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THE ROLE OF GEOMETRIC FACTORS IN URBAN CANYON MODELING: NEW PARAMETERIZATIONS AND SENSITIVITY ANALYSIS

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Abstract: In numerical forecasting models the description of the urban-atmosphere interaction, is carried out by parametric schemes that provide an estimation of turbulent heat fluxes exchanged by urban surfaces with the air aloft. Among the various existing models, the Town Energy Budget (TEB) employs an accurate description of physical phenomena usually observed in an urban environment. To calculate the radiative budget and the turbulent flows, TEB considers the canyon as an element placed in the urban space with an averaged orientation. To evaluate the role of the canyon orientation on the turbulent heat flux calculation exchanged with atmosphere, TEB scheme has been modified through the development and inclusion of new parameterizations. A sensitivity analysis was performed to verify the weight associated with the introduction of these new parameterizations, using the TEB model coupled with the mesoscale atmospheric model RAMS. The results show a relatively significant impact of the orientation, on the energy budget, although the walls surface temperatures modeled with the original TEB scheme differ noticeably from those calculated with the new parameterizations.

Key words: *canyon scheme, TEB, surface energy budget, RAMS.*

INTRODUCTION

In numerical forecasting models the description of the urban land and atmosphere interaction, is carried out by parametric schemes that provide an estimation of turbulent heat fluxes exchanged by urban surfaces with the layers above. Among the various existing models, the Town Energy Budget (TEB) (Masson V., 2000) employs an accurate description of physical phenomena usually observed in an urban environment, and at the same time, it adopts a scheme with a low computational cost. TEB evaluates the turbulent fluxes exchanged with the atmosphere, resolving the radiative and thermal budgets for the urban areas approximated by the canyon surfaces (i.e. roofs, walls and road). The TEB adopt an original representation of the urban surfaces, in which each canyon is characterized by an averaged orientation over 360°, and in which the opposing walls have the same geometric and thermal characteristics. In this frame of reference, the urban canyon is assumed to be equal to the space bounded by a road bordered by identical walls. Since the effect associated with the walls is actually described by a single surface, which assumes same values equal to the average values of two opposing walls, the TEB is de facto, according to the definition adopted by Porson et al. (2009), a three facet model. In a description, such as this, the urban canyon physical scheme, must be considered two dimensional. The main approximations adopted in TEB are represented by the: a three facet description with averaged orientation assumption (a), and by the canyon boundary effects neglecting (b).

These approximations are directly involved both in the calculation of sky view factors and in the radiative budget, both in the determination of wind speed profile inside the canyon and then for the aerodynamic resistances calculation. A canyon described in such a way, looks like an idealized element, very different from what is usually observed in a real city. In relation with the above mentioned approximations we define the TEB model as a level-0 canyon model (hereinafter L0CM), as both the two approximations has not been removed. Indeed a canyon model where true orientation is considered, is defined a level-1 canyon model (L1CM), as it becomes a four facets model; a canyon scheme in which both approximations are removed is called a level-2 canyon model (L2CM). For the two last models (L1CM and L2CM respectively) new parameterizations are necessary, in order to describe the thermal-radiative budget in a more complex physical system (relatively to L0CM). In this work just the L1CM parameterizations have been developed, in order to perform a sensitivity analysis which aims to identify the role of the canyon orientation in a TEB urban scheme framework.

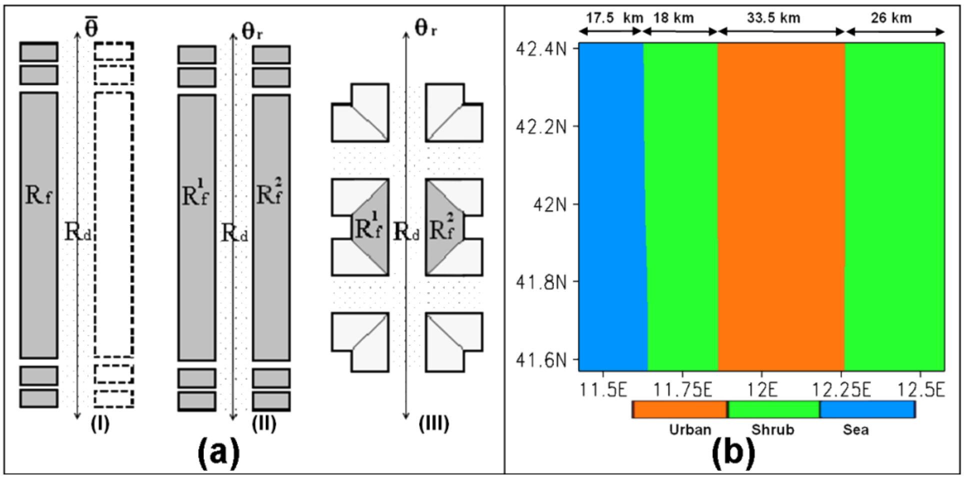

Figure 38. (a) Canyon model description, (from left) level-0 CM (I), level-1 CM (II) and level-2 CM (III); (b) simulation domain and land use map representation.

