Résolution fine des transferts thermiques couplés par Monte-Carlo en géométrie urbaine incluant les flux solaires directs et diffus

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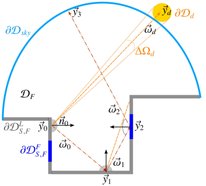
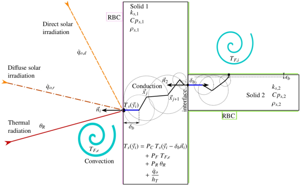
Overview

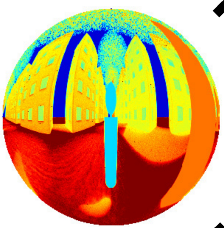


Solar irradiations probabilistic modelling

Probabilized thermal model

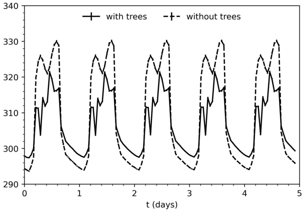


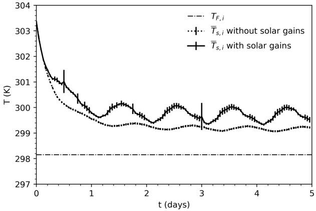
Monte Carlo computation of thermal environment



including transient weather data and thermal response of urban fabric

Mean radiant temperature





Internal building wall temperature

Content

Introduction

- Objective: To build a **reference thermal model** that can handle large and complex **urban geometry**

- Scientific questions:
  - including city geometry in **weather and climate services** (ANR MC2),
  - **influence of geometry**: detailed vs. simplified (e.g., 3D vs. 1D; homogenization; etc.),
  - numerical **validation** of the models or meshes in use,
  - better **understanding** of coupled mechanisms through sensitivity studies.

- Steps: To use **probabilistic** models with random walks for
  - thermal **conduction** (random walk-on-sphere, WOS),
  - **solar** and **infrared radiation** (multiple reflection ray-tracing).
  - Convection is accounted for with known h_F and T_F.

Introduction

- Temperature-derived **observables**:
  - **probe** computation (0, 1, 2, 3D), (e.g., thermocouples)
  - radiance temperature **rendering** (e.g., thermography),
  - parametric **sensitivities** (linear or non-linear, Symbolic MC).
- **Geometry**: triangulated surface from each volume, with their connections (conformal mesh)
- **Free software**: addition of solar irradiations in **stardis** (Méso-Star) funded by ANR MC2 project.

More details in the article *Caliot et al., 2024, International Journal of Heat and Mass Transfer*

Probabilistic model: conduction in solids (opaque)

$$
\begin{cases}
\frac{\partial}{\partial t} T_s(\vec{x},t) = \alpha \, \Delta T_s(\vec{x},t), & \vec{x} \in \mathcal{D}_S \;, \; t > \tau_I, \quad (1a) \\
T_s(\vec{x},t) = T_I, & \vec{x} \in \mathcal{D}_S \cup \partial\mathcal{D}_S, \; t \leqslant \tau_I, \quad (1b) \\
T_s(\vec{y},t) = T_D(\vec{y},t), & \vec{y} \in \partial\mathcal{D}_{S,D}, \; t > \tau_I, \quad (1c) \\
k_{s,1} \; \nabla T_s(\vec{y},t) \cdot \vec{n}_1 = k_{s,2} \; \nabla T_s(\vec{y},t) \cdot \vec{n}_2, & \vec{y} \in \partial\mathcal{D}_{S,S}, \; t > \tau_I, \quad (1d) \\
k_s \; \nabla T_s(\vec{y},t) \cdot \vec{n} = \dot{q}_F(\vec{y},t) + \dot{q}_R(\vec{y},t) + \dot{q}_o(\vec{y},t), & \vec{y} \in \partial\mathcal{D}_{S,F}, \; t > \tau_I, \quad (1e)
\end{cases}
$$

