A SUBGRID SURFACE SCHEME FOR THE ANALYSIS OF THE URBAN HEAT ISLAND OF ROME

Antonio Cantelli[1], *Paolo Monti*[1] *and Giovanni Leuzzi*[1]

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

Abstract: This paper describes preliminary modifications to a mesoscale model to better account for urban heat-storage. The approach involves integrating the Town Energy Budget (TEB) with the Regional Atmospheric Modelling System (RAMS). The integrated system has been applied to the Urban Heat Island (UHI) of Rome, Italy, and the surrounding area (Lazio Region), including the coastal area abutting the Tyrrhenian Sea. The numerical results show a significant improvement in the simulation of the UHI of Rome compared with that obtained using the original LEAF-2 scheme incorporated in RAMS.

Key words: *Numerical Model, Urban Heat Island, Town Energy budget, Sea breeze, Slope Flows.*

1. INTRODUCTION

The proper parameterization of the Urban Heat Island (UHI) in mesoscale models involves many difficulties, which include the different parameterization of momentum, temperature and humidity fluxes associated with the human modification of the surface. The picture is further complicated by the heterogeneity of the urban landscape that makes the solution of the problem very difficult to obtain because it requires detailed information about spatial distribution of the surface features. Nevertheless, accurate estimation of the UHI characteristics is of primary interest in assessing, among other things, weather forecast and pollutant dispersion. Thus, it is essential to be able to predict, with a certain degree of accuracy, meteorological fields in urban areas. In the past, there have been several efforts in this direction. As for example, the Objective Hysteresis Model (OHM, Grimmond, C. S. B. et al., 1991) is based on an empirical formula relating, among other things, the storage heat flux into buildings, ground substrate, to the net surface radiation. More recently, Walko, R. L. et al. (2000) proposed the LEAF-2 (Land Ecosystem-Atmospheric Feedback) model. LEAF-2 utilizes biophysical parameters, such as the roughness height, displacement height, albedo, emissivity, fractional coverage and leaf area index to model the fluxes corresponding with each grid cell. As shown in the literature, LEAF-2 scheme works well for rural environment but it seems to be not appropriate for applications in urban areas (Rozoff, C. M. et al., 2003). Martilli, A. et al. (2002) developed in the Finite Volume Model (FVM) a surface exchange scheme to simulate semi-explicitly the canopy layers with the "porosity-drag" approach. The city is modelled by an array of buildings having the same width, located at the same distance one from each other. The horizontal grid size of the model coincides with the street canyon length. The Town Energy Budget (TEB) model proposed by Masson, V. (2000) seems to be, at present, the most popular surface scheme integrated in numerical weather prediction models. The TEB model, starting from accurate topographic data and from the knowledge of the different types of materials respectively for roofs, walls and roads, allows a physically based calculation of the radiative budget as well as momentum, heat and ground fluxes. The TEB has been applied in several cases (Masson, V. et al., 2002 and Freitas, E. D. et al., 2007, among others) in which the actual features of the city (e.g. buildings, squares, etc.) are parameterized using a generalized canyon geometry.

In this work, starting form the knowledge of the detailed geometry of all the main urban canyons of the metropolitan area of Rome, Italy, a scheme is utilized that applies the parameterization of TEB model appropriately modified for our case. This scheme has been then coupled through a sub-grid with the Regional Atmospheric Modelling System (RAMS version 6.0). Model runs are performed to simulate typical summertime atmospheric fields occurring in the Lazio Region, where the city of Rome is located. Particular attention has been paid to the presence of the UHI and how it interacts with other local thermally induced circulations such as slope currents and sea breeze flows. The results are then compared with observations from measurements taken in the Roman urban area. A comparison with runs performed with the nonmodiefied RAMS using LEAF-2 is also made.

