Simulation of urban fluxes with a 3D canopy model

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15 May 2015

1. Introduction

The simulation of fluxes (e.g. radiative, sensible or latent heat fluxes…) is of great importance for fundamental or applied climatic studies carried out into the urban context. Several canopy models have been developed to simulate these processes into towns and some of them can be directly coupled with numerical weather models working at mesoscale (e.g. Masson, 2000). These mesoscale canopy models greatly improve the results of weather simulations over town, because they are able to reproduce the interactions between the boundary layer and the underlying urban canopy layer. In this kind of models, however, some simplifications are introduced to represent the town. For example, in a lot of surface schemes, the land covers are simulated separately (garden, built-up area), percentages are allocated to each cover and the residential areas are often simulated with the assumption of the urban canyon. Moreover, the horizontal resolution of the outputs is limited to the resolution of the mesoscale model itself. In some circumstances however, it is necessary to work at higher resolutions, to obtain more details on some interesting areas (one goes from mesoscale to microscale simulations). In these cases, it becomes necessary to take the real geometry of the town into account. This means that the shape of each town element (buildings, roads and trees) must be “realistically” reproduced in three dimensions. In this type of canopy models, the buildings can be depicted with their inclined roofs, balconies and windows and the artificial or vegetated areas can be introduced at their real places. As a consequence, the physical processes can be simulated very finely (at resolutions of some square meters if necessary). With such a detailed description level, all the fluxes can be better reproduced for each element. But some physical processes must be adapted to this new full 3D environment. It is for example the case of the radiative algorithms that must be simulated with specialized procedures to obtain the shadows, the anisotropic sky or the interreflections between all the objects. This dramatically increases the simulation time. LASER/F (LAtent, SEnsible, Radiation fluxes) is a 3D urban canopy model specially designed when high resolution is required for urban climatic studies. After more than ten years of development, the latest version is now able to simulate most of the physical processes. Several tests have been conducted to validate the model on real cases and under clear sky conditions (to allow the maximum thermal contrasts between the surface elements). In the following of the paper, the model is briefly described and the simulation results are validated (for two real case tests) with the measurements acquired during a field campaign specially designed to this aim.

2. The model

LASER/F is designed to work with the real geometry of the town in 3D. Each town element (building, road, tree…) is “realistically” reproduced with its shape into the simulation domain and associated with the most specific physical attributes as possible. However, in practice, the shape is simplified and the little geometrical details are neglected according to the computing power and the available digitized geometry. Because of the use of the 3D geometry and the resolution or the complexity of the radiative algorithms, the simulation time increases considerably (it is the reason why this type of simulation model is not used at the entire scale of a city for the moment). The positive aspect is that, theoretically, this kind of model will be able to bring major improvements into the results owing to their precision.

To reach the initial scientific objectives of the model, the simulation domain (scene), is prepared in a specific manner. The available information is organized as a 4 level hierarchic structure (Figure 1): (i) because LASER/F is designed to work potentially in-co-ordination with a mesoscale atmospheric model in which the atmosphere is divided into quadrilateral boxes (voxels), the urban canopy layer is divided into voxels of the same horizontal dimensions; (ii) each voxel contains its own numerical objects (representing buildings, the soil…); (iii) each object is made up with a collection of planar polygons (describing the facades, roofs, lawn, roads); (iv) at the finest level, each polygon is divided into small triangular meshes for which the energy balance equation is solved (the greater will be the number of meshes, the better will be the results, but the longer will be the computation time).