$$
\begin{aligned}
\dot{q}_F(\vec{y},t) &= h_F(\vec{y},t) \, [T_F(\vec{y},t) - T_s(\vec{y},t)], && (2) \\
\dot{q}_R(\vec{y},t) &= h_R(\vec{y}) \, [\theta_R(\vec{y},t) - T_s(\vec{y},t)], && (3) \\
\dot{q}_o(\vec{y},t) &= \int_0^{+\infty} d\lambda \int_{2\pi} d\Omega(\vec{\omega}) \; |\vec{\omega} \cdot \vec{n}| \; \varepsilon(\vec{y},\lambda) \; I_o(\vec{y},t,-\vec{\omega},\lambda). && (4)
\end{aligned}
$$

$$
T_s(\vec{y},t) = P_C \, T_s(\vec{y} - \delta_b \vec{n}, t) + P_F \, T_F(\vec{y},t) + \; P_R \, \theta_R(\vec{y},t) + \frac{\dot{q}_o(\vec{y},t)}{h_T}, \qquad (5)
$$

$$
P_C(\vec{y}_i,t) = \frac{k_s(\vec{y}_i,t)}{\delta_b \; h_T(\vec{y}_i,t)}, \qquad P_F(\vec{y}_i,t) = \frac{h_F(\vec{y}_i,t)}{h_T(\vec{y}_i,t)}, \qquad P_R(\vec{y}_i,t) = \frac{h_R(\vec{y}_i,t)}{h_T(\vec{y}_i,t)},
$$

$$
h_T(\vec{y},t) = \frac{k_s(\vec{y},t)}{\delta_b} + h_F(\vec{y},t) + h_R(\vec{y},t).
$$

Probabilistic model: coupling sub-paths at interfaces

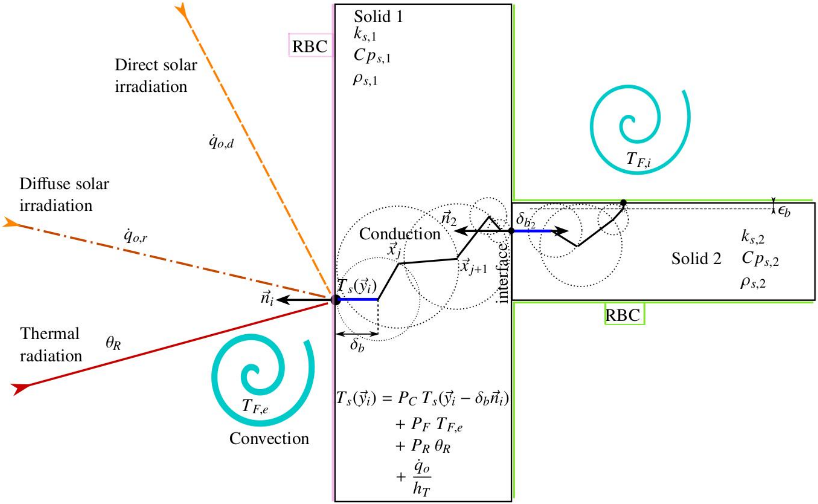
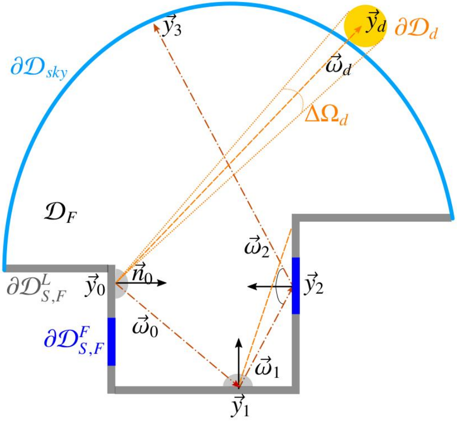


Figure: Representation of random paths starting at an outdoor wall with RBC to compute $T_s(\vec{y}_i)$

