H13-170

SENSITIVITY OF AN URBAN SUB-GRID SCHEME TO THE CANYONS ORIENTATIONS OVER A WIDE METROPOLITAN AREA

Antonio Cantelli[1], Paolo Monti[1], Giovanni Leuzzi[1] and Federico Failla[1]

[1]"Sapienza" Università di Roma, Via Eudossiana 18, 00184 Roma, Italy.

Abstract: In order to improve and incorporate the urban heat island (UHI) effects within mesoscale atmospheric models, Masson, V. (2000) proposed the physically-based model TEB (Town Energy Balance). In accordance with Porson, A. *et al.* (2009), the TEB can be defined as a three-facet model (hereinafter TFM), in that it utilizes three surfaces (roof, wall and road) to describe the canyon geometry. Unlike the TFM, the four facet model (hereinafter FFM), in the radiative and thermal budget, takes into account the facing walls of the canyon and their mutual orientation as well. Porson, A. *et al.* (2009) showed that the TFM exhibits a good agreement with the FFM, except for an error that comes from considering the average orientation of the urban canyons instead of the actual ones. However, the amplitude of the error associated with the TFM description on a wide urban area, (i.e., the domain of influence of a surface node in the computational grid) where the canyons show random orientations is still not well known. In order to investigate how much the averaging over the street canyon orientation affects the accuracy of the energy budget, an urban sub-grid scheme based on TEB was coupled with the Regional Atmospheric Modelling System (RAMS, Pielke, R.A. *et al.* 1992). Several model runs were then performed to simulate typical summertime atmospheric conditions as most favourable to observe the UHI effects over the urban area of Rome (Italy). The use of TEB-FFM, in association with a subgrid scheme, which takes into account each single canyon in the domain of influence of a grid node, effects significantly the sensible heat flux at the surface. The analysis allows us to ascertain that, for the purpose of atmospheric modelling, the choice of a proper urban sub-grid scheme must be supported by the knowledge of the detailed urban surface texture.

Key words: *urban heat island, urban energy budget, street canyon, TEB, RAMS.*

INTRODUCTION

In mesoscale atmospheric modelling, adequate reconstruction of the meteorological field over cities is essential for an accurate determination of the parameters governing transport and dispersion of pollutants in the urban boundary layer. In recent years, many efforts have been made by several authors to improve and integrate the city effects within the numerical weather prediction (NWP). Among the various schemes proposed in the past, the most popular are the single-layer model of Masson, V. (2000) and the multi-layer model of Martilli, A. *et al.* (2002). Between the two, the more easily implemented in a numerical model seems to be the Town Energy Budget (TEB) of Masson, V. (2000). The TEB has been used several times in mesoscale numerical models. For example, Lemonsu, A. and V. Masson (2002) described the interaction of the summer breeze with the city of Paris (France), while Freitas, E.D. *et al.* (2007) investigated the breeze circulation during winter over the metropolitan area of São Paulo (Brazil).

The TEB scheme is based on the canyon concept (e.g., Oke, T.R., 1987). The canyon is the space contained between two facing buildings, and it is delimited by four surfaces, respectively, the roof, the road and two walls. In accordance with the definitions given by Porson, A. *et al.* (2009), the TEB scheme can be defined as a three facet model in that it utilizes, in the radiative and thermal budget, an average temperature between the two walls. Unlike the TFM, the four facet model takes into account both the walls of the canyon and their mutual orientation as well. This means that the shadowing effect is calculated for both walls at every model time-step. Porson, A. *et al.* (2009) found that the FFM behaves similarly to the TFM; nevertheless, it allows the chance, for the purpose of atmospheric modelling, to use a true town representation (TTR), where all roads with their canyons associated to each grid urban node are taken into consideration. In this way, urban area is no longer described by a synthetic town representation (STR), where all the buildings have the same height and width and are located along identical roads, but the roads are different one from the other according to the real urban texture.