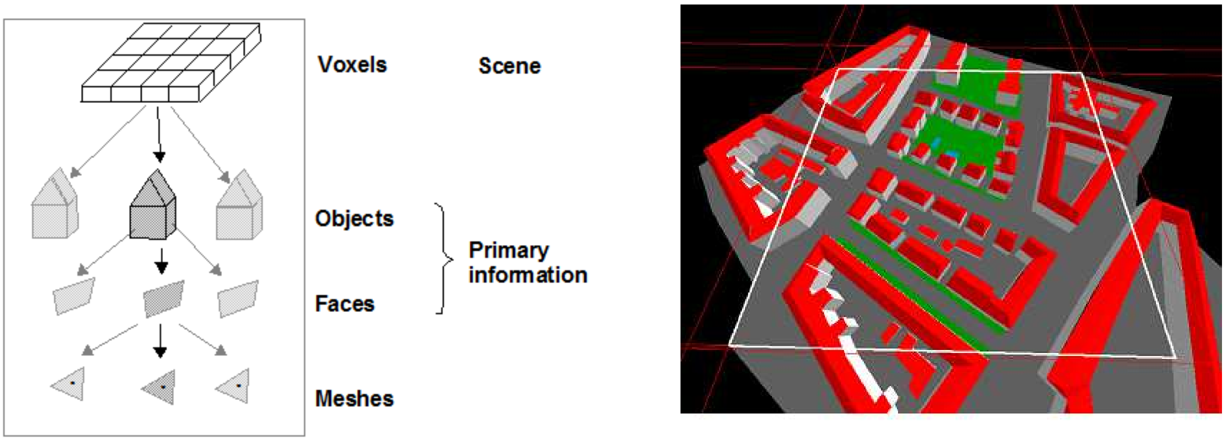

Fig. 1 Organization of the simulation domain (left) and an example of district (right).

To compute properly the energy balance of several kinds of elements, the objects are classified into a little number of main types (terrain, building, water…). This allows controlling the behavior of each object by a special set of equations according to the type (e.g. the water content of the natural ground is computed, but not for the wall or the roofs of a building). To be the closest to the reality, the polygons describing the roofs, facades (etc.) can be made with multiple layers of different materials. Of course, the thickness and the physical properties (e.g. density, thermal conductivity…) of these materials must be prescribed into a dedicated database. Here, the most difficult task consists to find precisely all the physiographic data necessary to describe the objects. This task is not easy, even for a small simulation domain: most often, no pre-existent information (database) exists about the exact nature of the ground or of the materials used to build the structures. For large simulation domains (as for a district, or even a town), assumptions (empirical generalization) must be done.

The simulation evolves according to the meteorological conditions that prevail at the boundaries of the surface scheme. For our case these boundary conditions are imposed at the top of each urban canopy voxel. They consist of several forcing variables whose values are imposed at regular time intervals. The most important of them are the atmospheric and radiative constraints (Table 1). As the UCL is divided into voxels, it is possible to plan to impose specific boundary conditions for each of them. The forcing variables can be obtained by two ways: (i) from a weather model; (ii) from measurements. When the boundary conditions are prescribed, the task of LASER/F consists to compute the state of each object, the state of the atmosphere into the voxels, as well as the radiative and energy exchanges into and out of the top of the UCL (i.e. the sensible heat flux…).

Solar direct (W/m²)	Solar diffuse (W/m²)	Atmospheric IR (W/m²)	Air temp. (C)	Air HR (%)
Wind speed (m/s)	Wind direction (deg)	Precipitation (mm)	Pressure (hPa)	

Table 1. List of the atmospheric forcing variables imposed over the roof level of each voxel.

3. The main simulated processes

The radiation into the urban canopy is simulated very finely. The direct solar radiation takes into account the obstacles by the surrounding objects, as well as, possibly, their transparency (see Kastendeuch and Najjar, 2009, Kastendeuch, 2012). The atmospheric diffuse radiation follows the "all weather model for sky luminance" of Perez *et al*. (1993). The procedure has the advantage of considering the sky as a non-uniform source of radiation whose intensity varies as a function of sunshine. The reflection is simulated as a diffuse process (the specular reflection do not exists). The interreflections between the elements are simulated with a "progressive refinement" method for radiosity algorithm (Cohen *et al*., 1988), a classical method used to render diffusively illuminated scenes in computer graphics.

The infrared radiation is handled by two different ways according to its origins: the atmosphere or the terrestrial objects. Contrary to the solar diffuse radiation, the atmosphere is seen as a homogeneous source (isotropic emission) of infrared radiation. When using this assumption, the atmospheric infrared radiation received by a terrestrial surface only depends on the well known "sky view factor" (Kastendeuch, 2013). When computing the sky view factor, the transparency effects are not taken into account: the objects are supposed to completely absorb the atmospheric infrared radiation they receive. The terrestrial infrared radiation follows the well-known Stephan-Boltzmann generalized law for the grey bodies. The Kirchhoff's law is applied between the absorptivity and the emissivity terms. The infrared reflection is isotrope and is added to the IR emission, to compute the multiple exchanges of infrared radiation between the terrestrial elements. These exchanges are simulated with the same radiosity algorithm than for the solar interreflections.