2. STUDIED AREA, MODEL DESCRIPTION AND METEOROLOGICAL STATIONS

The study domain is nearly centred over the city of Rome, which counts nearly 3.5 million inhabitants. Rome is located in a relatively flat area of the Lazio Region in central Italy, about 25 Km inland from the shoreline (latitude 41°50'N, longitude 12°30'E, 60 m above sea level, Fig. 1). With the exception of the west side, the city is surrounded by hills and high mountains (up to 2000 m above the sea level). The eastern side of the city is the southwestern border of the north-oriented Tiber Valley, while the shoreline lies along southeast-northwest. The observational study of Mastrantonio, G. et al. (2008) showed that the atmospheric circulation in the Lazio Region is strongly influenced by land and sea breeze regimes for large part of the year. Caballero, R. and A. Lavagnini (2002) and Monti, P. and G. Leuzzi (2005) numerically observed the importance on the resulting flow field of the interaction between the sea breeze and the UHI associated with the metropolitan area of Rome. However, the previous studies do not give a definitive answer because of the partial representation of urban surface characteristics used in their mesoscale models.

The RAMS (Pielke, R.A. et al. 1992; Cotton et al., 2001) is a prognostic non-hydrostatic model able to predict the evolution of the atmosphere by the space-time integration of the budget equations of mass, momentum, heat, moisture and turbulent kinetic energy. The RAMS code includes a large number of options to define the calculation domain, the land-use and soil categories, terrain-following coordinates, the interpolation of the terrain elevation, stretched vertical coordinates, nudging systems, two-way interactive grid nesting, the interpolation of global meteorological analysis on the 3D grids as RAMS requires an initial condition. The simulations are run on three interactive nested domains with horizontal resolutions varying from 16 down to 1 km. In particular, the largest domain (grid D01, 1000x1000 Km^2) has a horizontal resolution of 16 Km and covers large part of the Italian Peninsula, the second one (grid D02, 250x250 Km^2) has a horizontal resolution of 4 Km while the third one (grid D03, 60x60 Km^2), nearly centred on Rome, with 1 Km grid-mesh. In the vertical, 52 stretched sigma levels are used, with the lowest level at 12 m above the ground (for grid D03). The model domain top is at 19 km. The simulations are initialized by using the reanalysis taken at the synoptic hours from the UCAR (wttp:/dss/ucar.edu/datasets/ds083.2). Surface observations taken from six airports located within the Lazio Region (red circles in Fig. 1b) are also used during the simulations. Initial profiles of soil humidity and temperature are taken from the database of NOAA (National Oceanic and Atmosphere Administration) available in the NCEP/NCAR-Reanalysis-1, database.

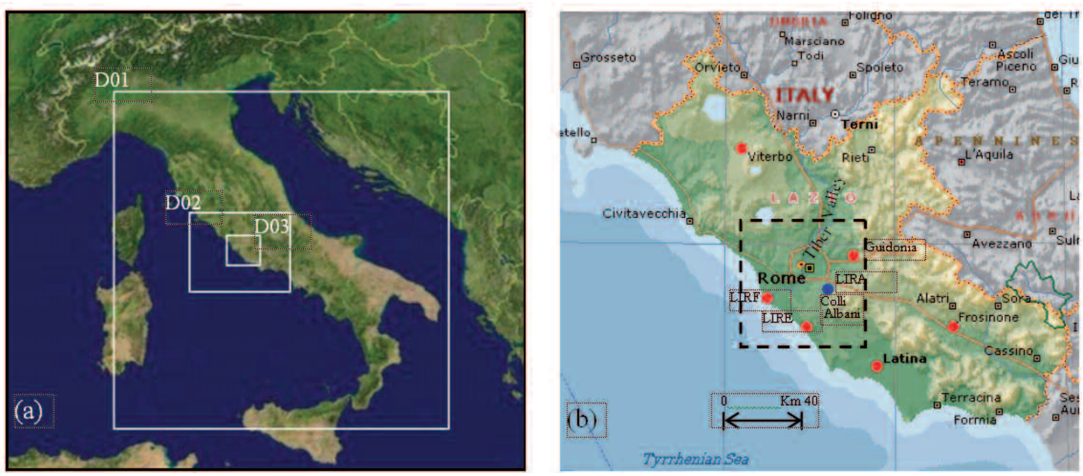

Figure 1. (a) Domain setup: D01 (resolution 16 Km), D02 (resolution 4 km) and D03 (resolution 1 km). (b) The Lazio Region and locations and names of the six airports (red circles). The blue circle shows the location of Ciampino airport (LIRA), while the black square indicates the inner gridded domain (DO3) centred over Rome.