THE L1CM PARAMETRIZATION

In the L1CM as mentioned above, is removed the approximation that consider an average orientation of canyon axis respect to the urban space, instead the true canyon orientation is considered. First of all, the use of the true orientation would changes the relationships that govern the solar radiation calculation of each surface belonging to the canyon. Using the same approach as indicated by Masson V. (2000), the incident solar radiation for the walls and for the road can be written as:

$$S\Downarrow_w(\theta^*) = \begin{cases} S\Downarrow \tan\lambda|\sin\theta^*|, & \lambda < \lambda_0 \\ S\Downarrow \frac{\mathrm{W}}{\mathrm{H}}|\sin\theta^*|, & \lambda \geq \lambda_0 \end{cases} \tag{1}$$

$$S\Downarrow_w(\theta^*) = \begin{cases} S\Downarrow \left(1 - \frac{H}{W|\sin\theta^*|}\tan\lambda\right), & \lambda < \lambda_0 \\ 0, & \lambda \geq \lambda_0 \end{cases} \tag{2}$$

Here $\lambda_0 = \tan^{-1}(W/H)$, H indicates the average building height in the canyon and W indicates the average road width; λ, is the zenith angle, $S\Downarrow$ is the direct solar radiation received by an horizontal surface, while $\theta^* = \gamma_S - \theta_r$, where γ_S is the clockwise angle between the north and the direction of the sun, and θ_r is the clockwise angle between the north and the canyon axis. Similarly, for the terms that describe the multiple reflections of solar radiation between two walls, the equations in TEB have been rewritten to take into account the addition of the opposite wall. This was achieved by modifying the sky view factors in order to isolate the contribution of each wall. Even in the calculation of the infrared radiation, an equation that includes the presence of two distinct wall, has been added. Conceptually, the equations of the infrared radiation does not stand apart from those provided in the TEB scheme, although several changes were introduced in the terms that compose them. About the calculation of turbulent fluxes exchanged by the canyon with the above atmosphere, the introduction of the canyon orientation has necessitated the adoption of a new scheme. In TEB model, the turbulent heat fluxes calculation is based on the bulk formulation (Garratt, 1994). The turbulent heat flux is determined as one calculates the temperature difference value among two layers, and the aerodynamic drag value; the latter depends strongly on the wind speed calculation near the surface, where heat exchange takes place. In order to determine the wind speed within the urban canyon, and to define its dependency on its orientation, it was decided to split this calculation, respect to the canyon wind speed components: .i.e. the longitudinal wind velocity component and the perpendiculars components. This approach follows the results proposed by Soulhac et al. (2008) where was proved how the average longitudinal wind speed intensity inside the canyon, remains almost constant respect to the canyon orientation, except for a wind perpendicular to the canyon axis, in which, as expected, the longitudinal wind component vanishes. Moreover in the same paper, a minor influence of the canyon orientation on the perpendicular components of the wind, was showed. These considerations allows a scheme in which a separate calculation of the various components of the wind in the canyon (i.e., perpendiculars and parallel) are performed. For the calculation of average longitudinal wind speed intensity, the formulation used (Soulhac et al., 2008) for an infinitely long canyon, could be written as:

$$\bar{u}_{//} = u_{ctop}\frac{\delta_i^2}{HW}\left[\frac{2\sqrt{2}}{C}(1-\beta)\left(1-\frac{\pi}{2}H(C)\right) + \beta\frac{2\alpha-3}{\alpha} + \left(\frac{W}{\delta_i} - \right)\left(\frac{\alpha-1}{\alpha}\right)\right] \tag{3}$$

with,

$$\alpha = \ln\left(\frac{\delta_i}{\bar{z}_{0can}}\right) \tag{4}$$

$$\beta = exp\left[\frac{C}{\sqrt{2}}\left(1-\frac{H}{\delta_i}\right)\right] \tag{5}$$