The ground heat flux (the transfer of heat trough the objects) is simulated for artificial or natural materials. For artificial materials, the heat conductivity is constant during the simulation, as it varies with time for the natural soil according to the water content of each layer. Hence, the ground heat flux will be different during dry or wet periods. For simplification, only a one-dimensional form of the equations is solved (the lateral transfers of heat or water are ignored). The temperature profiles (within the objects) can be obtained for any number of layers (the objects can be composed with several layers of different materials and different thickness). The surface temperatures are computed by applying an iterative process in which all the components of the energy balance equation must be in equilibrium (the radiative fluxes, as well as the thermal fluxes). The deepest temperature of the soil column is kept constant with time, but this is not the case for a wall of a building for which the inside temperature evolves during the day (this temperature is simulated with a simple specific building simulation model). One of the problems is that, at the beginning of the simulation, it is necessary to specify the initial values of some fields (at the surface or deeply), as the temperatures or the water content (this phase is known as “initialization”). Different solutions can be employed in accordance with the type of object (e.g. river, terrain, building): uniform or distinct values, interpolations between the surface and the deepest level (etc.). As a consequence, these fields can achieve some realistic values only after several time steps, the time of the model to reach certain equilibrium.

Sensible and latent heat fluxes are computed with an aerodynamic formulation that takes the stability of the air into account. The latent heat flux can be computed for water surfaces, wet artificial materials (limited by the superficial water reservoir), bare soil or vegetated covers. In the two later cases, the available soil water content also limits the evapotranspiration. At the end, the atmospheric characteristics (temperature, wind speed, humidity) of the urban canopy of each voxel are predicted (following the assumptions of Masson, 2000), as well as some other interesting outputs (as the average fluxes going out of the voxels).

This model was applied on two different situations to test its capacities: (i) on an urban canyon (part 4); (ii) on a part of a district (part 5).

4. Validation of the radiative algorithms

A first simulation was undertaken for a street of the city of Strasbourg (France, Figure 2). The detailed geometry of the street and its surroundings was especially digitized for the need of this kind of simulation (Figure 2). The site can be described as follows: the canyon is 200 m long, 22 m height, 24 m width (H/W ratio of 0.92) and is oriented at an azimuth of 35 degrees. On both sides of the central road, at the bottom of the façades, two vegetated stretches 5m wide (with trees, grass, bare soil, hedges…) are occupying the space (Figure 2, left). Only some main elements are retained for the simulation: the street itself, the two strips of grass, the facades and the roofs of the buildings (Figure 2, right). The shape of the buildings is simplified by the removal of all the details (i.e. chimneys, windows, and balconies…). This simulation represents the opportunity to validate the complete set of radiative algorithms, since the site has been equipped with instruments for an experimental measurement campaign that took place in summer 2002 (Najjar *et al*., 2004).

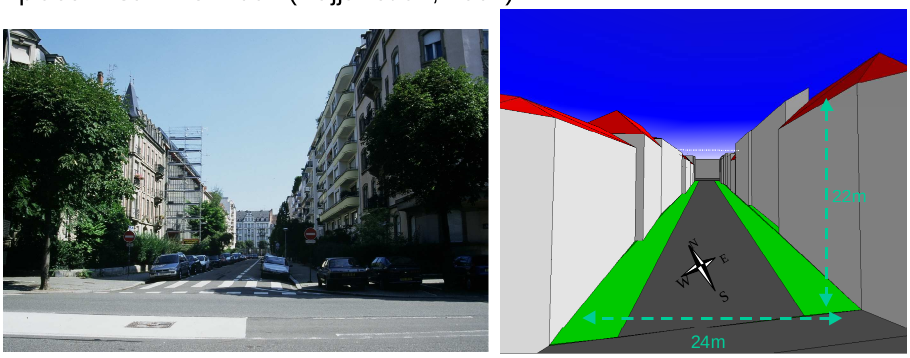

Fig. 2 Real case test of the Argonne site (Strasbourg, France).