Probabilistic model: radiation (diffuse or specular surfaces)

$$\begin{cases} \vec{\omega}_i \cdot \nabla I(\vec{x}, \vec{\omega}_i, \lambda) = 0\,, & \vec{x} \in \mathcal{D}_F\,, \quad (6a) \\ I(\vec{y}_i, -\vec{\omega}_i, \lambda) = \varepsilon(\vec{y}_{i+1}, -\vec{\omega}_i, \lambda)\, I_b(\vec{y}_{i+1}, \lambda) + & \\ \qquad \displaystyle\int_{2\pi} d\Omega(\vec{\omega}_{i+1})\, \rho''(\vec{y}_{i+1}, -\vec{\omega}_i | -\vec{\omega}_{i+1}, \lambda) \times & \\ \qquad |\vec{\omega}_{i+1} \cdot \vec{n}_{i+1}|\, I(\vec{y}_{i+1}, -\vec{\omega}_{i+1}, \lambda)\,, & \vec{y} \in \partial\mathcal{D}_{S,F}\,. \quad (6b) \end{cases}$$



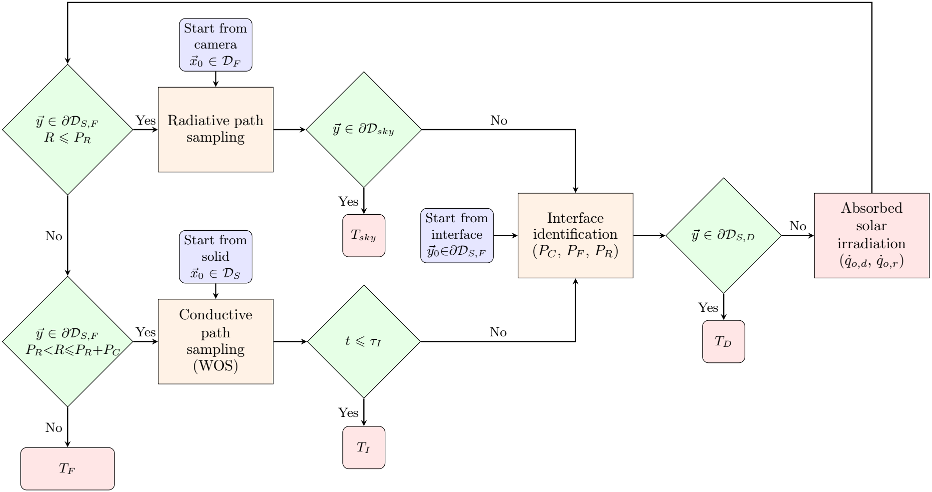
Probabilistic model: Monte Carlo

$$
\begin{aligned}
T_s(\vec{y}_0, t_0) \approx \tilde{T}_s(\vec{y}_0, t_0) &= \frac{1}{N} \sum_{k=1}^{N} W_k, \\
\tilde{\sigma}_{\tilde{T}_s} &= \frac{1}{\sqrt{N}} \sqrt{\frac{1}{N} \sum_{k=1}^{N} {W_k}^2 - \tilde{T}_s^2(\vec{y}_0, t_0)}.
\end{aligned}
$$

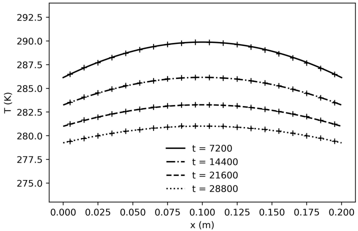
$$
\begin{aligned}
W_k(\vec{y}_0, t_0) = H(t_n \leqslant \tau_I)\, T_I \;+\; H(t_n > \tau_I) \Big\{ & H(\vec{y}_n \in \partial\mathcal{D}_{S,D})\, T_D(\vec{y}_n, t_n) + \\
& H(\vec{y}_n \in \partial\mathcal{D}_{S,F})\, T_F(\vec{y}_n, t_n) + H(\vec{y}_n \in \partial\mathcal{D}_{sky})\, T_{sky}(\vec{y}_n, \vec{\omega}_n, t_n) \Big\} + W_{o,k},
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
W_{o,k} = \frac{1}{h_T} \sum_{j=1}^{n_o} \Big\{ & W_{o,d}(\vec{y}_j) + \left(\sum_{m=1}^{n_{r,j}} H(\vec{y}_m \in \partial\mathcal{D}^L_{S,F})\, W^L_{o,r,d}(\vec{y}_m) \right) + \\
& W_{o,sky}(\vec{y}_{n_{r,j}+1}) + W^F_{o,r,d}(\vec{y}_{n_{r,j}+1}) \Big\}.
\end{aligned}
\tag{8}
$$

