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Abstract: Numerical Weather Prediction (NWP) models in connection with increasing capacities of computers in the last years have considerably increased the spatial (vertical and horizontal) resolution and practically become close to meso- and local-scale models. Nevertheless, in most NWP models, urban and non-urban areas are treated rather similarly, through similar sub-surface, surface and boundary layer formulations. No different/additional mechanisms or physics exist to account for specific urban dynamics and energetics and for their impact on atmospheric boundary layer. So, it is important to develop parameterizations of the urban effects in NWP models. The improvement of the urban meteorological forecast is also very important for the air pollution forecasting. The objective of this study is the modification of the Land Air Parameterization Scheme [Mihailovic, 1996] to include the parameterization of the urban effects. To this end, the original scheme was developed to take into account the complexity of urban surfaces through the new definition of wind profile over heterogeneous surface. The general equation for the wind speed profile depending on effective or aggregated values of roughness length and displacement height was used. To examine the model behavior, the numerical experiment for different parts of a hypothetical urban area has been performed. The results are in good agreement with the previous experimental observations. It was found that the most urbanized part of the city is the warmest, with a large sensible heat flux, large heat storage and weak latent heat flux. Simulated surface temperatures have shown the existence of urban heat island phenomenon.

Keywords: Urban modelling; Surface schemes; Roughness sublayer; Parameterization; Wind profile

1. INTRODUCTION

Numerical Weather Prediction (NWP) models in connection with increasing capacities of computers in the last years have considerably increased the spatial (vertical and horizontal) resolution and practically become close to meso- and local-scale models. Nevertheless, in most NWP models, urban and non-urban areas are treated rather similarly, through similar sub-surface, surface and boundary layer formulations. No different/additional mechanisms or physics exist to account for specific urban dynamics and energetics and for their impact on atmospheric boundary layer. So, it is important to develop parameterizations of the urban effects in NWP models. The improvement of the urban meteorological forecast is also very important for the air pollution forecasting.

Consistent treatment of the planetary boundary layer structure and evolution in meteorological and air quality models is critical. An improper parameterization of land-surface processes leads to uncertainties in calculating the boundary layer variables and further in predicting the temperature and wind fields. In urban areas the individual horizontal grid cells often enclose regions of large heterogeneities, requiring the use of effective or aggregated parameters to represent adequately each grid square.

The objective of this study is the modification of the Land Air Parameterization Scheme [Mihailovic, 1996] to include the parameterization of the urban effects. To this end, the original scheme was developed to take into account the complexity of urban surfaces through the new definition of wind profile over heterogeneous surface. To examine the model behavior, the numerical experiment for different parts of a hypothetical urban area has been performed.

2. MODEL USED

The model used in this study is a further development of the land-air parameterization scheme (LAPS). LAPS describes water vapor, heat and momentum transfer between the land surface and the atmosphere. The scheme is designed as a software package, which can be run as part of an atmospheric, hydrological or ecological model, or as a stand-alone model that operates with sixteen morphological and physiological input parameters. A detailed description and explanation of the scheme's structure, governing equations, the representation of energy fluxes and radiation, the parameterization of aerodynamic canopy characteristics, resistances and model hydrology can be found in Mihailovic [1996].

The original LAPS scheme was further developed to take into account the effects of heterogeneity of the underlying surface on wind profile. A unique wind profile is taken for the whole grid cell. Details of these calculations will be given in the following subsection. The new model considers different cover modes of the surface in each grid cell: vegetation, bare soil, rocky ground, water surface and urban area covered with the artificial materials. The model solves the equations for surface and deep soil temperature, interception storage variable and moisture contents of three soil layers for each cover mode. Mean values of these variables, weighted by each cover mode, are then determined for the whole grid cell. The term surface temperature refers to the ground surface for the bare soil, while for vegetation it represents the temperature inside the canopy air space, which is determined diagnostically from the energy balance equation [Mihailovic, 1996].