The simulation begins on August 13 of 2002 at 19 UTC to allow the initialization and the stabilization of the model during the first night of the simulation process (note that for Strasbourg, the local solar time is obtained by subtracting about 30 minutes to the UTC). The time step of the simulation is of a quarter of an hour (as fine as the forcing time step). The initial conditions are as follows: (i) the air temperature in the canyon is imposed from measurements (afterwards it is simulated); (ii) the surface temperature is uniform (it is set equal to the initial air temperature of the canyon); (iii) the soil or the road deep temperature is set equal to the average air temperature of the simulation period (it remains constant during all the simulation); (iv) the inner building temperature is set equal to the ground deep temperature (after which it is computed); (v) the temperatures of the multiple layers of the objects are linearly interpolated between the surface and the deep temperatures. During the simulation, the forcing data (e.g. radiation, pressure, relative humidity, wind speed…) are imposed from the measurements made over the roof level of the canyon by Najjar *et al*. (2004).

To allow the validation of the simulation outputs, several virtual sensors are introduced in the simulation scene at the exact places occupied by the real sensors during the 2002 experimental campaign. It should be emphasized that the way we proceed in this simulation work is the only one that allows such a comparison between simulation and measurements at a given point in canyon space. The virtual sensors can be of two types: (i) the radiative virtual sensors are able to analyze the radiation exchanges in all directions of the space with their

6 sides (they take the form of little cubes); (ii) the heat flux virtual sensors are able to give the averaged heat fluxes (sensible, latent and ground heat fluxes) from several meshes between two points (they are working like scintillometers, by integration).

Only some of the possible validations are shown in the following (the interested reader can refer to Kastendeuch and Najjar, 2009 for more information). The simulated global radiation is validated by comparing what is obtained into the simulation by a virtual device placed at half height (11.7 m) of the canyon with what was really measured by a horizontal albedometer at the same place during the experimental campaign (Figure 3, left). The simulated global radiation seems to be in good agreement with the measurements, both for the upper and the lower parts of the device. The mask effect is well reproduced during the morning (until 8 UTC) and the afternoon (from 16 UTC). The radiation received by the lower part is exclusively due to reflections on the objects and records very weak values (83 W m^{-2} maximum, against 810 W m^{-2} for the upper side). This gives a global albedo of 0.1 around noon. The deviation between the simulation and the measures are highest for the upper part and especially at the moment when the sun appears/disappears behind the buildings. On the whole, the simulation underestimates the radiation by 5 W m^{-2} for the upper part. For the lower part, the error fluctuates between +11 W m^{-2} (in the morning) and -15 W m^{-2} (in the afternoon). Slight reflectivity differences between the opposite walls of the canyon could explain this phenomenon.

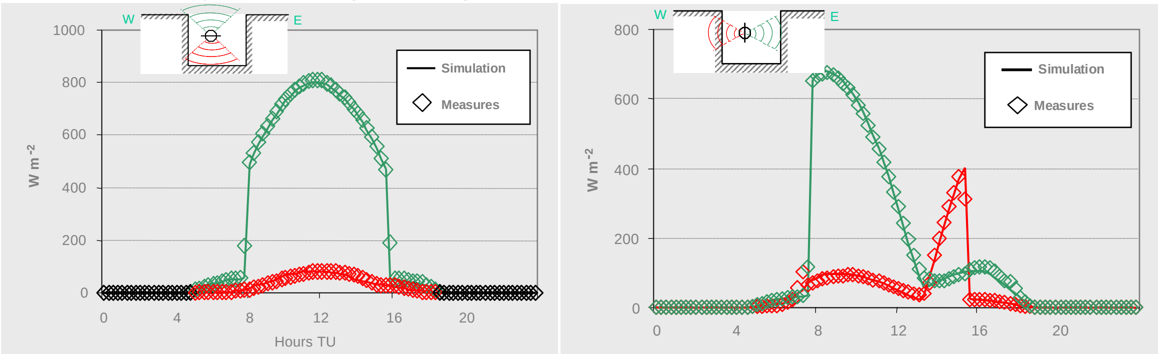

Fig. 3 Validation of the horizontal (left) and vertical (right) global radiation at mid height of the canyon

The same kind of comparisons can be made for a vertical albedometer placed nearly at the middle of the street and facing the canyon's walls (Figure 3, right). Considering the street azimuth (35° from the north), the two sides of the device (exposed respectively to the ESE and to the WNW) receive the maximum of radiation respectively during the morning and the afternoon. The complicated diurnal kinetic of this device is well reproduced by the model. Whatever the side, the global radiation exhibits two peaks of unequal intensity: the peak with the maximum of intensity arises when the sensor sees directly the sun, and the second arises when it receives the maximum of reflected radiation. Here too, the errors are minimized.

