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3D MODELING OF URBAN ENVIRONMENT TAKING INTO ACCOUNT THE ENERGY EXCHANGES BETWEEN THE BUILDINGS AND THE ATMOSPHERIC FLOW

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Abstract: City residents are subjected to modified thermal environments as well as increased air pollution. In order to better understand the phenomena occurring at urban scale and to study different scenarios more and more realistic simulation tools are developed. Nevertheless, many micrometeorological studies on flow and pollution dispersion assume a neutral atmosphere and most building energy balance models neglect the three-dimensional local variation of the flow and temperature fields. The aim of this work is to develop a three dimensional tool coupling thermal energy balance of the buildings and modelling of the atmospheric flow in urban areas. We have developed a three-dimensional microscale atmospheric radiative scheme in the atmospheric module of the 3D Computational Fluid Dynamics (CFD) code *Code_Saturne* adapted to complex geometry. In our simulations, we use a Reynolds Averaged Navier-Stokes (RANS) approach with a k-ε turbulence closure. The full coupling of the radiative transfer and fluid dynamics models has been validated with idealized cases. In this work, we simulate surface temperatures of a district of the city of Toulouse, in the South-West part of France, taking into account the 3D effects of the flow around the buildings, in real meteorological conditions. The mesh developed for the city center and the simulation conditions for the selected day of the campaign are presented. The results are evaluated with the measurements from the CAPITOUL (Canopy and Aerosol Particles Interactions in TOulouse Urban Layer) experiment, including brightness surface temperature measured by infrared imagery.

Key words: *CFD, urban energy models, 3D radiative transfer*

INTRODUCTION

Existing canopy models often use a statistical representation of building which is generally obtained through quantitative field survey or qualitative estimates. But in performing this geometric simplification there is no way to ensure that the simplified geometry match locally the actually city. In this work we want to represent the energy and momentum exchanges in portion of an existing city as realistically as possible. We developed a three-dimensional microscale atmospheric radiative scheme in a Computational Fluid Dynamics (CFD) code adapted to complex geometry. This model can study the thermal effects of buildings on the local atmospheric flow with a coupled dynamic-radiative model. Previously, the model was evaluated with idealized cases, using as a first step, a constant 3D wind field (Milliez, M. et al., 2006; Milliez, M., 2006). Furthermore, we have validated this approach by comparison with several surface wall temperatures from the Mock Urban Setting Test experiment. We have also discussed the influence on the surface temperatures of the internal building temperature and the wall thermal modeling, and compared the 3D modeling of the convective exchanges to simpler approaches used in other models (Qu, Y. et al., 2011). In this work, we aim to test the effects of complexity in urban geometry on the interaction between the airflows and the radiation exchanges with different surfaces. In order to evaluate our model to be as robust as possible with a large available experimental dataset in a real urban environment, we choose the Canopy and Aerosol Particle Interactions in TOulouse Urban Layer (CAPITOUL) experimental dataset.

MODEL DESCRIPTION

The simulations are performed with the 3D open-source CFD code *Code_Saturne* which can handle complex geometry and complex physics. Taking into account the larger scale meteorological conditions and the thermal stratification of the atmosphere, the atmospheric module of *Code_Saturne*, described in Milliez, M and B. Carissimo (2007), uses a detailed representation of the surfaces allowing a complex 3D spatial representation of wind speed, turbulence, and temperature. The numerical solver employs a finite-volume approach for co-located variables on an unstructured mesh. Time discretization is achieved through a fractional step scheme, with a prediction-correction step (Archambeau, F. et al., 2003). In our simulations, the turbulence in the entire fluid domain is parameterized with the standard k-ε formulation.

Radiative model

The radiative fluxes are computed using the Discrete Ordinate Method (DOM) (Fiveland, W. A., 1984) which solves the radiative transfer equation for a gray non-diffusive semi-transparent media by the directional propagation of the radiative wave. In our models, the angular discretization has two resolutions: 32 or 128 directions and the spatial discretization use the same mesh as the CFD model. Taking into account both short- and long-wave radiation separately, we have adapted a radiative heat transfer scheme available for combustion in *Code_Saturne*. Described in detail by Milliez, M (2006), the new atmospheric 3D radiative approach was developed in *Code_Saturne* for built-up areas. The main advantage of this model is that the radiative transfer equations is solved in the whole fluid domain and not only at solid faces (such as when using view factors), but also can be applied to non-transparent media (e.g. fog or pollution). In this work, we consider a transparent atmosphere between the buildings at the microscale of our simulations.

