DEVELOPMENT AND APPLICATION OF A SUBGRID URBAN SURFACE SCHEME OVER A WIDE METROPOLITAN AREA IN A LIMITED AREA MODEL

Antonio Cantelli[1], Paolo Monti[2], Giovanni Leuzzi[2]

[1]DIMA, "Sapienza" Università di Roma, Via Eudossiana 18, 00184 Roma, Italy
[2]DICEA, "Sapienza" Università di Roma, Via Eudossiana 18, 00184 Roma, Italy

Abstract: A subgrid model was developed in order to improve the surface energy budget evaluation over large urban areas. The model is capable to evaluate the energy budget of each building belonging to a built up area by employing an accurate canyon geometrical description. It was coupled with the limited area model RAMS and was applied to simulate the urban heat island over the metropolitan area of Rome. The model was initialized with an urban digital elevation model, accounting for nearly 360,000 buildings. The results shows that the subgrid model is able to reproduce the behaviour of the main meteorological quantities.

Key words: *Atmospheric Boundary Layer, Numerical Models, RAMS, Urban Heat Island, Town Energy budget****.***

INTRODUCTION

The correct simulation of the atmospheric circulation is of primary interest for the sake of urban air pollution modelling. In the last decade many efforts were carried out to improve the urban surface energy budget (SEB) coupled with numerical weather prediction models (NWPM). In order to overcome the difficulties that arise in modeling the urban SEB, several urban canopy schemes have been developed. These schemes are generally single layers (Dupont, S. and G. Mestayer 2006; Lee, S.H. and S.U. Park 2008; Ryu, Y.H. et al. 2011) or multi layers (Martilli, A. et al. 2002; Kondo, H. et al. 2005; Shubert, S. et al. 2012). In the former type, the first atmospheric NWPM level is placed above the urban canopy; in contrast, in the latter the atmospheric levels are immersed within the urban canopy. Among the single layer models, the TEB (Masson V., 2000) is one of the urban SEB schemes most applied over large cities (Freitas, E.D. et al. 2007; Lei, M. et al. 2008). The main TEB feature, is to describe all the urban surfaces that are involved in the energy balance. These surfaces are the roofs, the walls and the road that delimit the volume of air defined in the literature by Oke, T.R. (1995) as urban canyon (UC).

Since TEB is thought to be coupled with an NWPM, it describes the urban features contained in each grid-cell (of a dimension of a few hundred meters) of the numerical grid used by the NWPM. In order to make easier the coupling with the NWPM, the TEB assumes a simple urban geometry representation. In particular, three basic hypotheses for the UCs are adopted: (i) the canyons are equal among themselves, (ii) they have infinite length and (iii) they have no preferred orientation. This leads to consider a spatial mean of the geometrical characteristics of the portion of the urban area contained in the grid-cell and, therefore, of their effects on the turbulent fluxes exchanged by the TEB with the overlaying atmosphere. This simplifications makes the TEB easy to implement in an NWPM but, at the same time, some important urban features as squares and crossroads are not modelled by the SEB. Thus, in urban areas with characteristics far from the TEB simplified geometrical representation, the model may produce unrealistic turbulent heat fluxes and canopy air temperatures.

In order to improve the urban SEB modelling, the subgrid model STEB (Subgrid TEB) was developed. A previous version of the STEB based on the coupling of the original TEB scheme with the NWPM RAMS 6.0 (Cotton, W.R. et al. 2003) was presented in Cantelli, A. et al. (2011). In the present model version, the STEB shares with the TEB the same physics, but retains the true canyon azimuthal orientation and, at the same time, includes the canyon edge effects due to the crossroads (Cantelli, A. et al. 2013). This is possible since the model adopts a 3D infrared radiation budget that includes both finite-length streets and crossroads. Moreover, the STEB makes it possible to consider the roughness sublayer effects on the wind velocity within the canyons as well as on the turbulent fluxes. An important characteristic of STEB is the particular form of the adopted surface energy balance equations (Cantelli A, 2013), which allows easy ingestion of data provided an urban digital elevation models (UDEM). For the sake of brevity, the description of the STEB equations are not given here. Details on the model equations and sensitivity analysis of the STEB are given in Cantelli, A. et al. (2013).