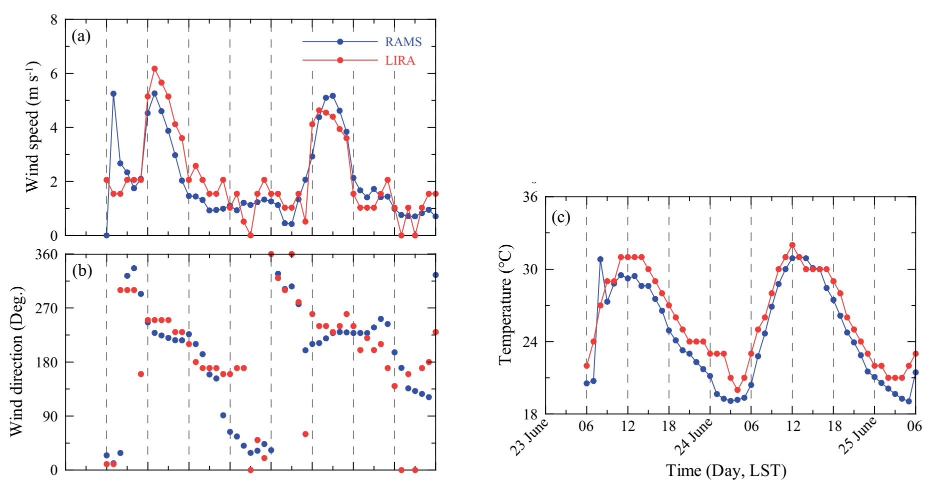

Figure 2. Observed (red circles) and simulated (blue circles) (a) wind speed at 10 m above the gound level (AGL), (b) wind direction at 10 m AGL and (c) temperature at 2 m AGL on 23-25 June 2005 as a function of the time of the day.

3. RESULTS AND DISCUSSION

Two tests of model performance evaluation are briefly presented in this section. The first one refers to the nonmodiefied RAMS simulation, which uses the original LEAF-2 model; the second one to the integrated RAMS-TEB system. Both the simulations cover a period of 48 hours: they start at 06 Local Standard Time (LST) of 23 June and stops at 06 LST of 25 June 2005. The meteorological conditions during the simulations were characterized by a high pressure system (Azore anticyclone) centred over the Iberian Peninsula; a nortwesterly geostrophic wind was present over the Italian Peninsula and the weather conditions were favourable to promote local thermally induced circulations.

The nonmodiefied RAMS simulation

In Figure 2a-c, time histories of wind speed (Fig. 2a), wind direction (Fig. 2b) and air temperature (Fig. 2c) predicted by RAMS are compared with the corresponding observations taken at Ciampino airport (LIRA, blue circle in Figure 1b). All the three figures show a reasonable good agreement between simulations and observations and, as expected, a daily oscillation characterizes the time behaviour of all the three variables. The wind speed suddenly increases at 12 LST as a consequence of the arrival of the sea breeze from the Tyrrhenian Sea. Such event is accompanied by a counter-clockwise veering of the wind direction from northwest to south-southwest and by the formation of a plateau in temperature being the sea breeze colder than the local air. This effect is particularly evident during the daytime of 24 June, when the temperature shows a maximum at 12 LST and then decreases of nearly 3 °C in two hours. During the nighttime the wind speed is mainly associated with the katabatic currents from north-northeast coming from the mountains surrounding Ciampino station; it attains a maximum nearly at 05 LST, when a minimum in temperature occurs.