2.1 Parameterization of roughness length and displacement height

Due to the large size of the roughness elements, the urban surface layer is split into the roughness sublayer, which extends above the tops of the roughness elements to about 3 times of their height and the inertial sublayer above. Strictly speaking, surface layer scaling (i.e. Monin-Obukhov similarity theory, MOST) is only valid within the inertial sublayer, because the flow in the roughness sublayer is strongly influenced by individual roughness elements. In spite of this, due to a lack of better knowledge, current practice in urban dispersion modelling is to use MOST even within the roughness sublayer.

In atmospheric models, the underlying surface consists of patches of solid and liquid part and plant communities with different morphological parameters, creating a very heterogeneous picture within a grid cell. Experimental evidence indicates that there is a significant departure of the wind profile above such heterogeneous surfaces from that predicted by the logarithmic relationship. This can seriously affect the transfer of momentum, heat and water vapor from the surface to the atmosphere.

To take into account the effects of heterogeneity of the underlying surface, we have modified the original LAPS scheme by using a general equation for the wind speed profile in the roughness sublayer under neutral conditions:

$$u(z) = \frac{u_*^a}{k\Lambda} \ln \frac{z - D}{Z_0}, \tag{1}$$

where u_*^a, Z_0 and D are the friction velocity, roughness length and displacement height above non-homogeneously covered grid cell, and Λ is a parameter describing the departure of a real wind profile in roughness sublayer from logarithmic relationship. If we consider a non-uniform underlying surface whose non-uniformity is expressed with the surface fractional covers σ_i (for vegetation), δ_i (for bare soil or water surface) and γ_i (for urbanised surface), and K, L and M are total numbers of homogeneous patches with vegetation, bare soil and urban land, respectively, then values for Z_0, D and Λ can be calculated from the following expressions:

$$Z_0 = \frac{1}{\Lambda}\left(\sum_{i=1}^{K} \frac{\sigma_i \alpha_i^2}{\sigma_i(\alpha_i - 1) + 1} z_{0v,i} + \right.$$

$$+\sum_{i=1}^{L}\delta_i z_{0b,i}+\sum_{i=1}^{M}\gamma_i z_{0u,i}\Bigg), \qquad (2)$$

$$D=\frac{1}{\Lambda}\left(\sum_{i=1}^{K}\sigma_i\alpha_i d_{v,i}+\sum_{i=1}^{M}\gamma_i d_{u,i}\right), \qquad (3)$$

$$\Lambda=\sum_{i=1}^{K}\sigma_i\alpha_i+\sum_{i=1}^{L}\delta_i+\sum_{i=1}^{M}\gamma_i\ , \qquad (4)$$

where $z_{0v,i}$, $z_{0b,i}$ and $z_{0u,i}$ are the roughness lengths for vegetation, bare and urban land, respectively; $d_{v,i}$ and $d_{u,i}$ are the displacement heights for vegetation and urban soil, respectively; and α_i is a dimensionless constant introduced by Mihailovic et al. [1999] that depends on morphological and aerodynamic characteristics of the vegetative cover whose values were derived empirically by Lalic [1997]. These expressions were derived by assuming that the aggregated mixing length at some level above non-homogeneous grid cell can be expressed as a linear combination of mixing lengths of homogeneous patches, weighted by the fraction covers. Details about all derivations can be found in Mihailovic et al. [1999] and Mihailovic et al. [2002a].

For non-neutral cases, the exchange coefficients for momentum K_m and heat transfer K_h are defined as

$$K_m=\frac{ku_*^a\Lambda(z-D)}{\Phi_m}, \qquad (5)$$

$$K_h=\frac{ku_*^a\Lambda(z-D)}{\Phi_h}, \qquad (6)$$

where the correction factors Φ_m and Φ_h are functions of the nondimensional height ζ and are defined according to Businger et al. [1971]. The functional forms of the correction factors were derived for an air column over very homogeneous terrain. While there is no guarantee that their form will not be altered over a patchy surface, in this study we have assumed that these relations can be maintained. The only differences between Φ_m and Φ_h, for homogeneous and non-homogenous underlying surfaces, stem from the different values of the parameter ζ, which implicitly depends on the fractional vegetation cover. Consequently, we have adopted the correction factors Φ_m and Φ_h with aggregated values of Z_0 and D estimated according to equations (2) and (3).