Surface temperature model

As a key parameter, surface temperature T_{sfc} (K) is determined by the surface energy balance and is related in a fundamental way to each of its component fluxes. In the previous work (Qu, Y. et al., 2011), the surface temperature was obtained by either with force-restore approach or wall thermal model. In order to take advantage of the each model, in this work, we model the ground temperature with force-restore method and the building surfaces (wall/roof) temperature with wall thermal model. Hence, the modeled surface temperature is separately treated by the relationship:

Ground temperature: force-restore method

This simple approach is widely used for soil models in meteorological models.

$$\frac{\partial T_g}{\partial t} = \frac{\sqrt{2\omega}}{\mu_g} Q_g^* - \omega (T_g - T_{g\,\mathrm{int}}) \tag{1}$$

Where T_g (K) is the ground temperature, ω is the Earth angular frequency (Hz), μ_g is the thermal admittance (J m^{-2} $s^{-0.5}$ K^{-1}), Q^*_g (W m^{-2}) is the total net flux and T_{gint} (K) is deep soil temperature.

Building surface temperature: Wall thermal model

We obtained the building surface temperature with a simple 1D conduction scheme with a given thickness e (m) and an average thermal conductivity λ (W K^{-1} m^{-1}):

$$\frac{\lambda}{e}(T_w - T_{w\,\mathrm{int}}) = Q_H + L^* + S^* \tag{2}$$

where T_w (K) and T_{wint} (K) is respectively the external and internal building temperature, Q_H (W m^{-2}) the sensible heat flux, L^* (W m^{-2}) and S^* (W m^{-2}) are net long- and short-wave radiative flux, respectively.

Brightness temperature

In this work, we compare the simulated and measured brightness surface temperature obtained from infrared imagery. A brightness surface temperature T_{br} (K) is defined here as the temperature that yields an emitted broadband thermal radiance equivalent to the sum of the true broadband emitted radiance (with reduction due to gray body emissivity) and the broadband reflected radiance (after infinite reflections for canyon surfaces):

$$T_{br} = \sqrt[4]{\varepsilon T_{sfc}{}^4 + \frac{(1-\varepsilon)L^{\downarrow}}{\sigma}} \tag{3}$$

where ε is the long-wave emissivity, σ the Stefan-Boltzmann constant and $L^{\downarrow}$ (W m^{-2}) incident long-wave radiation.

Convection model

The thermal energy equation of the flow is solved, both to determine stratification effects on vertical turbulent transport and to estimate the surface-air thermal gradient that controls convective heat transfer. Our model solves the 3D RANS equations using a rough wall boundary condition in the entire fluid domain. The heat transfer coefficient is computed for each solid sub-facet, depending on the local friction velocity and the thermal stratification:

$$h_f = \frac{\rho C_p u_* \kappa f_m}{\sigma_t \ln(\frac{d+z_0}{z_{0T}})\sqrt{f_h}} \tag{4}$$

where ρ is flow density (kg m^{-3}), C_p specific heat (J kg^{-1} K^{-1}), u^* is the friction velocity which is determined by iteration, k is von Karman constant, σ_t turbulent Prandtl number, d is distance to the wall (m), z_0 the roughness length (m), z_{0T} the thermal roughness length (m), f_m and f_h are the Louis stability functions (Louis, J. F., 1979).