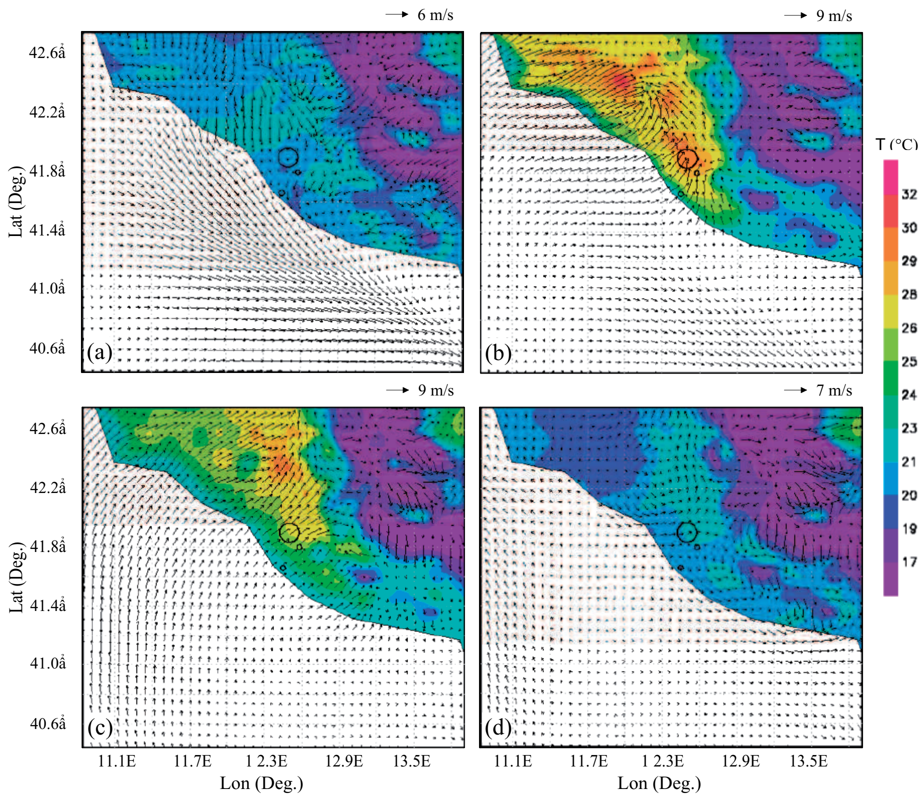

Figure 3. Predicted near surface wind vectors (arrows) and air temperature fields (colour map) referred to grid D02 at nearly 50 m AGL at (a) 06 LST of 24 June, (b) 12 LST of 24 June, (c) 18 LST of 24 June and (d) 00 LST of 25 June.

A sequence of results on grid D02 for June 24 is depicted in Figure 3. At 06 LST the land breeze is still flowing near the shoreline. At the same time, downslope (katabatic) currents coming from the main mountain systems (Figure 3a) are present. The previous phase keeps on until the early morning, when the sea breeze forms and intrudes horizontally into inland. The map reported in Figure 3b shows the flow field calculated by RAMS at 12 LST. A sea breeze from southwest is well-developed. It overcomes the metropolitan area of Rome and reaches regions located nearly 50 Km inland. Isolated upslope (anabatic) wind systems are also present over the mountain slopes. Later, the sea breeze and the anabatic flow coalesce into a single northern current (Figure 3c) canalized by the Tiber Valley. At 00 LST (Figure 3d) the katabatic flows intrudes down into the valleys, while a remnant of sea breeze still flows the Tiber Valley.

More detailed representations of the flow field in correspondence of the urban area are reported in Figure 4, where the results regarding grid D03 are given. At 06 LST of 24 June (Figure 4a) conditions of nocturnal boundary layer with predominantly light winds are present. A region of minimum in temperature occurs south of Rome, possibly as a consequence of cooling associated with the downslope-flowing region at the foot of Colli Albani.

At 12 LST the sea breeze is well-developed, with the front located nearly at the city centre. Anabatic flow and sea breeze merging is still visible close to LIRA as well as the up-slope flowing region over the Tiber Valley (Figure 4b). At 18 LST the sea breeze is present all over the domain (Figure 4c) with intensity smaller than that observed at 12 LST. Both Figures 4b and 4c well-illustrate the cooling effect of the sea breeze. Finally, at 00 LST a remnant of sea breeze is still present on the city but, as evident from Figure 4d, expected thermal anomaly induced by the urban area is essentially absent. In summary, we can state that despite the agreement shown in Figure 2 is encouraging and the overall flow field is reasonable, the lack of thermal anomaly within the urban area corroborates the previous findings which show that LEAF-2 scheme is inappropriate to describe properly UHIs.

