École des Ponts ParisTech
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Cerea
Centre d'Enseignement et de Recherche en Environnement Atmosphérique

eDF R&D

3D Modeling of urban environment taking into account the energy exchanges between the buildings and the atmosphere

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HARMO14, October 2011, Greece

Outline

1. Introduction

Context and objectives:

- Radiative scheme for mesoscale models are not suited for urban scale CFD studies (3D).
- Model the atmosphere in non neutral stratification in dispersion and risk assessment studies (take into account radiation budget in simulation of flow dynamics in built up areas).
- Develop radiative and thermal schemes adapted to 3D CFD modeling (Milliez 2006).
- Validation based on Mock Urban Setting Test (MUST) experiment (Qu et al. 2011a).
- Numerical study of the thermal effects of buildings on low-speed airflow (Qu et al. 2011b).
- Validation based on Canopy and Aerosol Particle Interactions in Toulouse Urban Layer (CAPITOUL) field campaign.

CFD model

- We perform the simulation with the 3D open-source CFD code *Code_Saturne* which can handle complex geometry and physics. (www.code-saturne.org)
- The atmospheric module takes into account the larger scale meteorological and the stratification of the atmosphere.
- k-є turbulence closure and a roughness wall law, taking into account stratification.

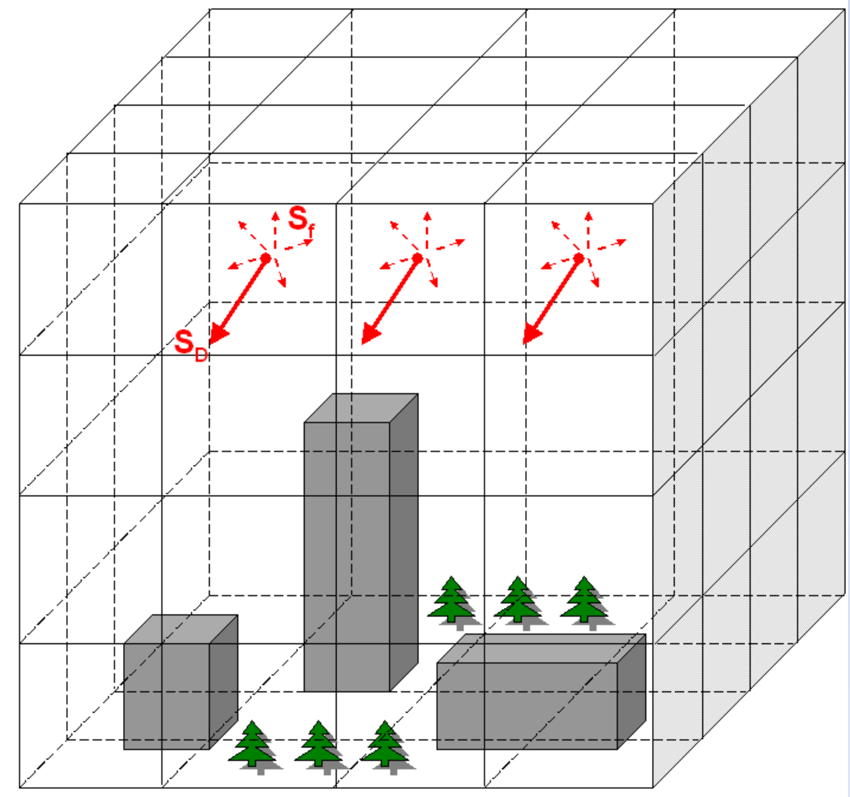
Local heat transfer coefficient : $$h_f = \frac{\rho C_p u_* \kappa f_h}{\sigma_t \ln\left(\frac{d + z_0}{z_{0T}}\right)\sqrt{f_m}}$$

2. Equations and models

Radiative model

- **Discrete Ordinate Method (DOM)** (Fiveland, 1984)

