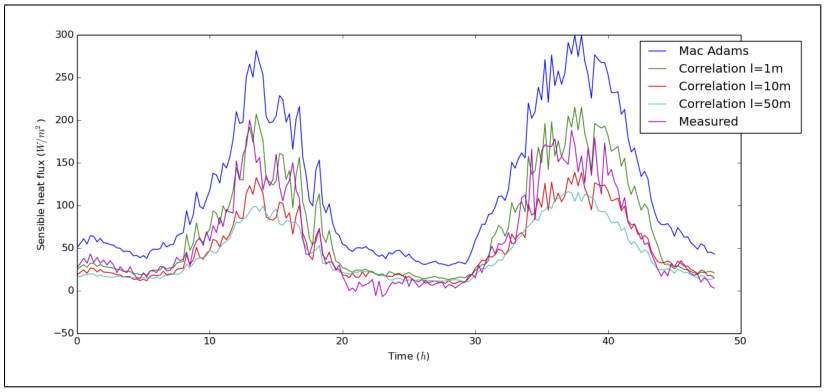


Figure 4: Comparison of sensible heat fluxes *(print in color)*

[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 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 50 m) is tested (Figure 4). Among the tree values tested, it appears that the 1m- characteristic length correlation method produces the lowest RMSE ($24.27W/m2$ ).

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

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

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

varying the convective heat transfer coefficient up to 40% of its initial value. 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 ($5^{th}$ and $6^{th}$ of june)

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

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

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

The temperature change associated to layer size modification has the same magnitude as the one associated to soil property modification of the layers 0 and 3. However, it is negligible compared to temperature change 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 ($5^{th}$ and $6^{th}$ of june)

*4.1.3. Deep boundary condition*

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

Finally, the convective heat transfer coefficient is the most influent parameter , followed by the material characteristics, the layer size and the deep boundary condition.

### *4.2. Model ability to reproduce heat conduction transfer: Validation*

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

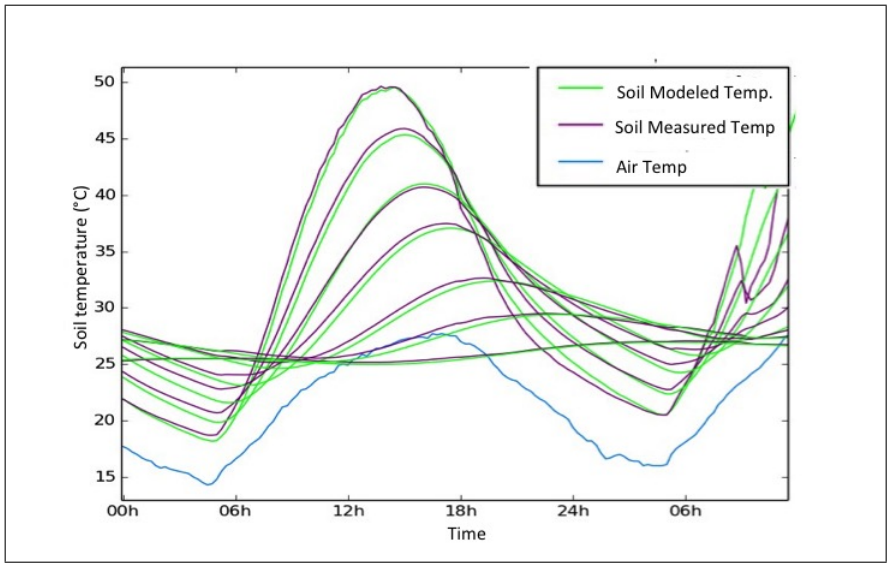


Figure 5: Comparison of simulated and measured temperatures at the surface and at several depths *(print in color)*

The model is evaluated during the $5^{th}$ and the $6^{th}$ of June. The model reproduces correctly the heat flux conduced into the different layers of the

soil as shown in the Figure 5. The maximum difference between the measured and simulated temperature at the surface is $1.91°C$ and the RMSE $0.75°C$.

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

| **Depth** | **Maximum absolute error** ($°C$) | **RMSE** ($°C$) | **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 ($5^{th}$ and $6^{th}$ of june)

### *4.3. Influence of the nodes distribution*

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

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

For the 4/6/2 points model, the RMSE is the same if the model is compared with the experimental data or with the ideal model. This means that the reduction of the model remains acceptable.

