EFFECTS OF TOPOGRAPHY ON URBAN HEAT ISLAND

Theodoros Nitis[1,2]*, Zvjezdana B. Klaić*[3] *and Nicolas Moussiopoulos*[1]
[1]Laboratory of Heat Transfer and Environmental Engineering, Aristotle University, Greece
[2] Department of Marine Sciences, University of the Aegean, Greece
[3]Andrija Mohorovičić Geophysical Institute, Department of Geophysics, Faculty of Science, University of Zagreb, Croatia

INTRODUCTION

One of the most important anthropogenic activities that have an impact on climate is the land use changes. In urban environments, human activities in combination with the replacement of natural landscape with hard, non-porous surfaces, affect the atmospheric boundary layer structure through a number of factors, such as heat, moisture and momentum exchange processes. The alteration of these factors results to the distinction of the urban atmospheric boundary layer from that of surrounding areas (*Fan, H.L. and D.J. Sailor,* 2005). Among the urban-rural differences, the most notable and well documented (*Kim, Y.K. and J.J. Baik*, 2005*)* is the relative warmth of the city compared to its pre-urban condition that is called Urban Heat Island (UHI). *Oke, T.R.* (1987) lists a number of causes of UHI: anthropogenic heating through the tops and sides of buildings, elevated absorption of incoming short-wave radiation, decreased outgoing long-wave radiation, long-wave radiation loss due to reduced sky factor, decreased evaporotranspiration, and reduced heat transport. Beyond to the general above mentioned causes, a number of factors such as topography, character of relief, urban structure, intensity of building and type of materials are also involved in the formation of the UHI (*Klysik, K. and K. Fortuniak,* 1999).
Furthermore, differences of albedo moisture, roughness length and thermal capacities in urban-rural areas, are often cited as the key causes for the UHI (*Liang, S. et al.,* 1999). These parameters are used by models to assess the complex soil-vegetation-atmosphere interactions. The variability of earth surface, especially on vegetation state, is a major problem in mesoscale meteorological models; therefore detailed data are essential for accurate simulations. Satellite remote sensing offers the capability to estimate a number of physical parameters involved in the parameterisation of the boundary layer process with high resolution; albedo and roughness length are among them. In mesoscale meteorological modelling, a constant value is most often assigned to these parameters regardless of seasonal changes and spatial variability; therefore, the use of remote sensing data could improve the models' results.
The main purpose of this paper is the study of the effects of topography on UHI and the Zagreb Greater Area (ZGA) was used as a case study. UHI modelling was improved by using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data to retrieve the surface parameters (albedo and roughness length) and a database for storing this information was developed. High-resolution simulations with a mesoscale meteorological model were performed for two summertime anticyclonic periods. Furthermore, in-situ observations were compared to simulated ones in order to assess the accuracy of the model performance. Finally, the importance of the impact of the area topography on the formation of the urban heat island is discussed.

STUDY AREA AND MODEL CONFIGURATION

The Zagreb Greater Area (inner domain on Fig. 1(a)) is characterised by the moderately complex topography. In 2003, 1.1 million people (the 26% of Croatian population) lived in Zagreb metropolitan area that covers an area of ~125 km^2 (*United Nations*, 2004). Though the UHI phenomenon appears typically during winter, in this paper it was studied during two summer periods. Summertime conditions are also of particular interest, since their impact on air quality, air conditioning energy demand, human comfort and heat related illnesses is important. Wind and temperature fields were simulated using the non-hydrostatic mesoscale model MEMO (*Kunz, R. and N. Moussiopoulos,* 1995) for the periods: (a) 9-10 June 2004 and (b) 17-23 July 2004, characterised by anticyclonic weather conditions. In order to account for all relevant orographic influences on the flow field, a nested system based on the expanded radiation boundary condition was applied, while the horizontal domain was extended to include a reasonable portion of land and sea masses (*Nitis, T. et al.,* 2004). Coarse grid simulations covered an area of 250×250 km^2 with a horizontal grid spacing of 5 km, while the fine grid simulations were performed within an area of 100×100 km^2 at a horizontal resolution of 2 km. Centres of both simulation domains were at the same point (Fig. 1(b)). Meteorological input information, consisting of vertical profiles of wind speed, wind direction and temperature was obtained from the Zagreb and Udine radiosonde stations.