DATA SELECTION FROM THE CAPITOUL EXPERIMENT

The CAPITOUL campaign is a joint experimental effort in urban climate which took place in Toulouse from February 2004 to February 2005 (Masson, V. et al., 2008). Study of the energetic exchanges between the surface and the atmosphere was one of the objectives. The study area is located in the central site of Toulouse around the corner of the two streets, Alsace-Lorraine and Pomme (yellow contour in Fig. 1a and Fig. 1b). In this neighborhood, vegetation is very scarce and buildings are typically 4–5 stories around 20 m height (Pigeon, G. et al., 2008). The base of the mast was on a roof at a height of 20 m, with the top of the mast being 47.5 m above the road. It provided data including sensible heat, latent heat, air temperature, wind speed and direction etc. continuously from mid-February 2004 to early March 2005. Nine infrared radiometers were set to observe permanently the surface radiation temperatures of the two walls and the pavement of the three surrounding streets. Thermal InfraRed (TIR) airborne images were obtained during several Intensive Observation Periods (IOP) with 2 airborne cameras on board of a Piper Aztec PA23 aircraft. The speed of the aircraft was 70 m s^{-1} and the camera acquisition frequency was 4.3 frames per second. The flight height was about 460 m, which results in a resolution between 1.5 and 3 m depending on the sight angle (Lagouarde, J-P. and M. Irvine, 2008). The images analyzed here are extracted from flight 431 of July 15, 2004, around 11:30 UT.

NUMERICAL SIMULATIONS

Simulation domain and mesh

Considering Alsace-Lorraine and Pomme roads as center of interest in the computational domain (Fig. 1), the dimension of the three-dimensional simulation domain is 891x 963 x 200 m. First, we import the urban database (AutoCAD format) of the Toulouse town hall into the commercial mesher ICEM CFD. The urban elements in the database are not individual houses or buildings but a group of the walls and roofs including a large number of internal fine walls which are unnecessary to be meshed. Moreover, the urban elements have a variety of heights but no soil element. So before the meshing step, it is necessary to do a preparatory work on the geometry. After a series of geometry optimization (remove the internal surface, simplify a part of details, create the ground then projected the buildings onto it etc.), we build a proper geometry topology as shown in Figure 2a. In real urban environment, all obstacles details cannot be resolved with sufficient detail, but their impact need to be parameterized. We describe the strategy for this study as follows. From the boundary of the domain to the center, we progressively retain more geometric details. That is, the buildings at these Alsace-Lorraine and Pomme streets in the center study area are modeled with fine details. Then, the surrounding buildings next to the center study area are simplified as urban blocks. Finally, the buildings in the region outside are treated with a high roughness value at this stage (eventually with drag-porosity in future work). The volumetric mesh used here is an unstructured grid of about 1, 6 M tetrahedral cells. The grid resolution varies from 0.8 m near the center to 24 m far from the center zone (Fig. 2b).

Initial and boundary conditions

The wind inlet boundary conditions are determined from measurements, using a meteorological mast which gives every 2 hours the wind velocity, turbulence kinetic energy, dissipation rate and potential temperature profiles. The variation of the deep soil temperature is neglected. Since most of buildings in the centre of Toulouse are from 19th century, walls are built with bricks and most are not insulated as well as the roofs (Pigeon, G. et al., 2008). Thus, at this stage, the internal building temperature is calculated with a temperature evolution equation as in our previous work (Qu, Y. et al., 2011). From some Toulouse pictures, we estimate the roughness value depending on its location (e.g. 0.1 m for roofs and walls in the center, 0.02m for street in the center and 1.5m for the outside region) and set value for both dynamic roughness length and thermal roughness length. Based on Pigeon, G. et al. (2008), we set the thermal properties such as surface conductivity and thickness. Since the values from Pigeon, G. et al. (2008) are averages over the 500-m radius around the surface energy balance station, watching some Toulouse pictures from Google Maps, we furthermore classify four wall painting color (rose, grey, whitewash and white) for the buildings in the center area to estimate the albedo. Modeling the urban energy balance in CAPITOUL consists in several steps. First we test only the radiative scheme without introducing the convective exchange. Second we specify a constant heat transfer coefficient to take into account a global wind field effects. Finally, we model detailed variable wind fields and their effects on the thermal transfer. Results presented in next section concern our first and second step.