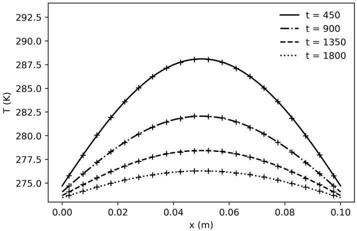
Probabilistic model: flowchart



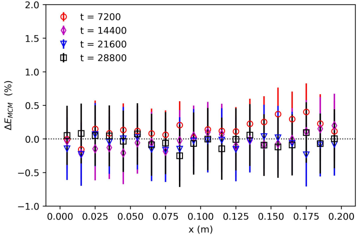
Numerical validation: 1D slab ($T_I = 293$ K, $T_F = 273$ K)



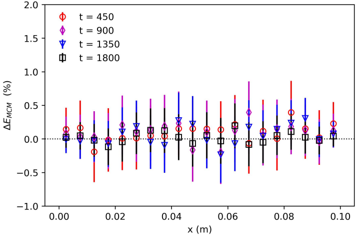
(a) Temperature profiles in concrete slab (Case 1)



(b) Temperature profiles in EPS slab (Case 1)

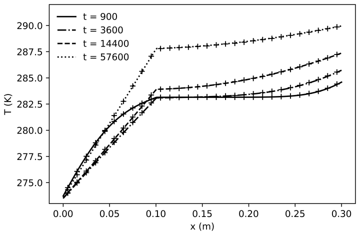


(c) Scaled differences with MCM

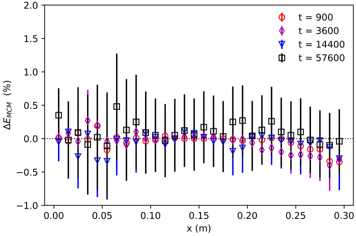


(d) Scaled differences with MCM

1D 2-layer slab ($T_I = 283$ K, $T_{F,i} = 273$ K, $T_{F,e} = 293$ K)

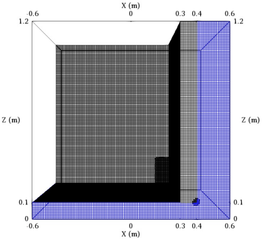


(a) Temperature profiles for Case 2

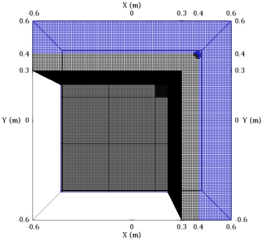


(b) Scaled differences with MCM confidence intervals for Case 2

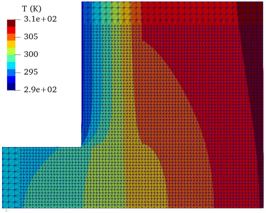
Numerical validation: 3D thermal bridge ($T_I = 293$ K, $T_{F,i} = 293$ K, $T_{F,e} = 313$ K)



(a) View in $+Y$ axis direction



(b) View in $-Z$ axis direction

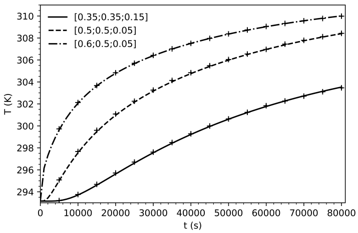


(c) Temperature field computed with OpenFoam ($-X$ axis view)

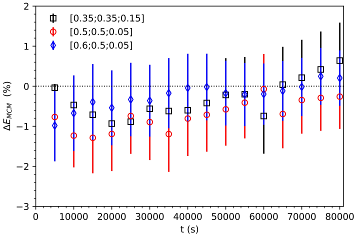
A comparison of T_s time evolution is drawn for three points:

- $[0.35; 0.35; 0.15]$ inside EPS,
- $[0.5; 0.5; 0.05]$ inside concrete, and
- $[0.6; 0.5; 0.05]$ outside concrete wall.