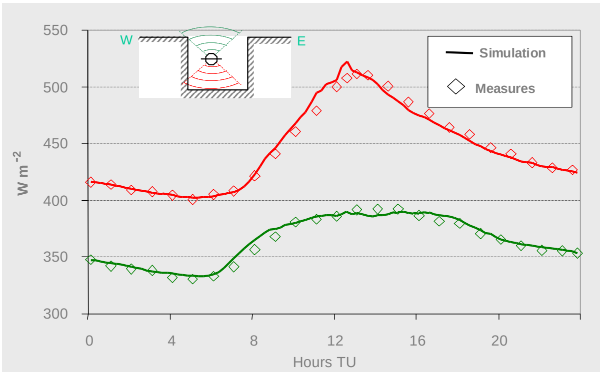

Fig. 4 Validation of the infrared radiation on a horizontal plane at mid height of the canyon

The infrared radiation is extremely influenced by the surface temperatures. The validation of this term is of fundamental importance to test the global quality of an energy balance model. Here, the simulated infrared radiation is compared to the measurements of two horizontal pyrgeometers placed at the middle of the canyon (Figure 4). As the device exposed to the ground (bottom) sees an object of relatively high brightness temperature, it logically records highest values than the device exposed to the sky (511 W m^{-2} against 390 W m^{-2}). The difference between the simulation and the measurements doesn't exceed 10 W m^{-2} for the upper device and 16 W m^{-2} for the lower device. The lower device tends to overestimate during the morning (the warming phase) and to underestimate during the afternoon (the cooling phase).

5. Validation of the heat fluxes on a district

Another real case test was conducted on an extended simulation domain to validate some other aspects of the model. The chosen area (see Figure 1, right) reproduces several typical blocks of a district of the Strasbourg conurbation (France). It combines various types of structures (houses, small buildings, garage) as well as several different ground covers (grass, roads, pool). The 3D geometry of the district comes from a database of the French national geographic institute (BD TOPO®, IGN). But, for the reason of a lack of data about this kind of information in the original IGN database, the final simulation domain neither contains trees nor windows. Furthermore, the shapes of the buildings are extremely simplified (no chimneys, balconies, stairs, flat facades…), the streets are flat and uniform, and there are no hedges or separating walls between the plots. The area is covered with artificial coating (55.1%, essentially roads and sidewalks), natural coating (12.3%, grass or bare soil) and with buildings (32.6%). The average building height (H) is of about 18m and the average distance between the facades (W) of 28.6m (this gives an H/W ratio of 0.63). As the materials of the different elements are not known precisely, they are imposed with the following hypothesis: the natural ground is covered everywhere with grass and the column of soil is made up with fine silt (17% sand, 70% silt, 13% clay); the roads are made up with a thin asphalt layer upon a thick ballast layer; the facades of the buildings are made up with a unique concrete layer (30 cm thick, no insulation) and the roofs are covered with tiles (no insulation). Standard physical characteristics are given to all the materials from tables found into the literature (for example, tables of material properties can be found in Pielke, 1984). To obtain the results at a sufficiently fine spatial resolution, and to preserve reasonable simulation time, the entire scene is fragmented into 9000 triangular meshes (with a surface area ranging from 2 to 60 m²). The urban canopy layer is covered by a network of voxels with a horizontal resolution of 250m and a height of 28.6m.

The simulation period take place between august 13 and 16 of 2002. As the model seems to be able to simulate accurately the radiation at specific locations into the urban canopy (see the previous chapter), this test is the occasion to change the scale and to focus on other aspects, especially on what is going out of the top of the urban canopy (as the sensible heat flux) or the storage of heat into the town (the ground heat flux).