  Spatial discretization uses the same mesh as the CFD model



- **Short and long-wave radiation**

$$S^{\downarrow} = S_D + S_f + S_e$$

$$S^{\uparrow} = \alpha S^{\downarrow}$$

$$L^{\downarrow} = L_a + L_e$$

$$L^{\uparrow} = \varepsilon \sigma T_w^4 + (1-\varepsilon)(L_a + L_e)$$

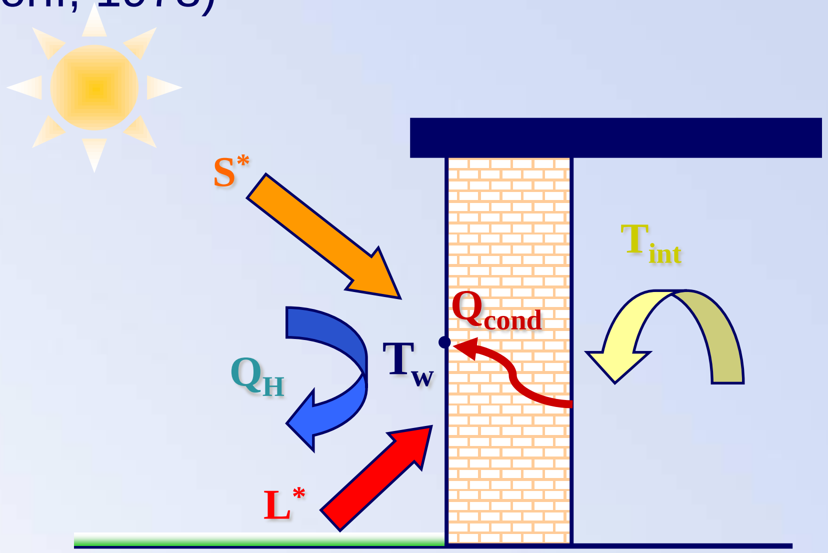
2. Equations and models

Hybrid surface temperature models:

- **Ground: Force-restore model** (Deardorff, 1978)

$$\frac{\partial T_g}{\partial t} = \frac{\sqrt{2\omega}}{\mu_g} Q_g^* - \omega(T_g - T_{g\,\mathrm{int}})$$

$$Q_w^* = L^* + S^* - Q_H - \underbrace{Q_{LE} - Q_F}_{\text{neglected}}$$



- **Buildings walls: Wall thermal model**

$$\underbrace{\frac{\lambda_w}{e_w}(T_w - T_{w\mathrm{int}})}_{Q_{cond}} = \underbrace{h_f(T_a - T_w)}_{Q_H} + \underbrace{\varepsilon_w(L_a + L_e - \sigma T_w^{\ 4})}_{L^*} + \underbrace{(1-\alpha)(S_D + S_f + S_e)}_{S^*}$$

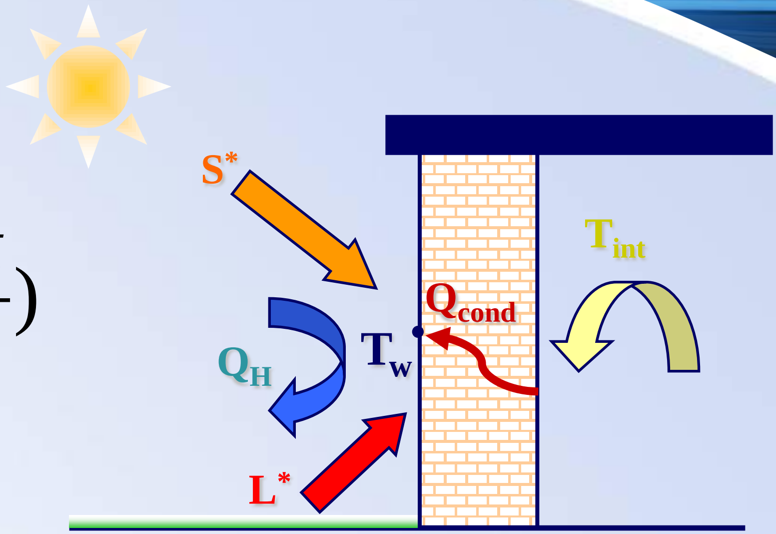
with

2. Equations and models

Internal building temperature

- Evolution equation (Masson et al., 2002)

$$T_{int}^{\;n+1} = T_{int}^{\;n-1}\left(\frac{\tau - \Delta t}{\tau}\right) + \underline{T}\left(\frac{\Delta t}{\tau}\right)$$