The use of TTR rather than STR changes the way in which the heat fluxes at street scale are linked to the turbulent fluxes above the roughness sub-layer at town scale. If, for every part of the city, the definition of the fractional building area, α_B, is possible, then, according to Masson, V. (2000) in STR, the total sensible turbulent flux towards the first model atmospheric layer is:

$$H = [\alpha_B H_{Roof} + (1-\alpha_B) H_{Top}] \tag{1}$$

where H_{roof} is the sensible heat flux due to the roof surfaces and H_{top} is the sensible heat flux associated with the top canyon contribution. In this case, the industrial heat releases are neglected. A similar expression is used for the latent heat flux. As shown by Masson, V. (2000), H_{roof} and H_{top} are non-linear functions of constant parameters (e.g., canyon aspect ratio, albedo, emissivity, etc.) as well as time dependent variables (surface temperatures, canyon wind velocity, stability parameters, among others). Therefore, equation (1), for the STR can be generalized as:

$$H_{STR}(t) = [\alpha_B f_{roof}(k, \varepsilon(t)) + (1-\alpha_B) f_{top}(h, \gamma(t))] \tag{2}$$

where k and h are constant parameters averaged over the influence domain of each grid node, while $\varepsilon(t)$ and $\gamma(t)$ indicate time dependent variables. From equation (2), the use of a STR implies that for each urban grid cell the sensible turbulent flux is simply driven by an average canyon. In contrast, in TTR, the surface energy budget is considered as an average calculated over all sensible turbulent fluxes associated to different canyons. This is equivalent to written equation (1) as:

$$H_{TTR}(t) = \frac{1}{N}\sum_{i=1}^{N}\left[\alpha_{Bi} f_{roof}(k_i, \varepsilon_i(t)) + (1-\alpha_{Bi}) f_{top}(h_i, \gamma_i(t))\right] \tag{3}$$

where *i* indicates the generic canyon which belongs to the domain of influence of a surface node in the computational grid. For a single canyon, Porson, A. *et al.* (2009) showed that the TFM exhibits a good agreement with the FFM. However, the amplitude of the error associated with a TFM description on a wide area described by the STR is still not known. The aim of this work is to investigate how much the averaging over the street canyon orientation, associated to the STR utilization, affects the accuracy of the urban energy budget.

STEB SCHEME AND STUDY DOMAIN

An urban sub-grid scheme based on TEB model is coupled with the Regional Atmospheric Modelling System (RAMS, version 6.0, Pielke, R.A. *et al.*, 1992) to investigate the difference between STR and TTR approaches in the case of the urban area of Rome (Italy). The TEB original scheme is modified in order to take into account the heat budget of both the canyon walls and their own orientation as needed by the FFM. Hereinafter, this scheme will be indicated as STEB (Subgrid Town Energy Budget).

In respect of the original TEB scheme, the STEB basically differs for the utilization of finite length canyon delimited by two facing walls. Furthermore, a formulation for the sky view factor that takes into account the boundary effect for each canyon surface is employed (Johnson, G.T. and I.D. Watson, 1984). For this reason, the assumption of canyon like an infinite segment is no longer applied. The canyon orientation relative to the sun's direction is introduced in the shortwave equation. The influence of canyon axis angle on the wind direction inside the canyon is modelled by using the semi-empirical algorithm of C. Georgakis and M. Santamouris (2005).

As mentioned above, the application of the RAMS-STEB requires a large canyon database, which includes all roads and their respective facing buildings for all the urban area. In order to build-up such database, a three-phase procedure is adopted.

In the first phase, all the roads contained in a shape file and associated with the Roman area are selected. In our case, more than 20800 streets are used. In the second phase, an urban digital elevation model (DEM) that covers about 5 km^2 of the city centre of Rome with a horizontal average resolution of 1 meter, is overlapped to the roads shape file. Finally, in the last phase, a canyon extracting algorithm is used to associate all the information required to properly describe the canyon geometry at each road (Fig. 1). Since the available DEM covers only a limited portion of the city centre, standard geometrical information is associated to each canyon where the utilization of extracting algorithm is not possible. All the canyons are displaced in each urban cell of the grid points, according to the TTR. Furthermore, starting from the knowledge of canyon geometry, the roughness length in the domain of influence of each surface node in the computational grid is calculated according to the formulation described by Britter, R.E. and S.R. Hanna (2003).