The sensible heat flux going out of the top of the central voxel of the simulation domain can be compared (Figure 5) with Sonic anemometer measurements of three experimental sites acquiring the flux 10 m over the roof level (PEGE, IPG) or just at roof level (Argonne). The simulation is globally consistent with the three measurements, but is constantly higher: slightly nighttime (of about 10 to 20 W m^{-2}), but more daytime (about 80 to sometimes more than 100 W m^{-2}).

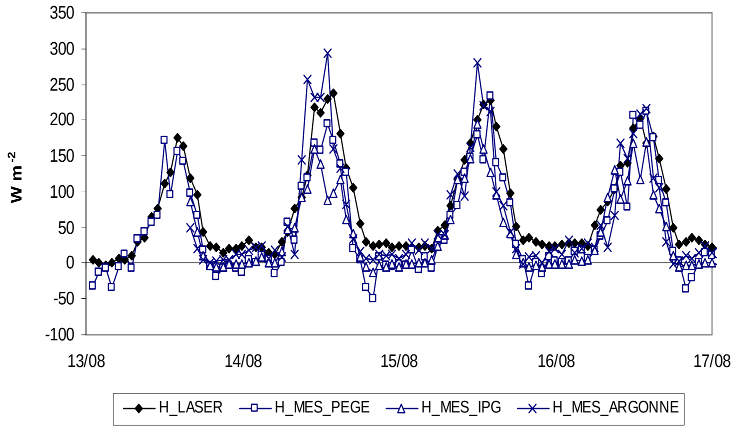

Fig. 5 Validation of the simulated sensible heat flux going out of the top of the voxel (H_LASER) with the data of three measurement sites (H_MES).

The heat flux into the ground is of special importance for the urban climate. It gives the part of the energy stored into the urban elements during the day and returned to the surface during the night. This term is concerned with two main problems: (i) it varies enormously in accordance with the physical properties of the materials (as the thermal conductivity), hence the importance to correctly parameterize the materials into the simulation; (ii) it is very difficult to measure this term directly with some devices during the experimental campaigns (and particularly spatially). To circumvent this later problem, it is possible to estimate the ground heat flux as the residual of the other terms of the energy balance. As a consequence, the experimental G values are obtained by applying this procedure for the PEGE, IPG and Argonne sites. From the point of view of the simulation, the G term is simply a spatial average (for the voxel) of the final value of the heat conduction equation applied on each ground element.

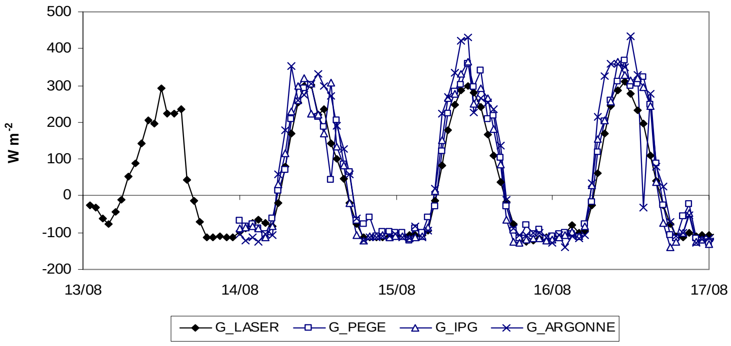

Fig. 6 Validation of the mean ground heat flux simulated for the voxel (G_LASER) with the ground heat flux estimated with the data of three measurement sites.

Despite these difficulties, the comparison between the simulated and experimental values is satisfactory (Figure 6). As expected, G points towards the surface during the night (negative value of about -100 W m^{-2}) and towards the depth of the materials during the day (positive value of up to +400 W m^{-2}). The differences between the measurements and the simulated values are rather weak nighttime (often less than 10 W m^{-2}), but become larger daytime.

6. Conclusion

The LASER/F simulation model can be considered as an urban canopy model specially designed for urban climate studies. It simulates the heat transfers and all the physical processes at high resolution if necessary (some square meters). It takes into account the "real" geometry of the town elements in 3D. Specialized algorithms are implemented to simulate the radiative exchanges and the characteristics of all the physical processes implied into the urban climate can be analyzed. The comparison between the simulated and the experimental values can be considered with satisfaction. New tests must be undertaken in the future to validate the model for natural land covers. An experimental campaign is actually in progress to obtain the values for a garden (Landes *et al*., 2014).

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