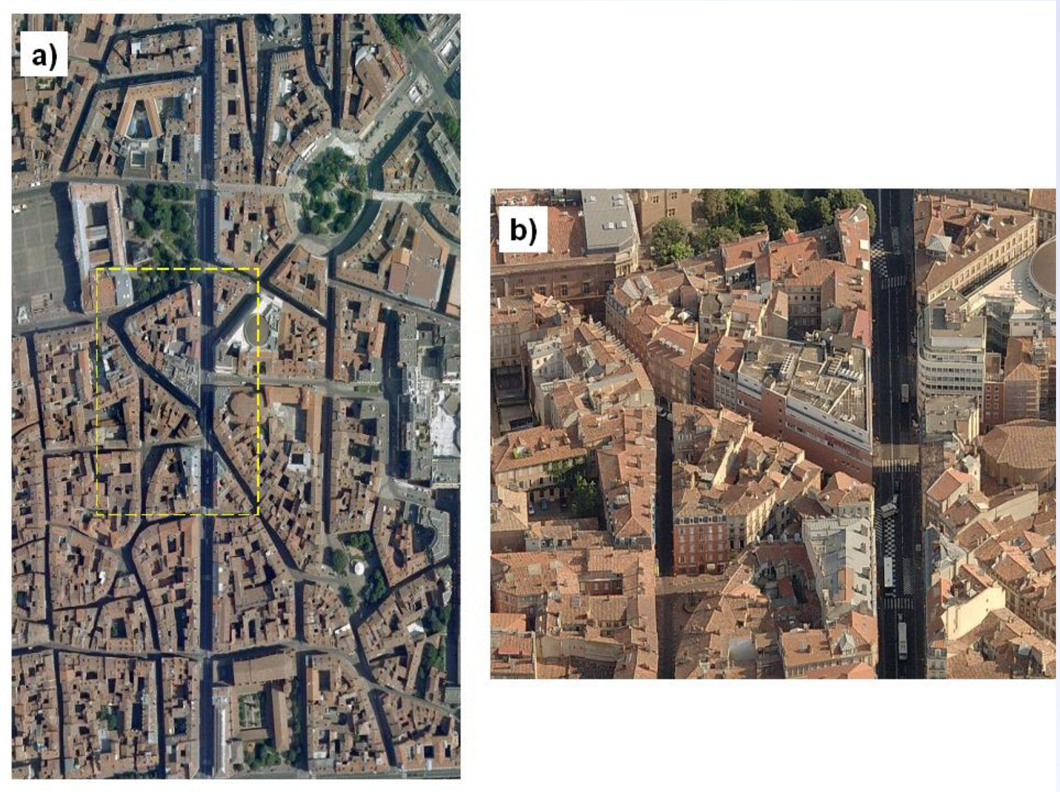


Comparisons with measured brightness surface temperature

$$T_{br} = \sqrt[4]{\varepsilon T_{sfc}^{\;4} + \frac{(1-\varepsilon)L^{\downarrow}}{\sigma}}$$

CAPITOUL project

- Canopy and Aerosol Particale Interactions in Toulouse Urban Layer (CAPITOUL) field took place from February 2004 to February 2005. (Masson et al., 2008)



- Aerial view of downtown Toulouse, France:

a) main study area, from Google Maps;

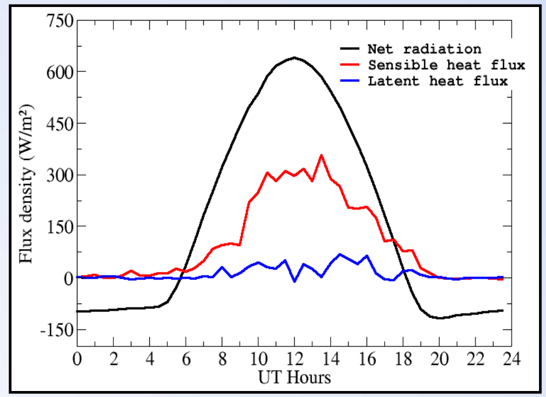
b) zoom in the selected area a) (yellow contour), from Bing Maps