Here $u_{ctop} = u(z_{top})|\cos\theta^*|$, $\bar{z}_{0can}$ is the average canyon roughness length, while δ_i=min(H,W/2). The C parameter that appears in the equation (3), and whose definition it's referred to the work of Soulhac et al. (2008), was calculated by the subsequent polynomial interpolation:

$$C = 0.016473\ln\frac{\bar{z}_{0can}}{\delta_i} + 4.399e^{-4}\left(\ln\frac{\bar{z}_{0can}}{\delta_i}\right)^2 - 1.7419\left(\ln\frac{\bar{z}_{0can}}{\delta_i}\right)^{-1} - 0.17227\left(\ln\frac{\bar{z}_{0can}}{\delta_i}\right)^{-2} + 0.41282 \tag{6}$$

The Struve function $H(C)\,\pi/2$, was determined according to Abramowitz M. and Stegun I.A. (1965). The calculation of the wind components perpendicular to the axis of the canyon, was executed following the approach developed by Harman et al. (2004). The authors, on the basis of experimental results obtained in the wind tunnel, assimilate the turbulent exchange in the vicinity of canyon wall, as that produced by a jet flow on the same wall. To derive the velocity of the jet, Harman et al. (2004) suggest a power law that describes the effect of the resistance exerted by the surfaces on the jet, which takes the following form:

$$u_i(x) = \frac{u_{ctop}}{b}exp\left(-0.18\,\frac{L_{se}}{H}\right)\int_b^{a+b} exp\left(-\alpha_2\,\frac{x}{H}\right)dx \qquad i = wall, road \tag{7}$$

In this case $u_{ctop} = u(z_{top})|\sin\theta^*|$, $\alpha_2 = 0.15\,max(1, 1.5H/W)$, while L_{se} was set equal to $L_{se} = \pi W/4$. The index i denotes the canyon surface for which the speed calculation occurs, while the limits of integration of the integral, identify the length of the surface. Both equations (6) and (7) require the knowledge of wind speed at altitude $z_{top} = H - d + z_{0m}$ in which d and z_{0m} denote respectively the displacement height and roughness height. For the calculation of these parameters were used the parametric relationships derived by Kastner-Klein and MW Rotach (2004):

$$d = 0.4H \frac{A_p}{A_T} exp\left[-2.2\left(\frac{A_p}{A_T} - 1\right)\right] + 0.6\frac{A_p}{A_T} \quad (8)$$

$$z_{0m} = 0.072H \frac{A_p}{A_T}\left\{exp\left[-2.2\left(\frac{A_p}{A_T} - 1\right)\right] - 1\right\} \quad (9)$$

Here A_p/A_T represents the ratio between the average plan area of roughness elements and total surface area. The profile of wind speed from the first node of the atmospheric model to the top of the canyon was extracted by the logarithmic low:

$$u(z_{top}) = \frac{u_*}{k}\left[\ln\left(\frac{z_{top}}{z_{0m}}\right) - \psi_m\left(\frac{z_{top}}{L}\right)\right] \quad (10)$$

The term $\psi_m(z_{top}/\mathrm{L})$ was calculated in accordance with the scheme of Mascart et al. (1995). The friction velocity u_*, is calculated directly by the atmospheric model. Once the values of $\bar{u}_{//}$, and $u_i(x)$ are known, the calculation of the turbulent sensible flux exchanged between the canyon and the first level of the atmospheric model, could be performed according to:

$$Q_{Hcan} = \rho\, c_p \frac{(T_{can} - T_a)}{r_{can}} \quad (11)$$

in which,

$$T_{can} = \left(\frac{T_{ew}}{r_{ew}} + \frac{T_r}{r_r} + \frac{T_{ww}}{r_{ww}} + \frac{T_a}{r_{can}}\right)\left(\frac{1}{r_{ew}} + \frac{1}{r_r} + \frac{1}{r_{ww}} + \frac{1}{r_{can}}\right)^{-1} \quad (12)$$

$$r_{can} = \left(u_a - \sqrt{u_r^2 + \bar{u}_{//}^2}\right) u_*^{-2} \quad (13)$$

$$r_i = \ln\left(\frac{0.1H}{z_{0mi}}\right)\ln\left(\frac{0.1H}{z_{0Hi}}\right)\left(k^2\sqrt{u_i^2 + \bar{u}_{//}^2}\right)^{-1} \qquad i = ew, ww, r \quad (14)$$

Here T_a, u_a are the temperature and the wind speed related to the first node of the atmospheric model, while ew, ww, r denote respectively the eastern wall, western wall and the road. T_{ew}, T_{ww} and T_r are the temperatures of the canyon surfaces, and as for the sensible roof heat flux, are calculated with the same formulation used in the TEB.
To make the results comparable with those generated by the L1CM, the wind speed parameterization in urban canyon for L0CM has been changed. According to Masson V. (2000) to take into account all possible orientations, the equation (10) was multiplied by $2/\pi$. The calculation of turbulent flows has been carried out in accordance with equations (11)-(14) taking into account that, in the L0CM only the temperature of one wall is present. The two schemes have then been tested through their implementation in the mesoscale numerical model RAMS 6.0, through a two-way connection.