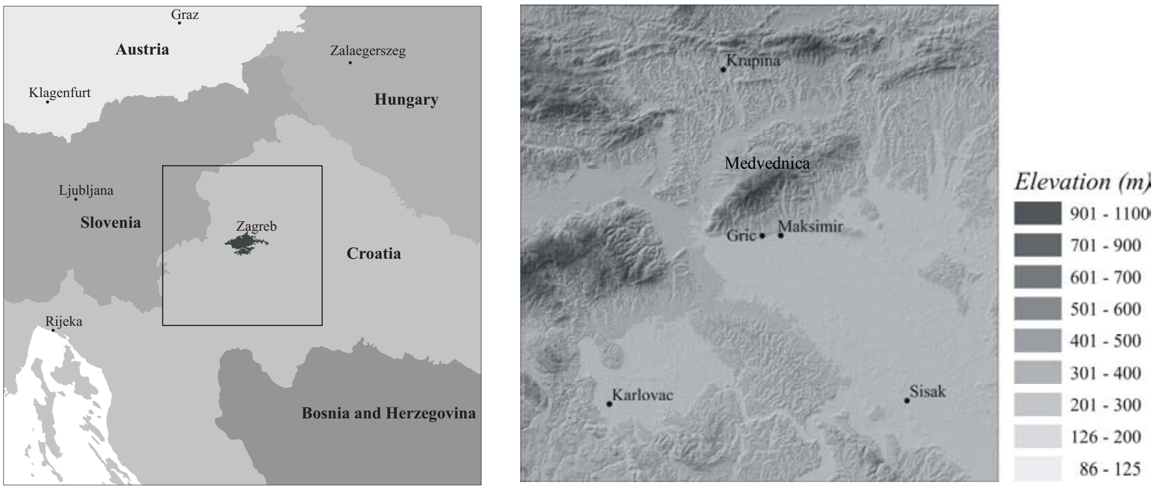

Fig. 1; (a) Configuration of nested grids. The outer frame indicates the coarse grid and the inner one the fine domain. (b) Anaglyph for the fine grid. The bullets indicate the positions of the routine measuring sites. The domain centre is in Zagreb (Latitude 45^o 48′ 15″ N, longitude 15^o 58′ 29″ E), 150 m above sea level, located in the foothill of mountain Medvednica.

DATABASE DEVELOPMENT

A detailed orography data set for the study area, was derived from the Shuttle Radar Topography Mission (SRTM) database (*GLCF*, 2004) that is the most complete high-resolution digital topographic database of Earth, with a horizontal grid of approximately 90 m, developed by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The land use data set originated from the Corine land cover 2000 (CLC2000) database (*EEA*, 2005), which is part of the European Commission programme to COoRdinate INformation on the Environment (Corine), developed by the Topic Centre on Terrestrial Environment (ETC/TE). CLC 2000 Land Cover database includes 44 land cover species its horizontal resolution is about 100 m and uses the Geographic projection. Normally, in MEMO applications the original 44 land use types are reduced to 7 more general types. However, in the present study, the requirement for more accurate representation of the urban environment led to the use of 12 general land use types. A short description concerning the processing of