3. NUMERICAL EXPERIMENT

3.1 Experimental setup

There is a general lack of data suitable for testing the corresponding modelling ideas. Therefore, to examine the model behavior, we have performed a numerical experiment for different parts of a hypothetical urban area. One-dimensional simulations were carried out with an imposed meteorological dataset collected at an agricultural site near Vienna (Austria) from 2 June to 31 August, 1995. The dataset contains downward solar short-wave radiation, precipitation, wind speed, temperature and relative humidity of the air at 2 m above the ground. Values of air variables so close to the surface are a limitation since most of the changes made to the surface parameters will affect these values [Dupont et al., 2000; Delage et al, 1999]. To remove this limitation, the measurements collected at 2 m were extrapolated up to 50 m and used as atmospheric forcing (without feedback). Details of these calculations are shown in Appendix.

Simulations were carried out over five typical European urban quarters, described in the table 1: "City Centre" (CC), "Residential Quarter" (RQ), "Green Quarter" (GQ), "Industrial-commercial Quarter" (ICQ) and "High Building Quarter" (HBQ). Each quarter has different proportions of bare, vegetation and urban land inside a grid cell.

Quarters	Bare soil	Vegetation	Artificial surface
CC	0%	10% mixed woodland	40% asphalt + 50% slate
RQ	20% loamy sand	5% mixed woodland + 25% grass	30% asphalt + 20% tile
GQ	10% loamy sand	15% mixed woodland + 60% grass	10% asphalt + 5% slate
ICQ	10% loamy sand	0%	50% asphalt + 40% steel
HBQ	5% loamy sand	25% mixed woodland	40% asphalt + 30% concrete

Table 1. Land cover rates for five typical European city quarters: CC (City Centre), RQ (Residential Quarter), (Green Quarter), ICQ (Industrial-Commercial Quarter) and HBQ (High Building Quarter). Adapted from Dupont et al. [2000].

Quarters	z_0 (m)	*d* (m)	*H* (m)	Urban surface form
CC	2.0	14.0	20.0	High-rise
RQ	0.5	3.5	5.0	Low density and height
GQ	0.3	2.1	3.0	Low density and height
ICQ	2	14.0	20.0	High-rise
HBQ	1.3	9.1	13.0	Tall and high density

Table 2. Values of roughness length and displacement height for artificial mode of five typical European city quarters, defined in table 1. These values are taken from the recommendation of Grimmond and Oke [1999].

Values of the roughness lengths and displacement heights for artificial surface mode are taken from Grimmond and Oke [1999]. These parameters are related to the average height of the urban elements, *H*, as z_0=0.7*H* and *d*=0.7*H*. Values of *H*, z_0 and *d* for each quarter are taken from table of typical values in this paper, and are given in table 2, together with the corresponding urban surface forms.

3.2 Results and discussion

Urbanisation of the natural landscape through the replacement of vegetation with roads, houses and buildings dramatically alters the surface energy balance and temperature field. To assess the change of natural climate due to urbanisation, we will consider differences in components of evaluated surface energy balance and surface temperature between different city quarters. Results for surface energy balances for two typical days in July are shown in Figure 1, and for surface temperatures in Figure 2.

3.2.1 Energy balance

For highly urbanized quarters (CC, ICQ and HBQ), the sensible heat flux (H) is the primary means of dissipating the daytime net radiation surplus. Sensible heat flux is directly related to the roughness of the surface. It is the largest for high-rise CC and ICQ, smaller for tall HBQ, and the smallest for low RQ and GQ. Therefore, the model is able to reproduce the fact that increased surface roughness leads to increased turbulent fluxes.

The latent heat flux (LE) is negligible for quarters where artificial materials cover 90% of the land (CC and ICQ), small for HBQ, and has the dominant role in energy balance for quarters with a large fraction of natural surface (GQ and RQ). Therefore, one effect of urbanization is the reduction of LE.