The STEB algorithm consists of a three steps procedure. In the first step, the smaller building artefact are filtered out and a coarse buildings representation is thus carried out (Figures 1a-b). In the second step, the roof area Ab, the surrounding road area Ar, the building height H and the azimuthal building orientation θ are associated to each building. An example of the real coarse building extracted in such a way is shown in the first two pictures reported in Figure 1c. In the last step, the actual building shape must be converted to be suitable for the STEB algorithm; this is done by spreading the Ab area on a rectangular-shaped building and spreading the surrounding Ar area accordingly.

The core of the integrated system consists of an interface between the RAMS and the STEB. Such interface recognizes the 'rural' or 'urban' nature of each surface node of the computational grid. If the node is 'rural', the surface energy budget is computed by the LEAF3 (Walko, R.L. et al. 2000) routine integrated in the original RAMS, otherwise (i.e., for 'urban nodes') the STEB model is activated. In the latter case, the interface assigns to the urban node the contribution of all the urban canyons contained within the domain of influence of the node. Thus, starting from the geometrical and physical characteristics of each building, the STEB integrates the energy budget corresponding to the considered surface grid node. In particular, for each time step, sensible heat flux, latent heat flux and infrared radiation will be computed as well as the corresponding values of mass, energy humidity and momentum fluxes exchanged between the urban canopy and the first 'air node' of RAMS.

To assess the STEB capability, a numerical simulation is carried out for a typical summer condition on a computational domain centred over the large urban area of Rome (Italy). The results are then compared with observations taken in the centre of Rome. Since the canopy model LEAF3 integrated in RAMS is known to be well-suited for rural soil but not for urban areas (Rozoff et al., 2003), a comparison with the results obtained by using the original LEAF3 scheme was also made.

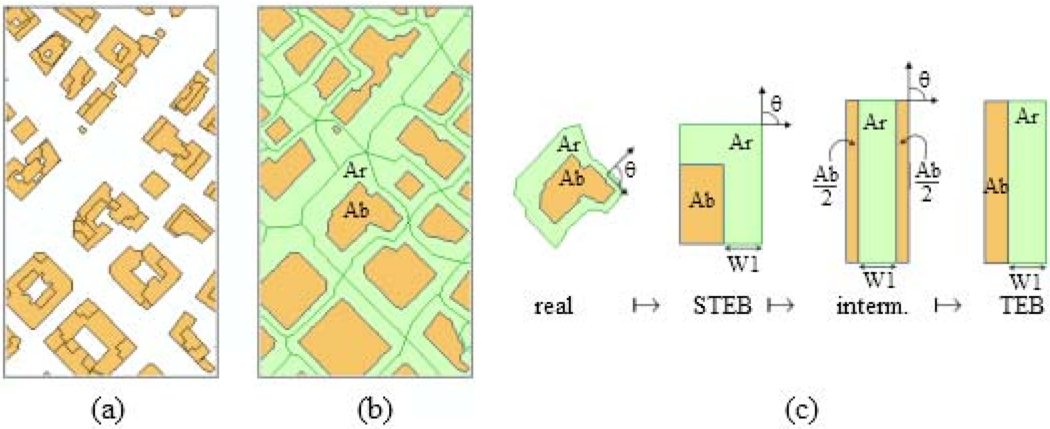

Figure 1. Sketch of the procedure adopted by the STEB algorithm used for the inclusion of the UDEM in the STEB. (a) Example of the original urban DEM referred to a small portion of Rome. (b) UDEM after the filtering procedure, where Ab and Ar identify, respectively, the roof area and the road surface area that surrounds each building. (c) Phases of the transformation of the building modelled in the STEB in the simpler canyon geometry used by the TEB. θ is the azimuthal building orientation and W1 the equivalent road width (see text for its definition).