MODIS satellite data for retrieving the surface parameters is given below. The roughness length was derived by application of simple empirical relationships between satellite radiometry and vegetation physiology. More precisely, the Normalized Difference Vegetation Index (NDVI), a parameter that indicates vegetation biomass level, was calculated by the formula, NDVI = [(NIR - Red)/(NIR + Red)], where NIR and Red are the radiances in the NIR and Red spectral bands, respectively. The formula, $z_o = \exp(-5.5 + 5.8 \cdot NDVI)$ was applied in order to calculate the roughness length (*Nitis, T. et al.,* 2004). Since the z_o is strongly dependent on the seasonal variations, it was calculated for the two time periods under study (June 2004 and July 2004).
Absorbed, reflected, and emitted radiation is the driving force causing temperature fluxes. Albedo as the fraction of incident radiation that is reflected by a surface is a critical parameter affecting the surface energy balance in mesoscale meteorological models, especially broadband shortwave (0.25–5.0 μm) albedo (*Liang, S. et al.,* 1999). In the present study, the MODIS/Terra+Aqua Albedo 16-Day 1 km product was used for the aforementioned time periods. The albedo was computed by integrating the Bi-directional Reflectance Distribution Function (BRDF) that describes the characteristic anisotropy of the land surface.

RESULTS AND DISCUSSION
The model performance was assessed by calculation of both the RMSE that represents the average error produced by the model and the index of agreement (d) which determines the degree of agreement between observed and simulated values (*Nitis, T. et al.,* 2005). The index of agreement showed that the model predictions of the surface wind speed and direction were good (d > 0.5), while for the surface temperature they were very good (d > 0.85). In conclusion, the evaluation shows that the model simulated the reality reasonably well, especially for temperature.

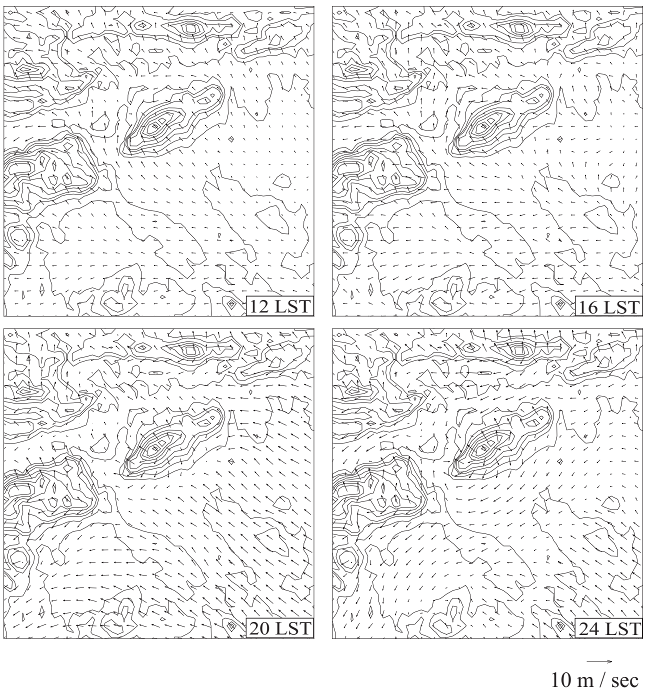

Fig. 2; Simulated surface wind fields (10 m AGL) for the fine domain at 12, 16, 20 and 24 LST for the 20th of July 2004.

In Fig. 2, modelled surface winds (10 m above ground) for the 20th of July 2004 and the fine grid domain are shown. These wind flow patterns allow an insight of up and downslope wind circulation patterns that are formed on the south-facing slopes of mountain Medvednica during the summer anticyclonic conditions (*Klaić, Z.B. et al.,* 2002). The 20th of July was selected for the description of the local circulation patterns, since it is representative of the flow field conditions for both study periods. At noon and during the afternoon, the spatial variation of the wind field in the centre of the domain, where the town of Zagreb is located, indicated the existence of a horizontal temperature gradient that favoured the development of an urban breeze cell directed towards the centre of Zagreb; in that way, the anabatic movements in the southern hillside of the mountain Medvednica were enhanced. Late in the afternoon, this local circulation started to be more enhanced due to the strengthening of the urban-rural temperature difference. During the evening hours, superposition of this and the downslope thermal circulation resulted in the weak winds over the Zagreb centre (Fig. 2, 20 LST). Thus, it could be concluded that the orography can induce more intense circulations over the city during daytime when the UHI is weaker than during nighttime. At midnight, the flow over the whole town turned to north-eastern due to the airflow splitting around the mountain barrier. At the south-facing slopes of the mountain nighttime katabatic winds persisted.