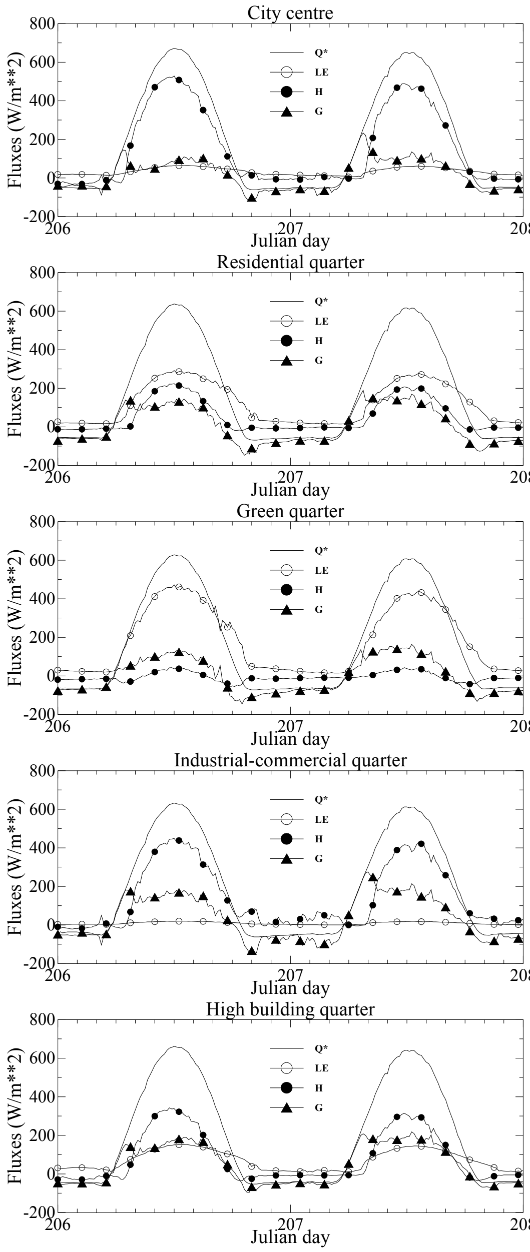

Figure 1. Components of energy balance of each quarter: net radiation (Q^*), latent heat flux (LE); sensible heat flux (H) and energy storage (G).

The energy storage (G) is also a significant term in the energy balance of urban areas. It is the largest for the industrial-commercial quarter because this quarter has flat roofs made of steel. These roofs store more heat than those made of other materials.

At night, when winds are usually light, the turbulent terms are small. The net radiative drain is mostly supplied from the heat storage.

These energy balances show the qualitatively agreement with the directly measured values in a suburban area in Vancuver [Cleugh and Oke, 1986].

3.2.2 Surface temperature

Urban heat island phenomenon is characterised by warmer temperatures in the city as compared to the surrounding rural area. Generally, the heat island occurs at night and is caused by the faster cooling of the rural area compared to the urban area. Artificial materials store heat during the day, and release it slowly during the night, due to their thermal properties. Other suggested causes can be found in Oke [1987]. As can be seen from Figure 2, surface temperatures predicted by LAPS show the existence of the urban heat island. Green quarter can be considered as the rural site. From the sunset and during the night, the warmer quarters are the most urbanized (ICQ, CC and HBQ) because they release the energy stored during the day. During the selected two days, the largest difference in surface temperatures, between the ICQ and GQ, was about 3 K in the middle of the night.

During the first part of the day, all quarters have similar surface temperatures, even the green quarter. This can be explained by two reasons. First, the roughness length of the green quarter is lower than in the other quarters, reducing surface heat transfers. And the second reason is that vegetation reacts rapidly to the net radiation increase because it does not store energy.

For the selected couple of days, green quarter has the lowest temperature at noon hours. This is due to the fact that the evapotranspirational cooling was large because the soil was relatively wet. During other periods with lower availability of soil moisture, midday surface temperatures of GQ were greater, comparable to those of other quarters.

4. CONCLUSIONS, RECOMMENDATIONS AND FURTHER PLANS

It is important to develop parameterizations of the urban effects in numeric weather prediction and air pollution models. Therefore, the Land Air Parameterization Scheme [Mihailovic, 1996] was developed to take into account the complexity of urban surfaces through the new definition of wind profile over a heterogeneous surface.