STUDIED AREA AND EXPERIMENTAL SETUP

The simulations are performed using three interactive nested domains with horizontal resolutions varying from 16 down to 1 km (Figure 2a). In particular, the largest domain (grid G1, 992x992 km^2) has a horizontal resolution of 16 km and covers large part of the Italian Peninsula, the second one (grid G2, 248x248 km^2) has a horizontal resolution of 4 km while the third one (grid G3, 58x58 km^2) is nearly centred on Rome with 1 km grid-mesh. In the vertical, 52 stretched sigma levels are used, with the lowest level at 11 m above the ground (for grid G3). The model domain top is at 19 km.

The simulations are initialized by using the reanalysis taken at the synoptic hours from the UCAR (ds091.0 datasets). Initial profiles of soil moisture and temperature were initialized by means of a previous run, 1 month long, performed in the same area. The simulation covers a period of time that extends from 26 to 29 July 2005. Nearly 360,000 buildings belonging to the Roman area were considered in the simulation (Figure 2b).

From the STEB scheme, the conversion to the TEB representation is straightforward, and it is easily obtained through building geometry data manipulation. Note that, although Figure 1c shows for the STEB an isolated building, the model stills maintains a canyon geometry in which facing walls are treated explicitly. This is possible because there is an equivalence between a building representation and the STEB canyon geometry.

RESULTS AND DISCUSSION

The simulations start at 06 UTC and last 66 hours. For the examined periods, two tests were carried out. In the first one the simulation with the original surface scheme LEAF3 was performed, while in the second one the STEB scheme was activated in correspondence of the urban area. Figure 3 shows the evolution of the air temperature, wind speed and wind velocity observed at about 15 m above the roof level at the Collegio Romano observatory located at the centre of Rome. Both LEAF3 and STEB schemes reproduces the average trend of the observations, and are able to simulate the sea breeze circulation that characterizes the Roman area. It is clear how the STEB improves the temperature prediction especially at night, when the effects of the urban heat island is larger. Even for the wind speed, the STEB furnishes more accurate results than LEAF3. This is not surprising, since the STEB improves, among other things, significantly the calculation of the areal distribution of the roughness length. For the wind direction, the two models give similar results: both show large errors especially at night. However, it must be noted that the observations are probably influenced by drag exerted by the complex urban geometry surrounding the meteorological station. Therefore we cannot exclude the presence of canalization effects which are too small to be resolved by the numerical grid used by RAMS in the present simulation.