In Fig. 3, the simulated wind fields and the temperature for the 10th of June 2004 and the 21th of July 2004, at 17 and 21 LST, are presented. The urban-nonurban temperature, and thus the UHI magnitude is expressed in terms of temperature at 150 m height, since Zagreb is located at this height. In the afternoon, the temperature patterns found in the south-facing slopes of the Medvednica mountain were the same for both periods studied. Moreover, the UHI is spatially uniform for both periods, although there is a difference between their max temperature values of 2 °K. The modelled 150 m temperature indicated that the maximum, for both cases, appeared during 17 LST in the centre of the city of Zagreb.

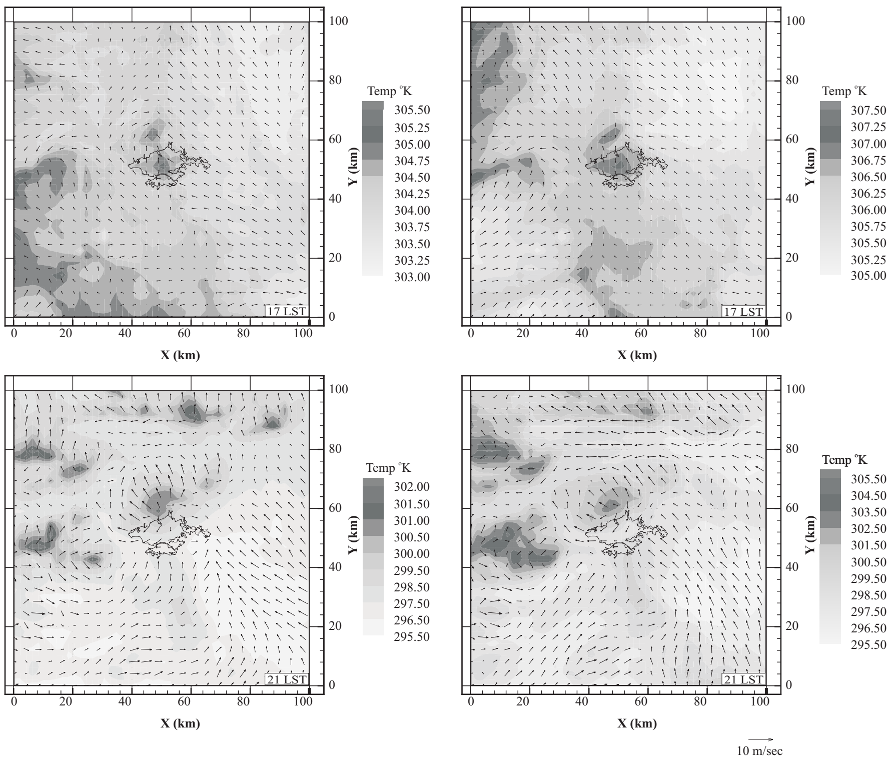

Fig. 3; Simulated surface wind fields (10 m AGL) and temperature isopleths (°K) at 150 m ASL, for the fine domain at 17 and 21 LST for the 10th of June (left) and the 21th of July (right) 2004. The city of Zagreb is outlined.

During the night the spatial distribution of temperature over the urban area was homogenious, indicating that the temporal evolution of the UHI stopped in the afternoon. A possible explanation could be the presence of katabatic movements from the southern slopes of the Medvednica Mountain, as well as a flow originated from the Pannonian valley (part of it is captured by the eastern part of the domain); the convergence of these turned the wind flow to the west, removing in that way the warm air masses over Zagreb and preventing further evolution of the UHI.

CONCLUSIONS

The UHI development for the ZGA was modelled with the three dimensional non-hydrostatic mesoscale model MEMO, for two different cases (9-10 June and 17-23 July 2004). The results demonstrated a successful multi-day simulation in the ZGA and a good agreement with the available observations. Moreover, it was shown that the local topography played an important role in the formation and the evolution of the UHI. However, further improvement could be achieved by the introduction of a canopy model, in order to represent the impact of urban areas on airflow in a more realistic way.

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