RESULTS AND DISCUSSION

Figure 3 from (a) to (c) shows the modeled and measured brightness surface temperatures, with two modeling approaches: radiative model only and coupling radiative and a constant heat transfer coefficient using the wall thermal scheme for the aircraft flight 431 of July 15, 2004 at 11:38. The result of the first simulation (Fig. 3a, radiative scheme alone) shows that the brightness temperatures are obviously higher than measurements. Especially on the roof, the difference is more than 20 °C. The modeled T_{br} is out of range. Taking a constant heat transfer coefficient means assuming a constant wind field in the domain. As expected, the result (Fig. 3c) shows a much better agreement with observation (Fig. 3b) in comparison to radiative model only case (Fig. 3a). In spite of the fact that we did not keep all the elementary details on the roofs with different orientations and slopes, the simulated temperatures present well the spatial variability of the temperatures. The difference rarely exceeds 10 °C. We notice also in the measurement (Fig. 3b) that at same roof and same orientation may differ by more than 5 °C, for instance at right bottom of the image. This may be due to heterogeneities in materials and geometry which can not be all accounted by modeling each individual area (or even every detail).

For building walls, either shaded or sunlit, the difference between measurement (Fig. 3b) and simulation with constant heat transfer coefficient (Fig. 3c) is generally less than 5 °C. In the measurement, some horizontal faces (e.g. buildings at left in center) are relatively warmer than others. This may be due to some external structures (e.g. balcony) that are not modeled but were exposed to the sun and therefore received more solar heating.

For the streets, a minimum 3 cells were set for the width; the model is able to simulate the sharpness of the shadow (Fig. 3b and Fig. 3c). The portion of the street brightness temperatures near the buildings is well reproduced. The averaged difference is less than 3 °C. The simulated sunny portion is underestimated by about 5 °C. We expect that the full heat transfer modeling with a more realistically heat transfer coefficient can reduce the gap.

Another Thermal InfraRed picture from same flight is shown in Fig 4a. Since we distinguish different albedo from painting colors, the model reproduced well the heterogeneity of the distribution of the brightness temperature, especially at roof level (Fig. 4b). The modeled surface temperature is also shown in Fig 4c. The value of the modeled surface temperatures is obviously larger than modeled brightness one. Because from equation (3), we can see that the brightness temperature is proportional to the product of the surface temperature and emissivity (the emissivity is usually smaller than 1).

CONCLUSION

We investigate the energy exchanges in a real city with the atmosphere during the CAPITOUL campaign, using new atmospheric radiative and thermal schemes implemented in the 3D CFD code (*Code_Saturne*). 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. Based on the literature data, we separate the building surface into 4 classes of albedo depending on painting colours. Simulations are evaluated with the comparison of the Thermal InfraRed airborne image from a flight in the day of 15th July 2004 during the CAPITOUL project. The modeled brightness temperature without including the convective effect is much higher than observation. Assumed a constant wind field makes a better agreement with measurement. Moreover, the result shows the importance of taking into account heterogeneities in materials and geometry may well present the spatial variability of the temperatures in complex urban areas.

More evaluations with the coupled dynamic-radiative model with CAPITOUL experiment are currently ongoing which includes the comparison with the measured radiative fluxes, sensible flux, surface temperature or brightness temperature diurnal variation, and standard deviation with hand-held IRT data.

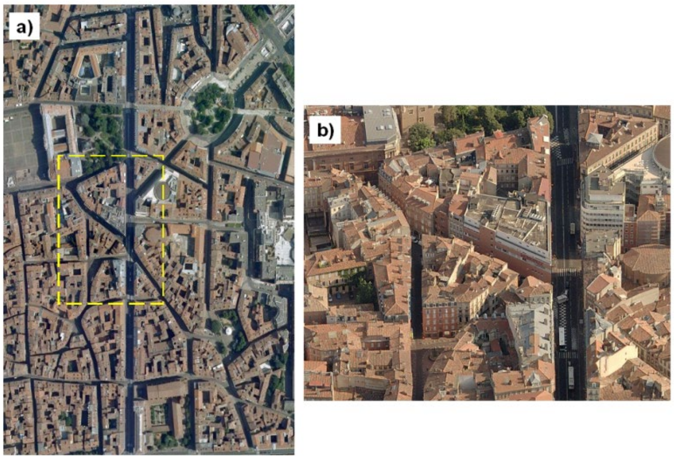

Figure 1. Aerial view of Toulouse downtown, France. a) main study area, from Google Maps; b) zoom in the selected area a) (yellow contour), from Bing Maps.