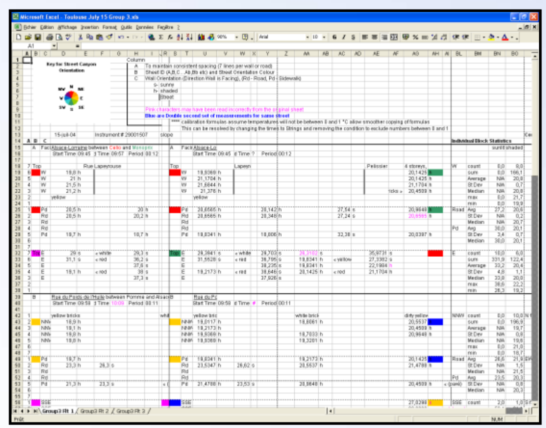
3. CAPITOUL field experiment

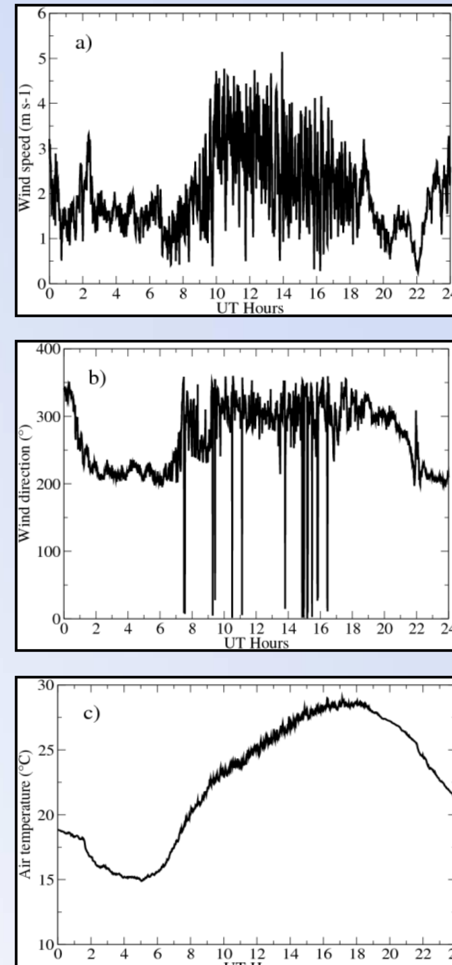
CAPITOUL project summary

- Study of the energetic exchanges between the surface and the atmosphere was one of the objectives.

- Meteorological data
- Infrared surface temperature measurement
- Hand-held IRT data
- Aircraft data
- Traffic count data