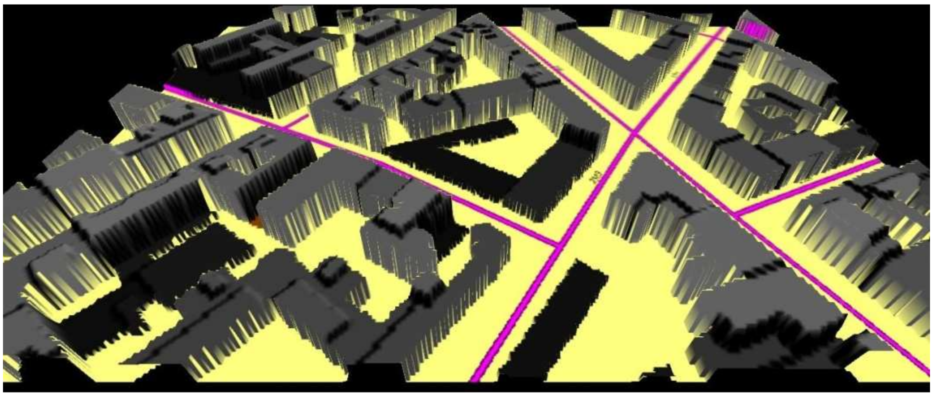

Figure 1. 3D view of the road graph (purple line) associated with the buildings (grey tone), for a small urban area of Rome.

For the sake of simplicity, for the emissivity and other thermal characteristics a single set of parameters is used to initialize the scheme for the whole city (Table 1). The initial internal building temperature was fixed to the value of 300 K. The microscale thermal parameters of individual facets with their respective sub-layers are defined following Masson, V. *et al.* (2002).

Two model runs are then performed to simulate typical summertime atmospheric conditions as most favourable to observe the UHI effects. In the first one, the coupled system RAMS-STEB is used (hereinafter Run A), while in the second one, the unmodified TEB scheme coupled with RAMS (hereinafter Run B) is adopted. The results are then compared with observations from measurements taken in the Roman urban area.

To perform the simulations three interactive nested domains are then selected (Fig. 2). The first coarse grid (960x960 km^2, hereinafter D01) covers a big portion of Italian peninsula. The grid cell size in the eastward and northward direction is set to 16 km. This parameter is chosen to simulate profitably the synoptic meteorological features. The second grid (240x240 km^2, hereinafter D02) is placed over central Italy, with a horizontal grid cell size fixed to 4 km. Finally, the finest grid (60x60 km^2, hereinafter D03), covers, with a horizontal resolution of 1 km, the main area of the Tiber river basin, including Rome urban area. At this scale, it is possible to simulate directly the presence of the UHI and to understand how it interacts with other local thermally induced circulations such as slope currents and sea breeze flows.

Table 1. Input parameters for TEB scheme.

Parameter	Unit	Value
Roof albedo	-	0.15
Wall albedo	-	0.35
Road albedo	-	0.12
Roof emissivity	-	0.91
Wall emissivity	-	0.85
Road emissivity	-	0.95
Initial internal building temperature	K	300
Roof roughness length	m	0.15
Road roughness length	m	0.1

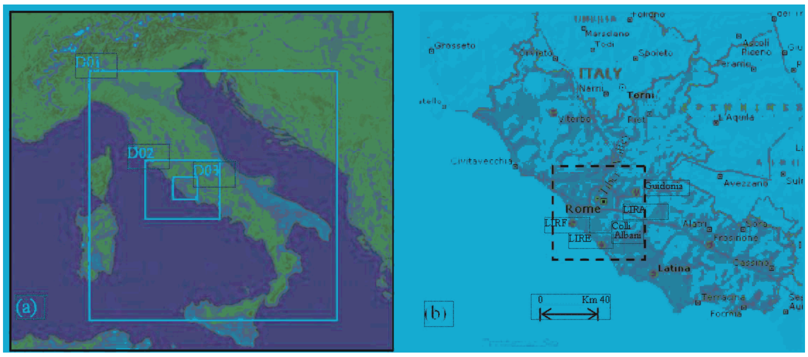

Figure 2. (a) Domain setup: D01 (resolution 16 Km), D02 (resolution 4 km) and D03 (resolution 1 km). (b) Enlarged view of (a) including the Lazio Region. The blue circle corresponds to Ciampino airport (LIRA), while the black square indicates the inner gridded domain (DO3) centred over Rome.

After the grids setting, initial and boundary conditions are then performed. The simulations are initialized by using the reanalysis taken at the synoptic hours from the UCAR (ds083.2 datasets). Great care was taken to define initial soil moisture condition. Due to the lack of consistent data in available meteorological datasets, to define the ground humidity, a lead simulation on D01 only for the month that precedes the two runs is also performed. This technique allows defining the initial soil moisture field in a more precise way than with other procedure and assures a lesser noise in the very start-up of the simulation.