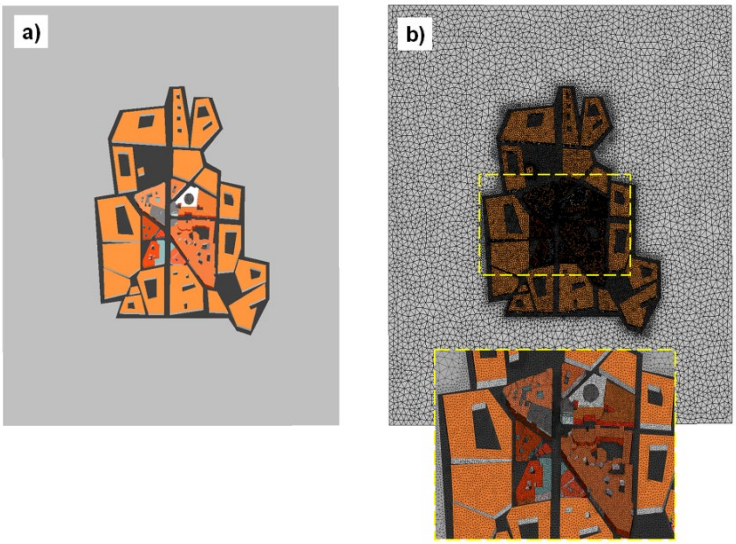

Figure 2. Central site area: a) processed geometry by ICEM CFD; b) Tetrahedral mesh with zoom on the central area

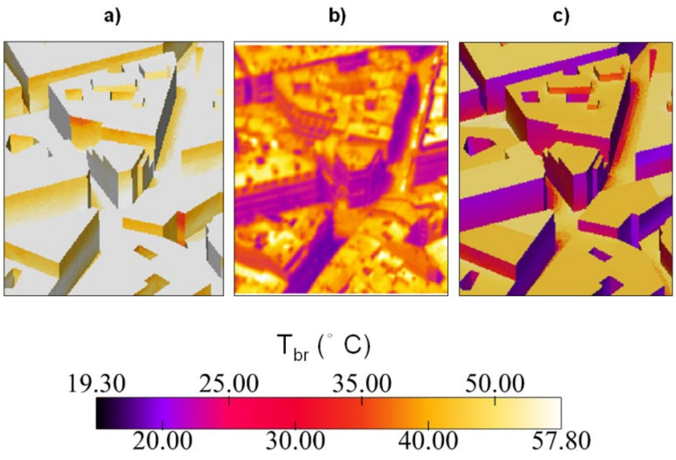

Figure 3. Comparison between the simulated brightness temperatures and Thermal infrared (TIR) airborne images of July 15, 2005, at 11:38 during flight 431: a) Modeled brightness temperature without taking into account the convection; b) TIR picture (189 x 118 pixels), source from Hénon (2008) ; c) Modeled brightness temperature with a constant heat transfer coefficient.

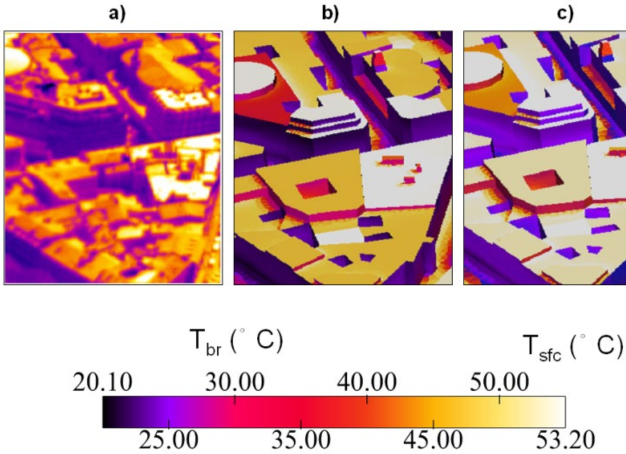

Figure 4. Comparison between the simulated brightness temperatures, surface temperatures, and Thermal infrared (TIR) airborne images of July 15, 2005, at 11:40during flight 431: a) TIR picture (189 x 118 pixels), source from Hénon (2008); b) Modeled brightness temperature with a constant heat transfer coefficient; c) same as b) but for modeled surface temperature.

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