To examine the model behavior, the numerical experiment has been performed. The key findings of this experiment are:

1. The simulated components of urban energy balance are in qualitatively agreement with the observed values.
2. The simulated surface temperatures show the existence of the well-known urban heat island phenomenon.

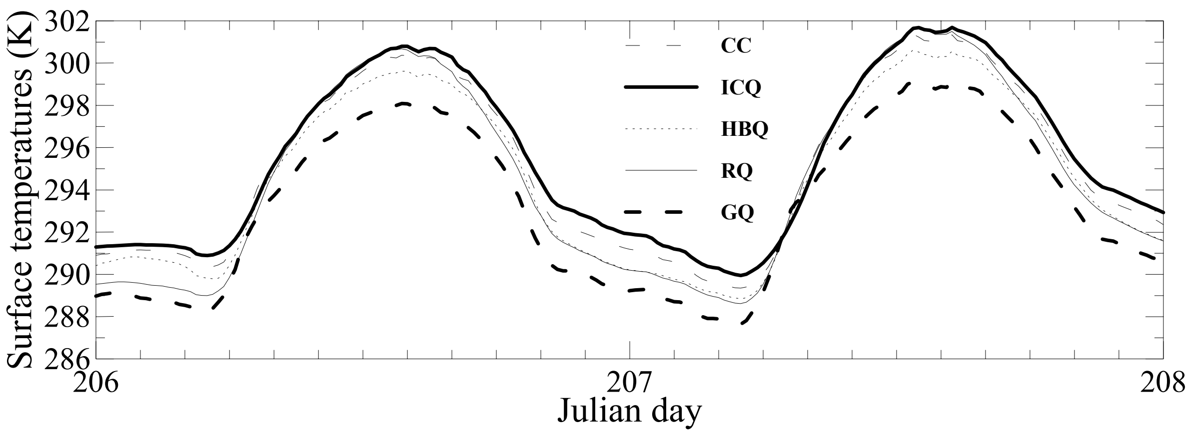

Figure 2. Simulated surface temperatures of: City Centre (CC), Residential Quarter (RQ), Green Quarter (GQ), Industrial-commercial Quarter (ICQ) and High Building Quarter (HBQ).

The model in its present form or with the slight modifications might be applied to examination of the influence of density and height of urban buildings, man-made heat flux, changes of albedo and other characteristics of urban climate. The model gives a possibility of simulating and describing the influence of selected factors on the atmospheric state over an urban area.

Our next goal will be to modify the LAPS by implying the new parameterization for albedo of a very heterogeneous surface, suggested by Mihailovic et al. [2002b].

5. ACKNOWLEDGMENTS

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6. APPENDIX

This appendix describes the generation of the meteorological inputs for LAPS at a height of 50 m from measurements at 2 m. The downward solar short-wave flux and precipitation are unchanged. The downward long-wave flux (not measured directly) is calculated as

$$L\downarrow = \varepsilon_a \sigma T_{50}^4 , \qquad \text{(A.1)}$$

where σ is Stefan-Boltzmann proportionality constant, T_{50} is a temperature at 50 m and ε_a is atmospheric emissivity which is an empiric function of 50-m water vapor pressure.

Wind speed varies approximately logarithmically with height in the surface layer. Assuming the log wind profile, wind speeds at 50 m were calculated from measurements at 2 m and the value of aerodynamic roughness length (we assumed 0.05 m).

The mean temperature and relative humidity $\overline{X}$ are first calculated from the measurements for each day and then individual values at every 15 minutes at 50 m, X_{50}, are calculated from the measured value at 2 m, X_2, according to the following formula:

$$X_{50} = \overline{X} + \left(X_2 - \overline{X}\right) \cdot \frac{\ln 1000 - \ln 50}{\ln 1000 - \ln 2} . \qquad \text{(A.2)}$$

Equation (A.2) assumes that the differences between individual values and the current daily mean decrease logarithmically with height vanish at 1000 m. Water vapor pressures are then calculated from values of temperature and relative humidity at 50 m.

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