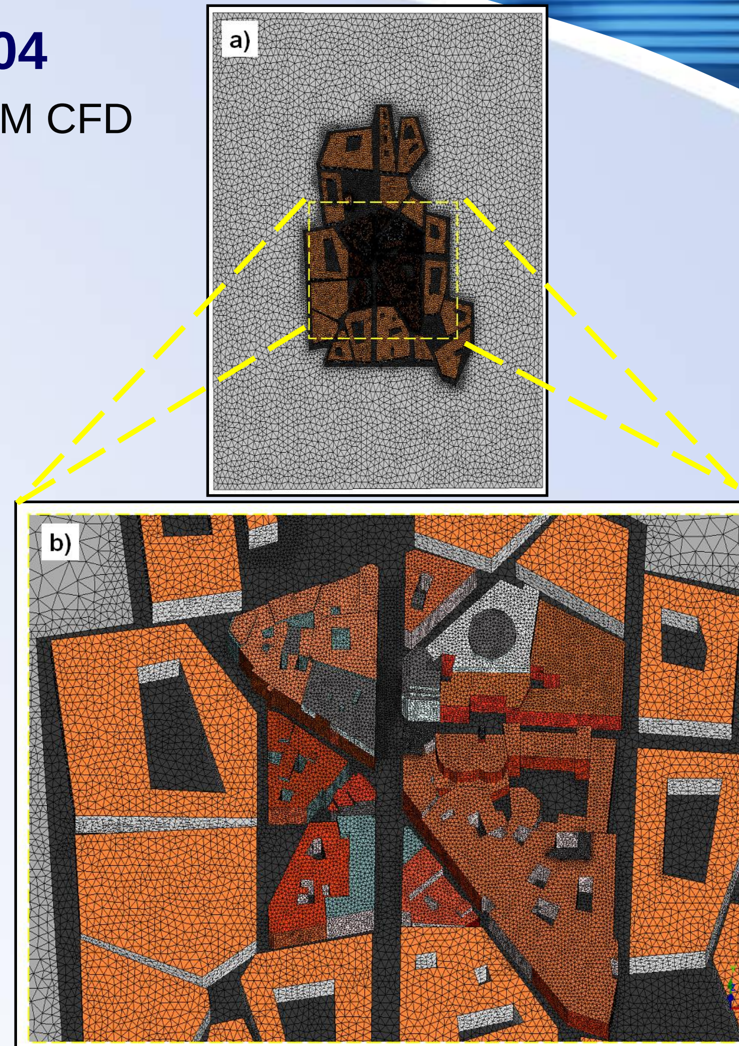




4. Simulation results

Simulation set-up for July 15th 2004

- Central site area geometry processed by ICEM CFD
- Domain size: 891x963x200 m



- Mesh strategy

- Simulation mesh, total mesh ~1,8 M

4. Simulation results

Simulation for July 15th 2004

- Initial and boundary conditions

	Surface albedo α	Surface emissivity ε	Layer	Depth (m)	Material	Heat capacity ($10^6\,J\,m^{-3}\,K^{-1}$)	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
Wall	0.25	0.92	1	0.01	Red bricks	1.58	1.15
			2	0.05			
			3	0.18			
			4	0.05			
			5	0.01			
Roof	0.15	0.90	1	0.01	Red tiles	1.58	1.15
			2	0.05			
			3	0.02	Wood	2.20	0.20
			4	0.01			
Road	0.08	0.95	1	0.01	Asphalt	1.74	0.82
			2	0.04			
			3	0.20	Stone aggregate	2.00	2.1
			4	1.00	Gravel and soil	1.40	0.4

(Pigeon et al., 2008)

- Classification of 4 colors for the buildings surfaces

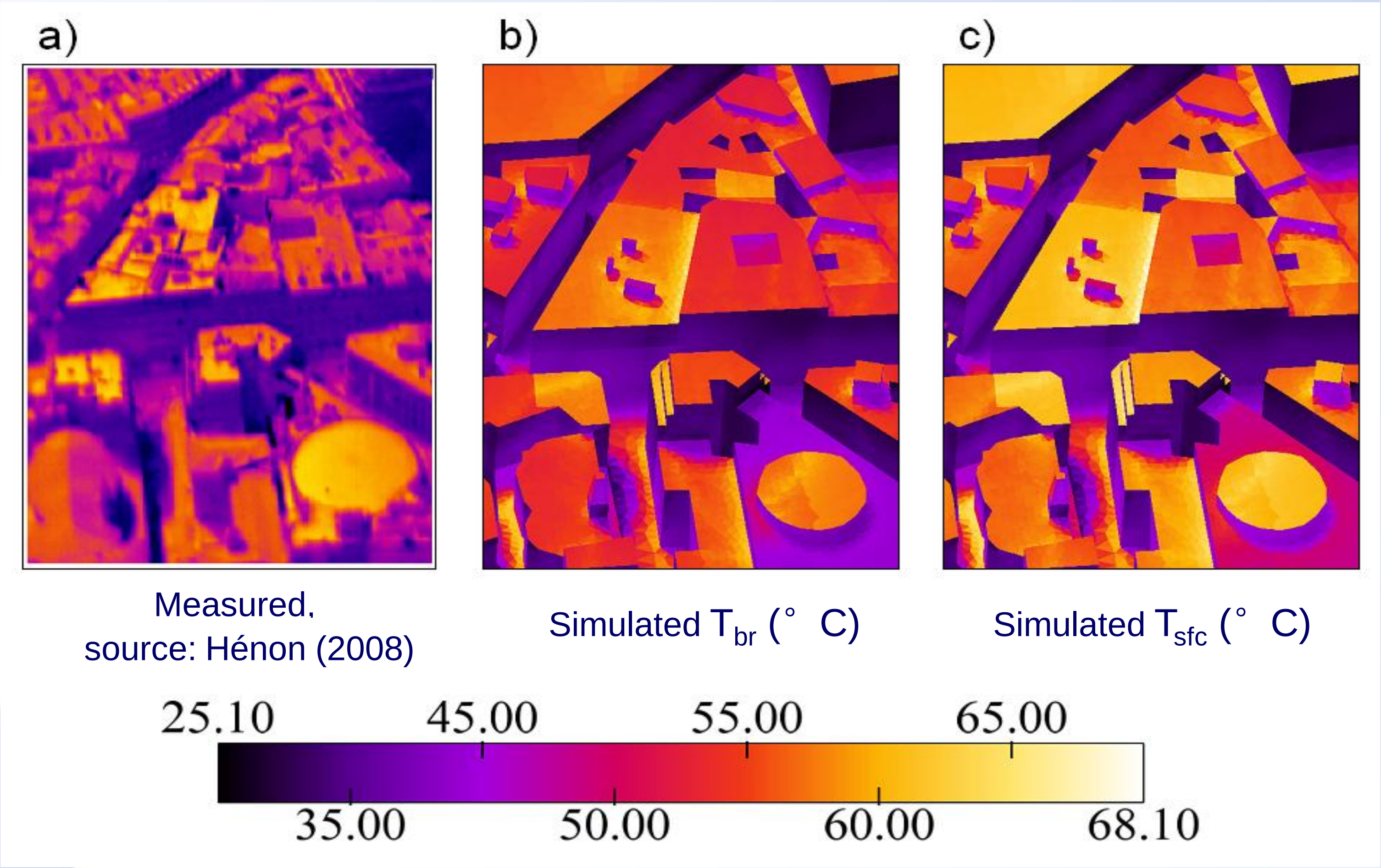
Paint color	albedo
White	0.6
Whitewash	0.5
Rose	0.3
Gray	0.15