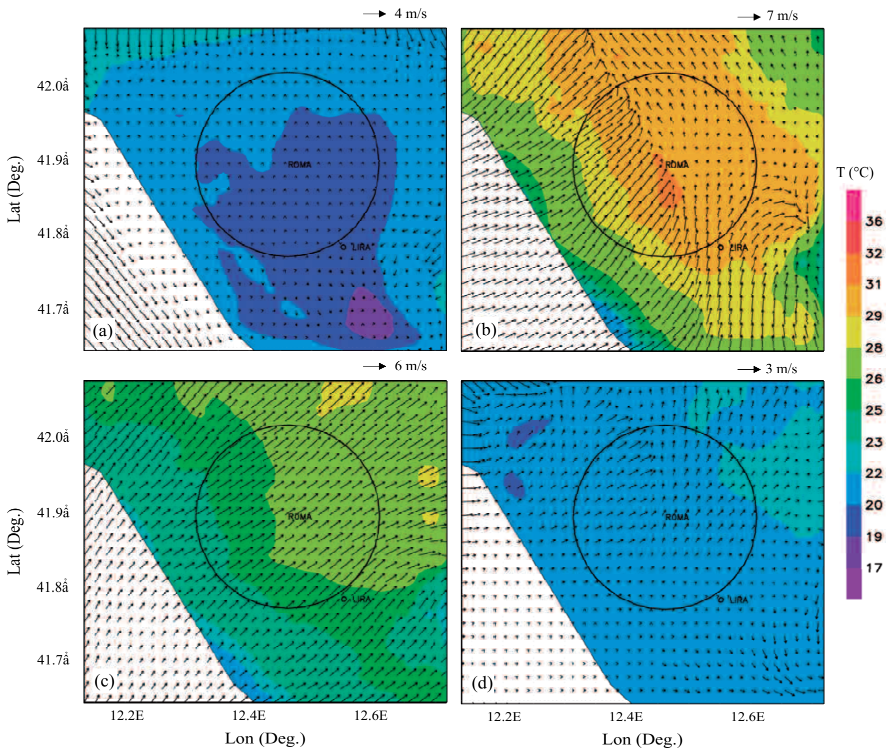

Figure 4. As in Figure 3, but for grid D03 with LEAF-2.

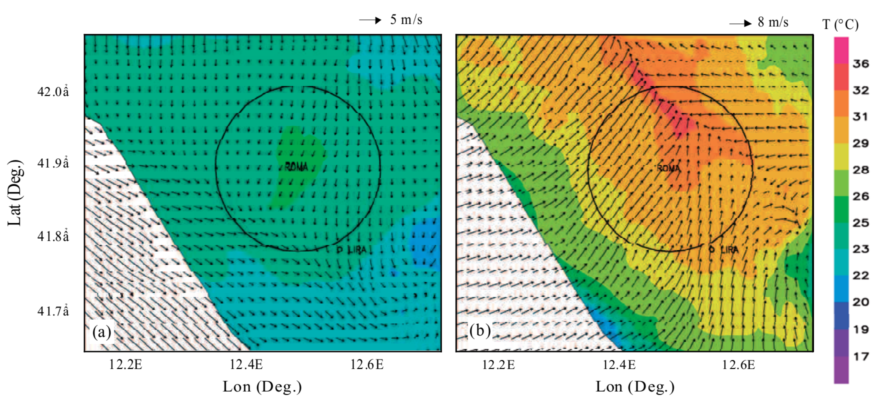

Figure 5. As in Figure 4, but with TEB at (a) 06 LST and (b) 12 LST.

The integrated system RAMS-TEB

The TEB model is founded on the scheme proposed by Masson V. (2000); here, only a brief outline of the model is given. The urban energy budget is based on the canyon approach and takes into account separately the contribution for roads, walls and roofs. For this preliminary analysis, about 8600 roads, corresponding to all main urban canyons of the metropolitan area of Rome, are considered. By comparing Figures 4 and 5, where the results regarding grid D03 with TEB are depicted, two distinct, but correlated, differences are well-visible, i.e., the general increment both in temperature and wind velocity in Rome and the surrounding area. This is not surprising in that the larger sensible heat flux simulated by the TEB with respect to LEAF-2 results in a greater turbulent kinetic energy which, in turn, promotes larger vertical mixing of momentum that causes an increase of the wind speed in the surface layer. The work is still in progress and only one comparison between the simulated and the observed temperature taken in a station located close to the centre of the city is given here (Figure 6). The runs show an overall significant improvement of the simulated temperature when

TEB is used instead of LEAF-2. This is shown to be particularly true from the comparison during the nighttime, when the significance of the UHI should be of primary importance.