RESULTS

In order to perform the sensitivity analysis and to isolate the contribution of the canyon orientation on the turbulent fluxes calculation, a very simple computational domain in terms of topography and land use, has been realized inside the RAMS model. The domain has an horizontal width of 96x96 km2, with a grid step of 2 km. 44 vertical levels extend up to an altitude of approx. 21000 m a.g.l. (above ground level); the first node on the vertical line is placed at an altitude of 5 m a.g.l.. The domain has an almost flat terrain except for the urban area characterized by a ground altitude (above sea level) of 20 m, due to the presence of the urban canyons. Land use is characterized by four areas that extend longitudinally and identify, from west to east, respectively: a 17.5 km wide sea cover, a 18 km wide land covered with Mediterranean shrubs, a 33 km wide urban land and finally a 26 km wide rural ground covered with Mediterranean shrubs. Runs last 48 hours and were performed during typical summer weather conditions in July, located around 42 N, 12E. For the L0CM a single simulation was executed, while for the L1CM 6 runs where performed. For each L1CM run, a different orientation of the canyon in the plan was chosen, expressed by the angle θ_r who took respectively the values of 0 °, 30 °, 60 °, 90 °, 120 ° and 150 ° measured clockwise from the north. The angle 180 ° was not considered because it provides equal result respect to 0 °. The same goes for the angles between 180 ° and 360 °, for reasons of symmetry. The urban canyon geometry is characterized by an aspect ratio H / W = 1, with H = W = 20 m. Three levels were considered for each surface constituting the urban canyon in accordance with the TEB scheme. The thickness and the thermal characteristics of the levels are reported in Table 1. The initial temperature for the buildings and for all the layers, was set equal to outside air temperature. The TEB allows the addition of a certain amount of sensible heat flux due to anthropogenic sources. In this case, for both schemes, has been used a constant anthropogenic source in the energy budget, by adding the amount Q_{Ha}= 10 W/m^2; for the urban cover, throughout the entire duration of the runs, the latent heat flux was set equal to zero. The fluid dynamics field was initialized with a vertical profile taken at 06 UTC. In order to reduce the effects due to the uncertainty in initial conditions, all the output values were extracted, starting from 24 hours after the beginning of the simulations.

The results show a small difference in the turbulent heat fluxes obtained with the L0CM, respect to the L1CM. Overall, the sensible heat flux, obtained with the L1CM exhibits a lower value respect to those obtained with L0CM, as displayed in Figure 2a and 2b. This trend appear clearly in Figure 3a, which shows as the sensible heat flux simulated by L0CM, is on average about 13 W/m^2 greater respect to that simulated with the L1CM. The larger contribution to this increment, comes mainly from the different simulated wall temperatures. The lack of effective shading in the L0CM, results in a high average outdoor wall temperature, which is an average 10.9 ° K higher than the average wall temperatures with L1CM. This heat surplus does not imply an expected increase in sensible heat flux values. This could be associated to the low turbulent transport in the urban canyon occurred probably due to low wind speed intensity simulated with the RAMS, near surface, and due to the low air humidity value above the urban canopy in response to the absence of the latent turbulent heat flux.