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

For all models, non-cumulative errors are observed. For instance, the 4/3/2 model accuracy (1.56 $^{\circ}C$) remains lower than the loss of accuracy due to the node number reduction (1.36$^{\circ}C$) added to the error between measurements and the ideal model (0.75$^{\circ}C$).

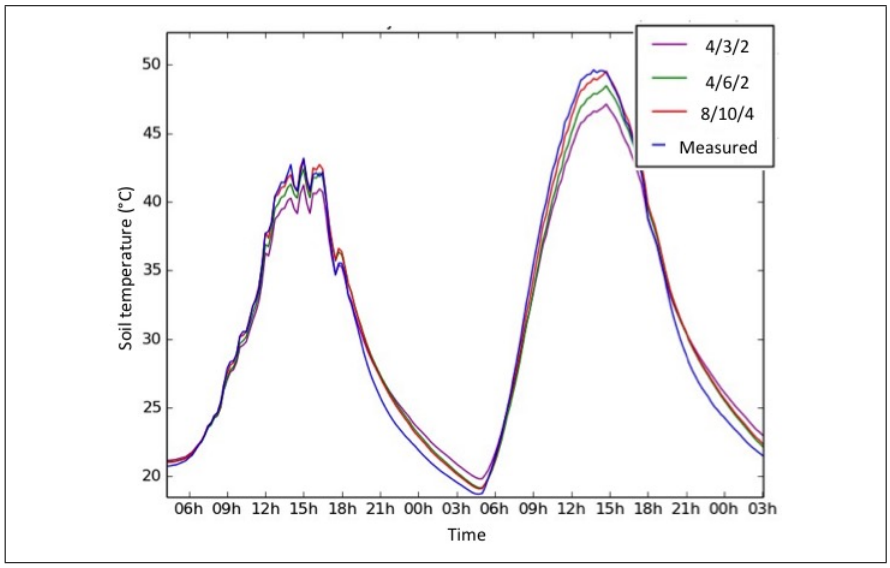


Figure 6: Surface temperature calculated with the different numbers of nodes compared to measured one.*(print in color)*

Figure 6 compares the surface temperature evolution of the different models with the measured one. Firstly, all the models represent well the time evolution of the surface temperature. Nevertheless, the daily maximum and minimum peak are underestimated. This is due to the nodes number reduction that leads to worsen the representation of the heat transfer into the

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

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

## 5. Discussion

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

### *5.1. Comparison with other model accuracy*

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

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

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

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

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

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

| **Article** | **Surface type** | **Meteorological conditions** | **Maximum surface temperature C** | **Amplitude** | **Numerical discretization** | **RMSE** $^{\circ}C$ |
|---|---|---|---|---|---|---|
| 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 |
| Yang and al. (2013, [5]) | Tiles, concrete, asphalt, paved, grass | Hot and Dry (August) | 70 | 40 | 14 nodes | 1.98 |
| 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

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

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

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

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

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

In general, one needs to be careful considering the results of this comparison for several other reasons :

- surface temperature used as the reference temperature for each study comes from surface temperature measurement. Uncertainty on such measurement might be the same magnitude than the RMSE observed, which makes comparison between models difficult.

- The comparison of the models performance is given for study in similar conditions. Nevertheless they cannot be exactly the same. Localization is not the same, weather conditions differ, surface type or at least soil composition is not exactly the same.

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

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

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

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

Table 12 presents the results of the comparison between the surface temperature model for each of the nodes distribution compared to the ideal

model. In the case of the 8/10/4 points model, the maximum absolute difference is $0.58°C$ and for the 4/3/2 points model $2.18°C$. The mean absolute difference for the first node distribution is only $0.1°C$ whereas the one of the 4/3/2 distribution is $0.33°C$, which remains in the order of magnitude of the measurement uncertainty.

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

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

## 6. Conclusion

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.

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

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

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

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

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

two clear and sunny days. The RMSE between estimated and observed temperature is calculated for surface temperature and ground temperature at several depths. Surface temperature RMSE is $0.75°C$, RMSE for temperature at 34cm of depth is $0.21°C$. The results validate the ability of the model to well reproduce the heat storage into the ground.

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

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

This paper provides a complete overview of a soil model performance, comparing it with experimental data, ideal model and literature results. Because of the measurement uncertainty, better performances would be difficult to obtain and especially to assess. Nevertheless, the comparison of the model performances with results from literature would require a benchmark. The presented model, now validated is now ready to include the moisture transfers and in particular the evaporation of water at the soil surface so that to

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

## Acknowledgements

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