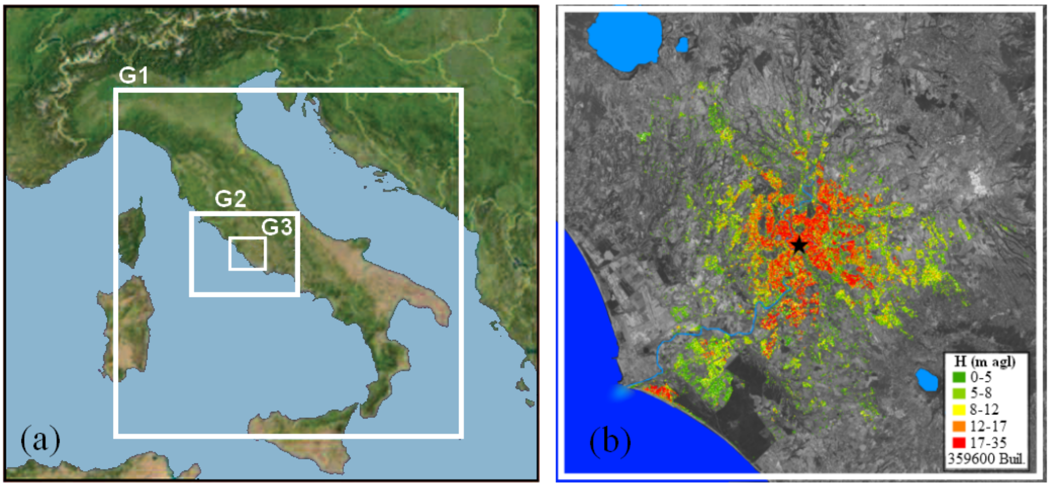

Figure 2. (a) Computational domain employed in RAMS and relative nested grid decomposition: G1 (horizontal resolution: 16 Km), G2 (4 km) and G3 (1 km). (b) Enlarged view of (a) including the inner gridded domain (G3) centred over Rome metropolitan area. Colours indicate the buildings height from Urban DEM for Rome city. The black star indicates the site where meteorological observations were conducted.

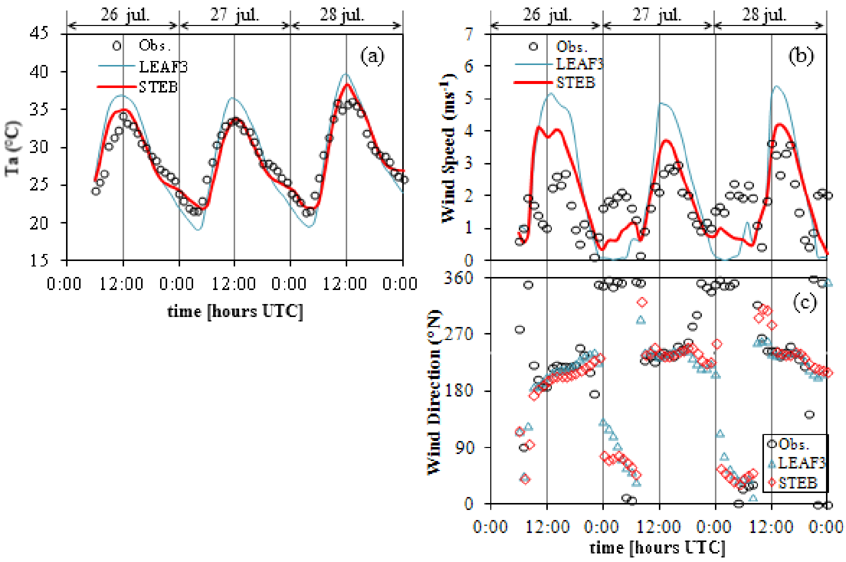

Figure 1. Measured (black circles) and simulated (red line: STEB, blue line: LEAF3) temperature (a), wind speed (b) and wind direction (c) as a function of the time of the day. The numerical results refer to the first level (z≈11 m agl) of the atmospheric model corresponding to the centre of Rome (black star in Figure 2b).

Since the TEB is a well-validated model (Masson, V. et al. 2002), it is of interest to analyse the differences between TEB and STEB in the urban surface energy balance calculation. For this reason, a third simulation in which the TEB scheme was used in place of the STEB, was performed. In this case, the buildings modelled as explained above for the STEB are converted according to the TEB canyon geometry. In the conversion process, attention was paid to maintain the equivalence of the buildings surfaces extension. In this regard, the plan areal fraction $\lambda_p = Ab/(Ab + Ar)$ was preserved by setting the proper value of the equivalent canyon length L (Cantelli, A. et al. 2013). As showed by these authors, starting from the value of λ_p and the road width W1 for a STEB canyon, the equivalent length for the TEB canyon which retains λ_p is:

$$L = W1\left(-1 + \frac{1}{\sqrt{\lambda_p}}\right)^{-1} \tag{1}$$

An useful quantity for the purposes of a comparison is the turbulent sensible heat flux Q_H [Wm^{-2}] exchanged between the urban scheme and the first RAMS vertical level. Figure 4 shows the turbulent heat flux difference ΔQ_H calculated over G3 grid as $\Delta Q_H = Q_H^{TEB} - Q_H^{STEB}$. Both day and night TEB model produces a slightly higher Q_H respect to that simulated by the STEB. This is mainly due to the differences between the sky view factor (SVF) calculation. SVFs describe the portion of the sky as seen from a canyon surface and then are involved directly in the infrared budget calculation. The explicit description of crossroads in STEB results in higher SVFs values with respect to those calculate by the TEB. As a consequence, in the STEB the canyon surfaces “see” a greater portion of the sky, which in turn produces a lower radiative trapping. The latter enhances the canyon surfaces cooling which consequently produces a lower Q_H exchanged with the RAMS. The lower temperature of the surfaces modelled by the STEB agrees with the finding of Lemonsu, A. et al (2004), who stated that the TEB overestimates the temperature of the canyon surfaces.

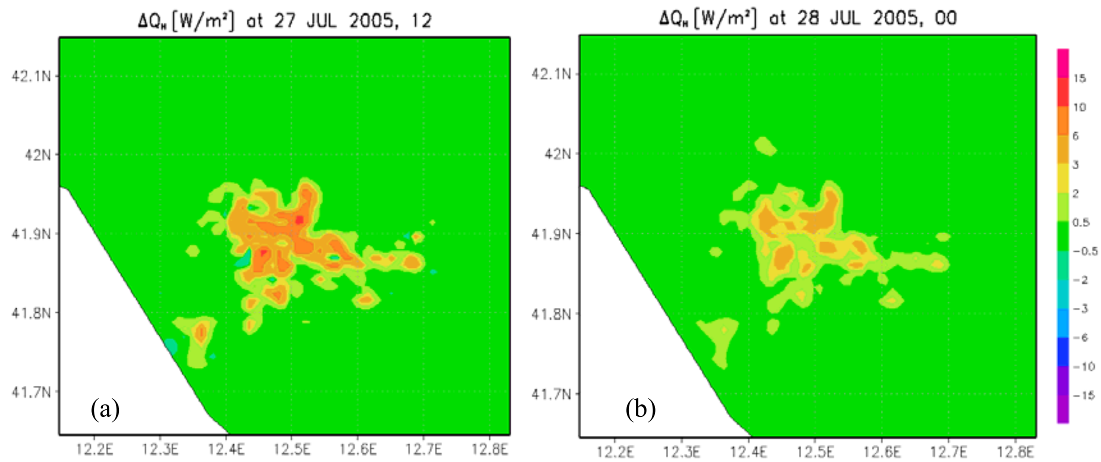

Figure 2. Colours depict the sensible heat flux difference ΔQ_H [Wm^{-2}] calculated as TEB–STEB, on G3 grid at 12 UTC (a) and at 00 UTC (b) extracted at the first atmospheric model node z=11 m agl.

CONCLUSIONS

The subgrid model STEB was developed to improve the surface energy budget over urban areas in numerical weather prediction models. STEB is built upon the TEB model, but considers a more complex canyon geometry. It provides a 3D radiative budget that takes in to account also the crossroads which delimit the canyon roads. Moreover, a particular capability of the model allows the fair integration with urban DEMs, and makes it possible to consider the budget of all buildings belonging to each urban computational cell. STEB was implemented in the numerical model RAMS to simulate the Rome urban heat island in summer condition. Results show a good reasonable good agreement with observations, especially for temperature and wind speed. STEB improves the evaluation of meteorological quantity over urban areas, and appears to be an useful tool that retains the urban surface inhomogeneity in the SEB calculation.

REFERENCES

Cantelli, A., P. Monti and G. Leuzzi, 2011: An investigation of the urban heat island of Rome through a canyon-based subgrid scheme. *Int. J. Environ. Pollution*, **47**, 239-247.