Numerical validation: 3D thermal bridge ($T_I = 293$ K, $T_{F,i} = 293$ K, $T_{F,e} = 313$ K)



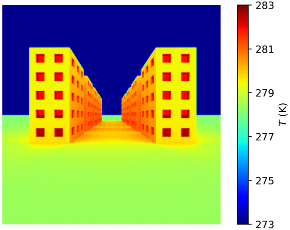
(a) Transient temperatures for three locations in Case 3



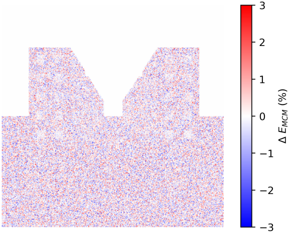
(b) Scaled differences with MCM confidence intervals for three locations in Case 3

Numerical validation: radiation in urban geometry ($T_s = 283$ K, $T_{sky} = 273$ K)

(a) HTRDR-Urban rendering (Case 4)

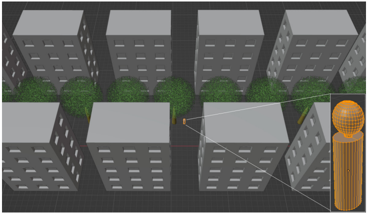


(b) Reference radiance temperature computed with HTRDR-Urban (Case 4)

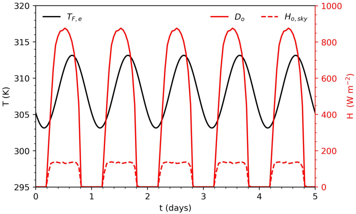


(c) Scaled differences between our code and HTRDR-Urban (Case 4)

Application to a heat wave scenario: conditions



(a) Building lines with trees and centred body surface (S_b)

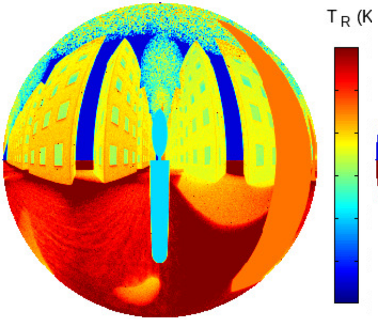


(b) Temporal evolution of air temperature and solar irradiations

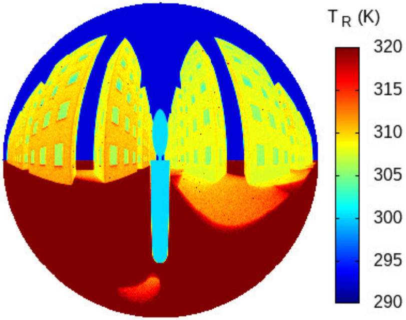
$$T_{F,e}(t) = 308.15 + 5\sin(2\,\pi\,[t - 0.4]), \tag{9}$$

	T_I	$T_{F,i}$	T_g	T_b	$T_{F,e}$	T_{sky}	
heat	305.211	298.15	283.15	300.15	Eq. 9	$T_{F,e} - 20$	
wave scenario	S_i (m^2)	S_b (m^2)	h_F (W m^{-2} K^{-1})	θ_d (rd)	N (-)	δ_b (mm)	ϵ_b (mm)
	33168	1.77	10	4.65×10^{-3}	10^5	2	0.5

Application to a heat wave scenario: observables



(a) Thermal environment accounting for trees



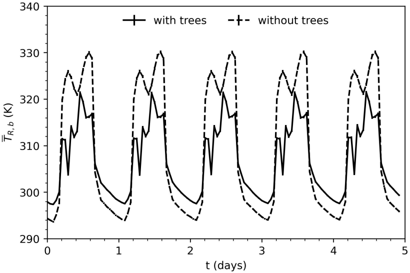
(b) Thermal environment without trees

$$\overline{T}_{R,b}(t) = \left[\frac{1}{\sigma_{SB}\, S_b} \int_{S_b} dA(\vec{y}_0)\; H_b(\vec{y}_0, t)\right]^{\frac{1}{4}}, \tag{10}$$