- Implementation with sereval levels for heat transfer:

1) no wind
2) h_f constant
3) full radiative-dynamical coupling

4. Simulation results

- **Simulation of July 15th 2004**
- Thermal infrared (TIR) airborne images 1412 UT during flight 432 (Lagouarde et al. 2010):



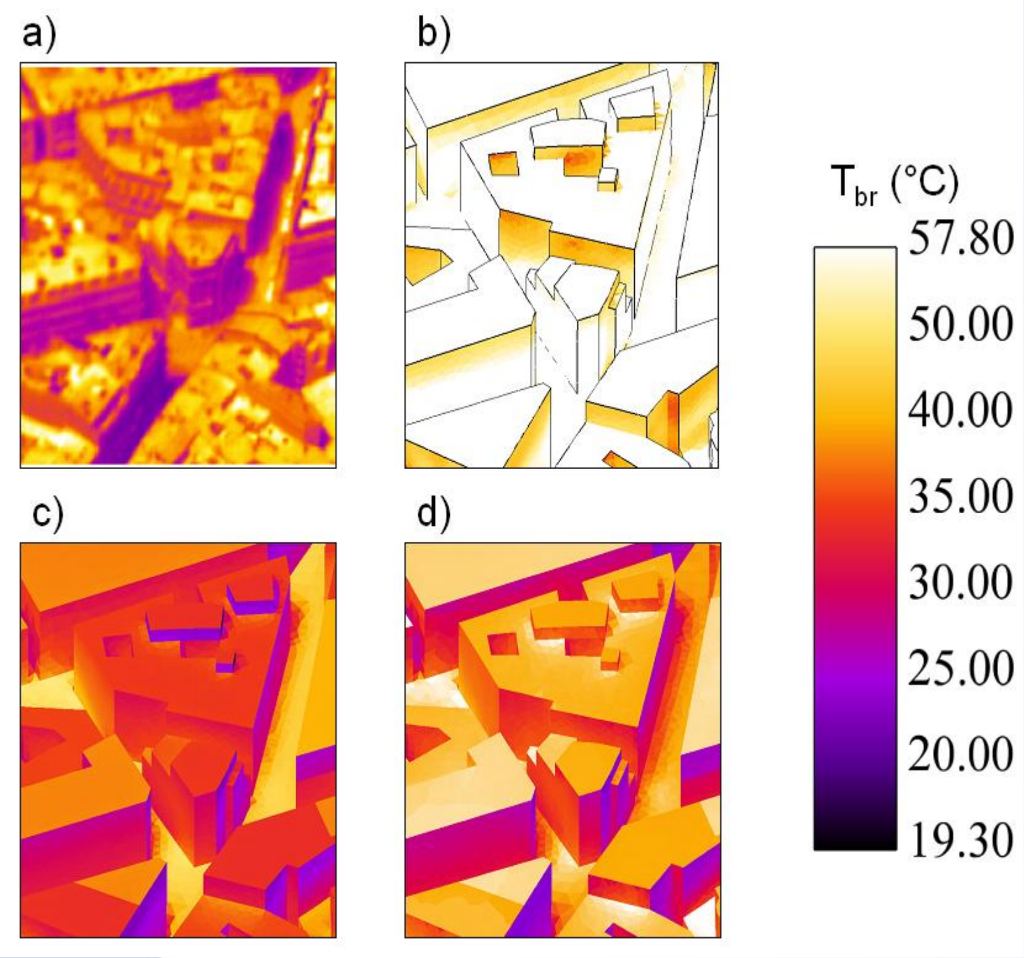
Measured, source: Hénon (2008)