Cantelli, A., P. Monti and G. Leuzzi, 2013: Numerical study of the urban geometrical representation impact in a surface energy budget model. *Environ. Fluid Mech.*, Submitted.

Cotton, W.R., R.A. Pielke, R.L. Walko, G.E. Liston, C.J. Tremback, H. Jiang, R.L. McAnnelly, J.Y. Harrington, M.E. Nicholls, G.G. Carrio and J.P. McFadden, 2003: RAMS 2001: Current status and future directions. *Meteorol. Atmos. Phys.*, **82**, 5-29.

Dupont, S. and G. Mestayer, 2006: Parameterization of the urban budget with the submesoscale soil model. *J. Appl. Meteorol. Climatol.*, **45**, 1744-1765.

Freitas, E.D., C.M. Rozoff, W.R. Cotton and P.L.S. Dias, 2007: Interactions of an urban heat island and seabreeze circulations during winter over the metropolitan area of São Paulo, Brazil. *Bound.-Layer Meteorol.*, **122**, 43–65.

Kondo, H., Y. Genchi, Y. Kikegawa, Y. Ohashi, H. Yoshikado and H. Komiyama, 2005: Development of a multi-layer urban canopy model for the analysis of energy consumption in a big city: Structure of the urban canopy model and its basic performance. *Bound.-Layer Meteorol.*, **116**, 395-421.

Lee, S.H. and S.U. Park, 2008: A vegetated urban canopy model for meteorological and environmental modeling. *Bound.-Layer Meteorol.*, **126**, 73-102.

Lei, M., D. Niyogi, C. Kishtawal, R.A. Pielke, A. Beltrán-Przekurat, T.E. Nobis and S.S. Vaidya, 2008: Effect of explicit urban land surface representation on the simulation of the 26 July 2005 heavy rain event over Mumbai, India. *Atmos. Chem. Phys. Discuss.*, **8**, 8773–8816.

Lemonsu, A., C.S.B. Grimmond and V. Masson, 2004: Modelling the surface energy balance of the core of an old Mediterranean city: Marseille. *J. Appl Meteorol.*, **43**, 312–27.

Martilli, A., A. Clappier and M.W. Rotach, 2002: An urban surface exchange parameterization for mesoscale models. *Boundary-Layer Meteorol.*, **104**, 261-304.

Masson, V. ,2000: A physically based scheme for the urban energy budget in atmospheric models. *Boundary-Layer Meteorol.,* **94**, 357-397.

Masson, V., C.S.B. Grimmond and T.R. Oke, 2002: Evaluation of the Tower Energy Balance (TEB) scheme with direct measurements from dry districts in two cities. *J. Appl. Meteorol.*, **41**, 1011-1026.

Oke, T.R., 1995: The heat island of the urban boundary layer: characteristics, causes and effects. In: Cermak et al. (eds.), *Wind Climate in Cities*, (pp.81-107), Dordrecht: Kluwer Academic Publishers.

Ryu, Y.H., J.J. Baik and S.H. Lee, 2011: A new single-layer urban canopy model for use in mesoscale atmospheric models. *J. Appl. Meteorol.*, **50**, 1773-1794.

Rozoff, C.M., WR. Cotton and J.O. Adegoke, 2003: Simulation of St. Louis, Missouri, land use impacts on thunderstorms. *J. Appl. Meteorol.*, **42**, 716-738.

Schubert, S., S. Grossman-Clarke, A. Martilli, 2012: A double-canyon radiation scheme for multi-layer urban canopy models. *Bound.-Layer Meteorol.*, **145**, 439-468.

Walko, R.L., L.E. Band, J. Baron, T.G.F. Kittel, R. Lammers, T.J. Lee, D. Ojima, R.A. Pielke, C. Taylor, C. Tague, C.J. Tremback and P.L. Vidale, 2000: Coupled atmosphere-biosphere-hydrology models for environmental modelling. *J. Appl. Meteorol.*, **39**, 931-944.