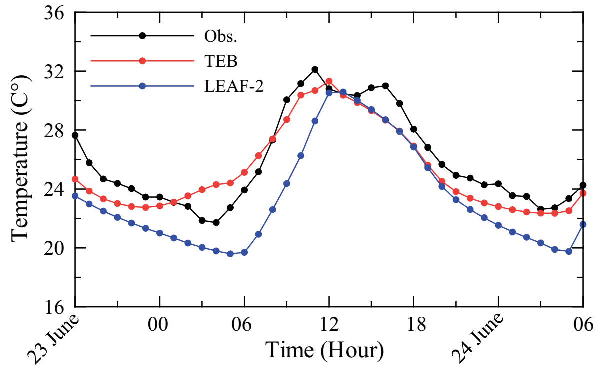

Figure 6. Observed (black circles) and simulated (red circles: TEB; blue circles: LEAF-2) temperature time history taken in a station located in the centre of Rome at nearly 15 m AGL.

4. CONCLUSIONS

The mesoscale model RAMS (version 6.0) is used to investigate the typical summertime atmospheric fields occurring in the Lazio Region (central Italy), which is the area surrounding the city of Rome. It is shown that the wind circulation is governed by land and sea breeze regimes. Comparisons between the numerical simulation and observations taken in a station located in a rural area show a reasonable good agreement. Within the urban area, on the contrary, the agreement is poor. This might be due to the fact that the urban parameterization based on the LEAF-2 integrated in RAMS is not appropriate for applications in urban areas. Modifications to the mesoscale model to better account for urban heat-storage associated with Rome are carried out. The approach involves integrating the Town Energy Budget (TEB) with the RAMS. For this analysis, about 8600 roads, corresponding to all main urban canyons of the metropolitan area of Rome, are considered. The preliminary results show an encouraging improvement in the simulation of the UHI of Rome compared with that obtained using the original LEAF-2 scheme incorporated in RAMS.

REFERENCES

Caballero, R. and A. Lavagnini, 2002: A numerical investigation of the sea breeze and slope flows around Rome. *Il Nuovo Cimento*, **25C**, 287-304.

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. *Met. and Atm. Phys.*, **82**, 5-29.

Freitas, E.D., C.M. Rozoff, W.R. Cotton and P.L. Silva Dias, 2007: Interaction of an urban heat island and a sea-breeze circulations during winter over the metropolitan area of Sao Paulo, Brazil. *Bound.-Layer Met.*, **122**, 43-65.

Grimmond, C.S.B., H.A. Cleugh and T.R. Oke, 1991: An objective urban heat storage model and its comparison with other schemes. *Atmospheric Environment*, **25B**, 311-326.

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

Masson, V., 2000: A physically based scheme for the urban energy budget in atmospheric models. *Bound.-Layer Met.*, **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. *Journal of Applied Meteorology*, **41**, 1011-1026.

Mastrantonio, G., I. Petenko, A. Viola, S. Argentini, L. Coniglio, P. Monti and G. Leuzzi, 2008: Influence of the synoptic circulation on the local wind field in a coastal area of the Tyrrhenian Sea. IOP Conf. Series: *Earth and Environmental Sciences*, **1**. DOI: 10.1088/1755-1307/1/1/012049.

Monti, P. and G. Leuzzi, 2005: A numerical study of mesoscale airflow and dispersion over coastal complex terrain. *International Journal of Environment and Pollution*, **25**, 239-250.

Oke, T. R., 1995: The heat island of the urban boundary layer: characteristics, causes and effects. In *Wind Climate in Cities*, Cermak et al., Eds., NATO ASI Series E, Vol. 277, Kluwer.

Pielke, R.A., W.R. Cotton, R.L. Walko, C.J. Tremback, W.A. Lyons, L.D. Grasso, M.E. Nicholls, M.D. Moran, D.A. Wesley, T.J Lee and J.H. Copeland, 1992: A comprehensive Meteorological Modeling System – RAMS. *Meteorology and Atmospheric Physics*, **49**, 69-91.

Rozoff, C.M., W.R. Cotton and J.O. Adegoke, 2003: Simulation of St. Louis, Missouri, land use impacts on thunderstorms. *Journal of Applied Meteorology*, **42**, 716-738.

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. *Journal of Applied Meteorology*, **39**, 931-944.