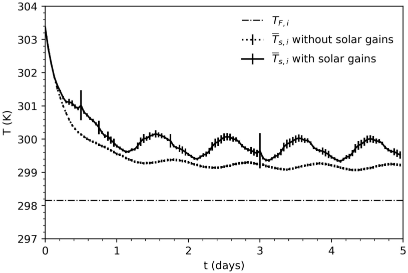
$$H_b(\vec{y}_0, t) = \int_0^{+\infty} d\lambda \int_{2\pi} d\Omega(\vec{\omega}_0)\; |\vec{\omega}_0 \cdot \vec{n}_0|\; I(\vec{y}_0, t, -\vec{\omega}_0, \lambda).$$

$$\overline{T}_{s,i}(t) = \frac{1}{S_i} \int_{S_i} dA(\vec{y}_0)\; T_s(\vec{y}_0, t), \tag{11}$$

Application to a heat wave scenario: $\overline{T}_{R,b}(t)$, $\overline{T}_{s,i}(t)$



(a) Temporal MRT on the body surface during the heat wave scenario



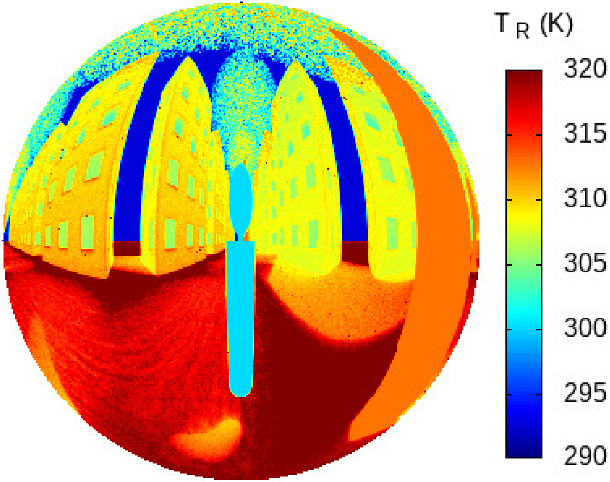
(b) Temporal average internal wall temperature during the heat wave scenario

Conclusion and future work

- Conclusion:
  - **Validation** of a probabilistic heat transfer model in urban geometry with solar irradiation
  - The approach manage complex **urban geometry** with trees
  - Specular surfaces introduce **variance** in MC estimates (increase N)

- Future work:
  - **Enrich** the model (Eq. for T_F, non-linear physics $\rightarrow$ ANR MCMET)
  - **Compare** with other approaches (codes) for validation and tests of assumptions (new contacts)
  - **Weather** services: two-way coupling with **CFD** ($\rightarrow$ ANR MC2)
  - **Climate** services: one-way coupling with **climate data** ($\rightarrow$ ANR MC2)
  - Apply to **inverse problems** in urban geometry (thermography, thermocouples, etc.)

Merci pour votre attention



Appendix

	T_I (K)	$T_{F,i}$ (K)	$T_{F,e}$ (K)	h_F (W m^{-2} K^{-1})	Δx (mm)	Δt (s)	N (-)	δ_b (mm)	ϵ_b (mm)
Case 1	293.15	273.15	273.15	10	1	0.72	10^5	Δx	$\delta_b/4$
Case 2	283.15	273.15	293.15	10	1	0.72	10^5	Δx	$\delta_b/4$
Case 3	293.15	293.15	313.15	10	10	2	10^5	$\Delta x/7$	$\delta_b/4$

		T (K)	P_ρ	$(n,\ k)$
Case 4	ground	283.15	0.5	–
	walls	283.15	0.5	–
	windows	283.15	–	$(1.7, 0.636)$
	sky	273.15	0	–

Appendix

Material	λ_s (W m^{-1} K^{-1})	ρ_s (kg m^{-3})	$C_{p,s}$ (J kg^{-1} K^{-1})	d (m)	P_{ρ_o} or (n, k)	P_{ρ_R} or (n, k)
concrete	1.8	2400	1000	0.4	0.8	0.2
EPS	0.035	20	1300	–	–	–
ground	1	1300	1900	10	0.5	0.2
glass	1	2500	900	0.005	$(1.52, 0)$	$(1.7, 0.636)$
body	–	–	–	–	0	0
tree	–	–	–	–	0.2	0