Simulated T_{br} (° C)

Simulated T_{sfc} (° C)

Simulation of July 15th 2004

- Thermal infrared (TIR) airborne images 11:38 during flight 431(Lagouarde et al. 2010):

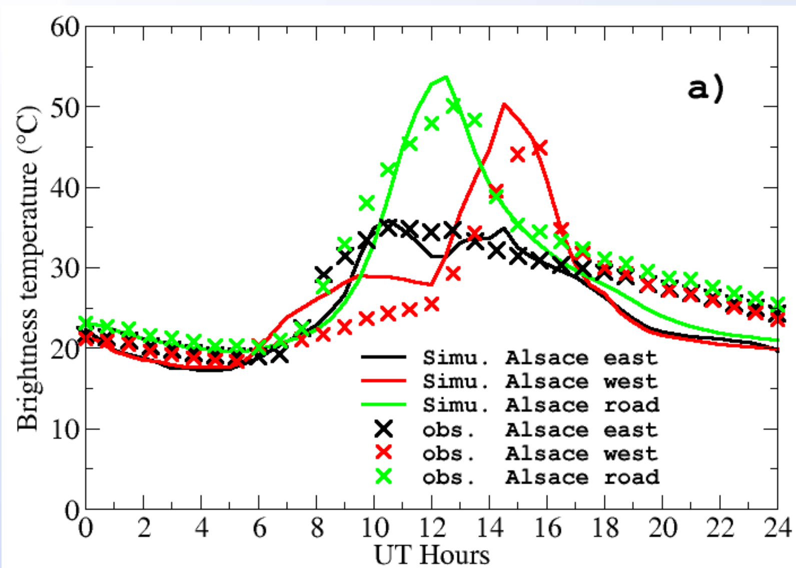


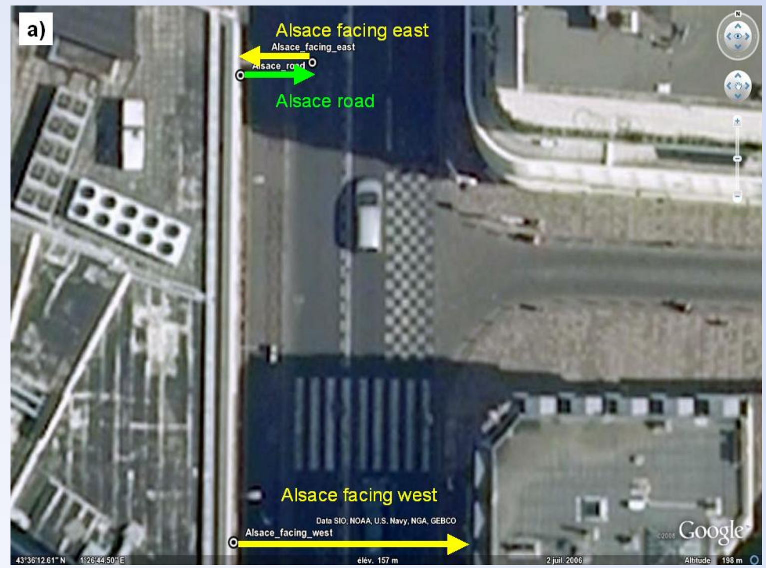
- a) Measured,
  source from Hénon (2008)
- b) Simulated T_{br} without wind
- c) Simulated T_{br} with h_f constant
- d) Simulated T_{br} with full coupling