EXPERIMENT RESULTS

Both runs A and B start at 06Z 26 June 2005 and last 48 hours. During this period typical summer weather conditions occurred, characterized by the presence of a persistent high pressure system and a northwesterly geostrophic wind. These conditions, in the case of clear skies, paved the way to the formation of the UHI which interacted with other thermally induced circulations such as sea breezes and slope winds.

To assess the capability of the STEB (Run A), time series of wind speed, wind direction and air temperature taken at a meteorological site located in the city centre of Rome, are compared with the numerical results of the simulation as shown in Figure 3. The run evidences a reasonable agreement with observations. It is interesting to note the capability of the model to reproduce the wind field modification (around the 12 Z) due to the interaction of sea breeze with UHI. The simulation is less accurate during the night and at the early morning hours. This is confirmed by the wind direction time series. Similarly, for air temperature time series the numerical simulation reproduces the observation reasonably well.

Detailed representations of the sensible heat flux difference between the Run A and Run B simulations ($\Delta H=H_A-H_B$) in correspondence of the urban area are reported in Figure 4. The strong spatial inhomogeneity of ΔH is a direct consequence of the detailed description of the major streets of the city of Rome used in simulation A. It is possible to observe how the ΔH magnitude appears stronger during the central hours of the day (Fig. 4b). This may be related to the different shortwave equations utilized between the two surface schemes. That is further supported observing the little value of ΔH during the night time (Figure 4d), when the incoming shortwave radiation clearly does not give any contribution to the surface energy budget. Furthermore, in all Figures 4a-d, a systematic discontinuity in ΔH distribution appears between the city centre and its neighbour. This is due to the different ways adopted to define the canyon geometry inside the urban area. As mentioned above, despite the true roads orientation adopted in the whole town, the real canyon geometry is used only inside the area covered by the urban DEM.

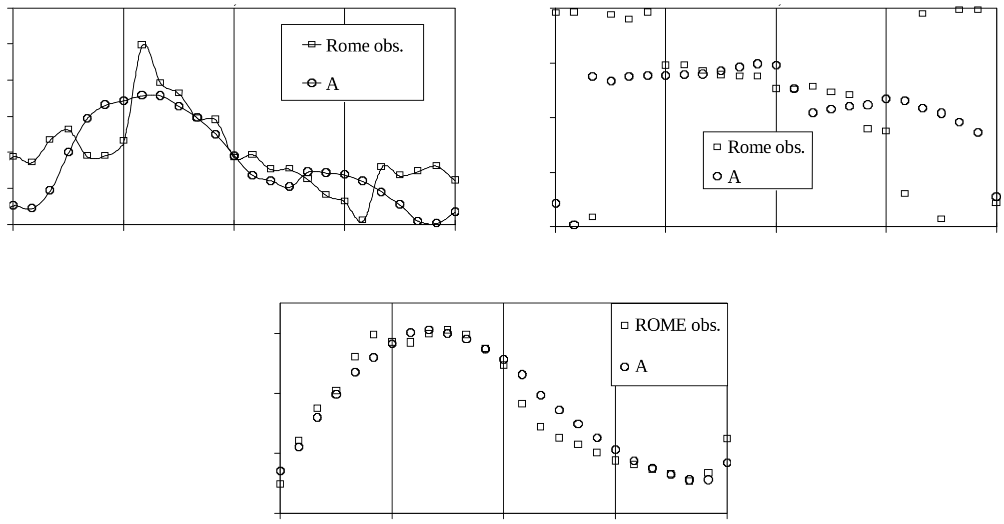

Figure 3. Comparison between observed (line with squares) and simulated (line with circles) wind speed (a), wind direction (b) and air temperature (c) at 10 m above ground level (agl) close to the centre of Rome, as a function of the hour (Z) of the day.