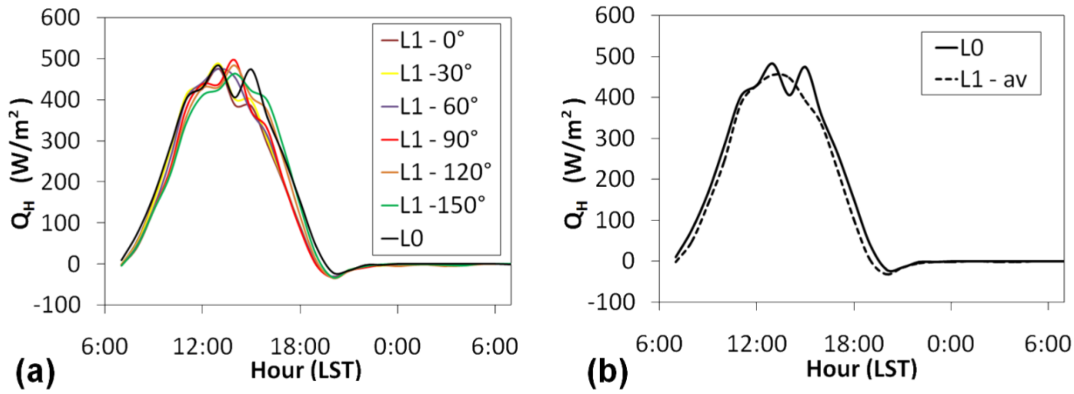

Figure 39. (a) Surface sensible heat flux Q_H (Wm^{-2}) for L0CM and for L1CM runs with all different canyon orientations. (b) Surface sensible heat flux Q_H (Wm^{-2}) evolution at first model node for L0CM (here L0) and for L1CM (here L1-av); the latter is obtained, for sake of simplicity, performing an average of all fluxes coming from all different orientation.

Table 8. Thermal parameters for roofs, walls, and roads used in TEB L0CM and L1CM. Layer sequence: *el* indicate external layer nearest to the surface, *ml* is middle layer, *il* is internal layer. Here d is thickness of layer (m), C is heat capacity of layer (MJ m^{-3} K^{-1}), λ is thermal conductivity (W m^{-1} K^{-1}), α is the surface albedo and ε the emissivity.

	Roof *el*	Roof *ml*	Roof *il*	Road *el*	Road *ml*	Road *il*	Walls *el*	Walls *ml*	Walls *il*
λ	0.98	0.98	1.51	0.82	2.1	0.4	1.51	0.60	1.51
C	2.1	1.6	2.01	1.7	2.0	1.4	2.01	1.2	2.01
d	0.057	0.27	0.02	0.05	0.2	1	0.02	0.26	0.02
α	0.20	-	-	0.10	-	-	0.25	-	-
ε	0.9	-	-	0.95	-	-	0.85	-	-

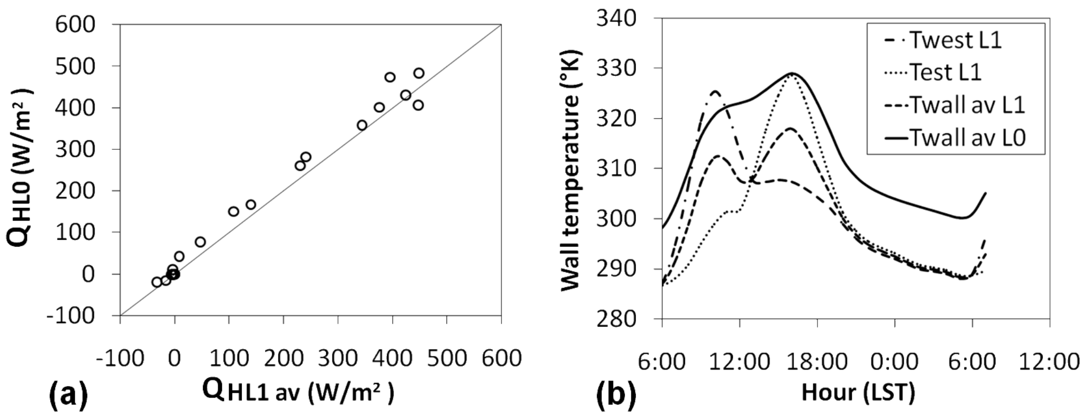

Figure 40. (a) Surface sensible heat flux Q_H (Wm^{-2}) for L0CM (here Q_{HL0}) vs L1CM (here Q_{HL1av}) averaged on all orientation, (b) Surface temperature trend (°K) for L1CM walls and for L0CM wall.

CONCLUSION

The original TEB scheme, or L0CM, as defined here, was amended to introduce the parameter of the true canyon orientation in the urban space. A new parameterization for the wind speed, which takes into account the angle of incidence of the wind compared to the canyon axis, has been introduced. Moreover the schemes that regulates the solar radiation has been modified to take in to account the shadowing of both walls. A TEB model, modified in such a way, was defined L1CM. A 48 hours run was performed with the mesoscale atmospheric model RAMS coupled with L0CM and L1CM. The results show a slight tendency to overestimate the turbulent sensible heat fluxes by L0CM respect to the L1CM. The temperature evolution of the wall, for the L0CM, shows a trend much greater than the average temperature of the L1CM walls. More runs are needed to evaluate the difference between the two patterns due to different initial conditions.

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