4. Simulation results

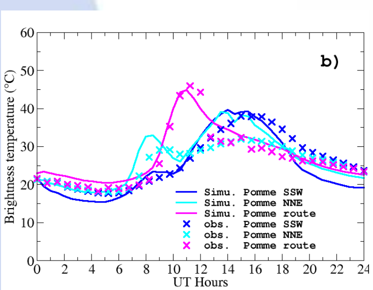
Simulation of July 15th 2004

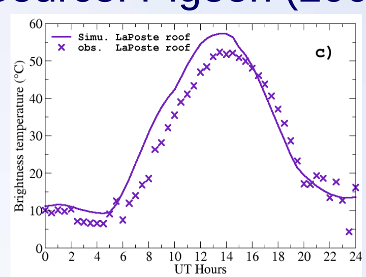
- Measurement-simulation comparison for diurnal evolution for brightness temperature of different positions of the infrared thermometers





Source: Pigeon (2004)





5. Conclusions

Conclusions

- We have investigated the energy exchanges in a real city with the atmosphere during the CAPITOUL campaign, using new atmospheric radiative and thermal schemes implemented in *Code_Saturne*, and compared it with measurements.
- A pre-processing is realized including the optimization of the complex geometry and creation of a high quality tetrahedral mesh for this study.
- It also requires determining the complex thermal parameters which take into account the actual variability of materials in the district.
- The comparison with IRT airborne images shows the importance of taking into account heterogeneities in materials and geometry to represent the spatial variability of the temperatures in complex urban areas.
- The comparison with the measured diurnal evolution of brightness temperature measurements and model simulations are encouraging fair.

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References

• Deardorf, J. W., 1978: Efficient prediction of ground surface temperature and moisture with inclusion of a layer of vegetation. *J. Geophys. Res*., **83**, 1889–1903

• Fiveland, W. A., 1984: Discrete-ordinates solutions of the radiative transport equation for rectangular enclosure. *J. Heat Tran*., **106**, 699–706

• Hénon, A., 2008: Températures mesurées, modélisées, et observées par télédétection infrarouge, dans la canopée urbaine: modélisation aéro-thermo-radiatif des flux de chaleur urbains. Ph.D. thesis, École Centrale de Nantes, 253 pp., [in French]

Thank you !

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• Lagouarde, J. P., A. Hénon, B. Kurz, P. Moreau, M. Irvine, J. Voogt, and P. Mestayer, 2010: Modelling daytime thermal infrared directional anisotropy over Toulouse city centre. Remote Sens. Environ., 114, 87–105

• Masson, V., C. S. B. Grimmond, and T. R. Oke, 2002: Evaluation of the Town Energy Balance (TEB) Scheme with Direct Measurements from Dry Districts in Two cities. J. Appl. Meteor., 41, 1011–1026

• Masson, V., et al., 2008: The Canopy and Aerosol Particles Interactions in TOulouse Urban Layer (CAPITOUL) experiment. Meteor. Atmos. Phys., 102, 135–157

• Milliez, M., 2006: Modélisation micro-météorologique en milieu urbain: dispersion des polluants et prise en compte des effets radiatifs, Ph.D. Thesis, Ecole Nationale des Ponts et Chaussées. 228 pp., [in French, available on line at http://cerea.enpc.fr/fr/theses.html]

• Pigeon, G., M. A. Moscicki, J. A. Voogt, and V. Masson, 2008: Simulation of fall and winter surfac energy balance over a dense urban area using the TEB scheme. Meteorol. Atmos. Phys., 102, 159–171

• Qu, Y, M. Milliez, L. Musson-Genon, B. Carissimo, 2011: Micrometeorological modeling of radiative and convective effects with a building resolving code, J. Appl. Meteor. Climatol (2011) Vol. 50, No. 8. 1713-1724

• Qu, Y, M. Milliez, L. Musson-Genon, B. Carissimo, 2011: Numerical study of the thermal effects of buildings on low-speed airflow taking into account 3D atmospheric radiation in urban canopy: paper submitted to J. Wind Eng. Ind. Aerodyn.