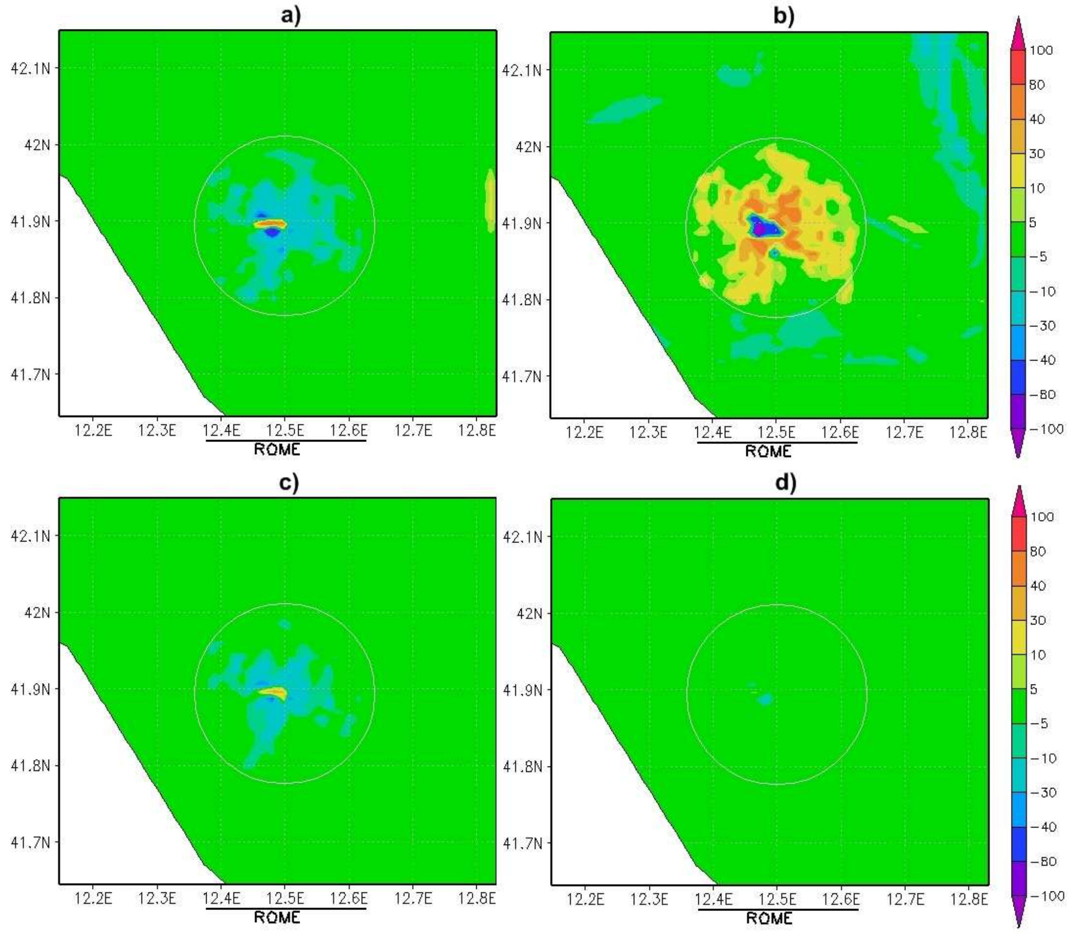

Figure 4. Sensible heat flux difference $\Delta H=H_A-H_B$ (colour in W m^{-2}) in grid G3 (the white circle indicates Rome) on 27 June 2005, at 06Z (a), 12Z (b), 18Z (c) and 00Z (d).

CONCLUSIONS

In order to improve and incorporate UHI effects within mesoscale atmospheric models, the subgrid scheme STEB based on TEB is proposed. The STEB utilizes all the real canyons which are present in the urban area. The original TEB features are adapted to the new subgrid scheme, introducing different parameterization for shortwave budget, sky view factor and canyon wind speed calculation. Moreover, the availability of a large urban digital elevation model (DEM) is utilized to calculate properly the roughness length. Both schemes are coupled with the regional atmospheric model RAMS in order to investigate the UHI and its interaction with other local thermally induced circulations over the urban area of Rome (Italy) during 26-28 June 2005. Two numerical runs are then performed to assess the different capabilities of TEB and STEB schemes to reproduce correctly the urban surface energy budget.

Time series of wind speed, wind direction and air temperature taken at a meteorological site located in the city centre, are compared with the numerical results of the STEB simulation. It is found that the utilization of an average direction as in original TEB scheme could lead to an error in shortwave energy budget calculation, especially during the central hours of the day. Although more accurate results require a complete urban DEM, it is clear how the canyon geometry uncertainties affect the numerical simulation with regard to surface sensible heat flux budget. Further analyses are needed to assess the role of these uncertainties on air temperature tendency.

The authors are grateful to Dr. C. Gariazzo and Dr. A. Pellicioni who provided part of the observational data set used for the comparison, and to Prof. M.G. Crespi and Dr. F. Pieralice for the DEM.

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