AIR-QUALITY AND CLIMATE INTERACTION WITHIN URBAN ENVIRONMENT

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Abstract: Recent studies show considerable effect of atmospheric chemistry and aerosols on climate on regional and local scale, especially within the industrial and urbanized areas. Moreover, there is strong potential of urban environment to affect these processes, especially due to urban heat island.

For the purpose of qualifying and quantifying these effects the surface parameterisation in regional climate model RegCM has been extended with Single Layer Urban Canopy Model (SLUCM), which can be used both in dynamic scale within BATS scheme and more detailed SUBBATS scale. Experimental tests of the urban parameterization has been performed on Central Europe region in 10 km resolution with 2 km resolution of SUBBATS scheme. Results clearly show urban heat island (UHI) patterns for most the big cities or urbanized areas in the region and sensitivity tests with eliminating urban and suburban land use types provide the estimate of urban parameterization influence.

Parameters of the scheme are tuned for Central Europe cities with special emphasis to Prague within the UHI Project. Detailed analysis at 2 km scale shows the local features of the UHI in Prague region. These improved simulations with urban parameterization included are used for offline coupling with CAMx to assess the effects on air quality in the region.

Key words: *urban heat island, urban environment, urban canopy, regional climate modelling, air quality*

INTRODUCTION

Big cities or urban aglomerations can significantly impact both climate and environment. Due to the emissions of large amount of gaseous species and aerosols, which affect the composition and chemistry of the atmosphere (Timothy et al., 2009) and thus it can have adverse effect on the environment in the cities and their vicinity. Moreover, this can negatively impact the population (Gurjar et al., 2010). In addition, this pathway can result in indirect impact on the meteorology and climate as well, due to radiation impact of the atmospheric composition on the thermal balance, the temperature, especially within the canopy layer in the cities, can change.

However, the primary reason for temperature increase within the cities or urban aglomerations with respect to the rural vicinity, is the effect of so called urban heat island (UHI, Oke, 1973), which is mainly due to construction elements within the urban environment. This is largely covered by artificial objects, buildings, using by large stone, bricks or concrete, and by quite large spaces often paved. This kind of surface clearly differs from natural surfaces (e. g. grassland, forest) by mechanical, radiative, thermal, and hydraulic properties, therefore, these surfaces represent additional sinks and sources of momentum and heat, affecting the mechanical, thermodynamical, and hydrological properties of the atmosphere (Lee et al., 2010). Neverthelles, the changes of meteorological conditions within the urban areas due to UHI can further affect the air-quality. This has been studied recently by e.g. Ryu et al. (2013), they found significant impact on the ozone day and night-time levels especially due to circulation pattern changes for the Seoul metropolitan area.

As the air-quality issues are discussed in more details by Huszar et al. (2013), in this study we will focus on the aspects of climate conditions changes in urban environment, yet especially on those with strong potential to impact the air-quality, based on the same experiment setup. For the region of Central Europe, we will investigate the impact of the urban environment by means of its introducing into the regional climate model. As the spatial scale of the meteorological influence due to the cities is much smaller than the scale resolved by the mesoscale model, inclusion of urban land-surface requires additional parameterizations. The most common parameterizations considering the urban effects are the slab models (bulk parameterization), where the urban surface constants (e.g., surface albedo, roughness length, and moisture availability) can vary to better describe those of the urban surfaces. This treatment however ignores the three-dimensional character of the urban meteorological phenomena, moreover, in feasible resolutions the urban environment cannot be well resolved. Therefore, a more accurate approach is provided using urban canopy models (single layered – SLUCM, or multi-layered MLUCM) coupled to the driving mesoscale model (Chen et al. 2011). Our study describes in more details the implementation of such a SLUCM into our regional climate chemistry modelling system.

URBAN PARAMETERIZATION AND EXPERIMENTAL SETUP

Cities affect the boundary layer properties thus having direct influence on the meteorological conditions and therefore on the climate. The urban surface is covered by large number of artificial object with complex 3 dimensional structure and considerable vertical size. Specific characteristics in urban morphology can be involved in complicated physical processes such as increased momentum drag, radiation trapping between buildings (effect of vertical surfaces), and heat conduction by the artificial surfaces. There had been many field measurements in cities that found characteristic features of mean flow, turbulence and thermal structures in the urban boundary layer (e.g. Allwine et al., 2002; Rotach et al., 2005).

Although there is a trend (enabled by the faster computational resources) to increase the spatial resolution of the mesoscale models, regional weather prediction and climate models still fail to capture appropriately the impact of local urban features on the mesoscale meteorology and climate without special sub-grid scale treatment. This accelerated the implementation and application of urban canopy sub-models (Chen et al., 2010 or Lee et al., 2010). For the regional climate model RegCM4 we have chosen the Single Layer Urban Canopy Model (SLUCM) developed by Kusaka et al. (2001) and Kusaka and Kimura (2004); this scheme is proven to perform well in simulating the urban environment and it is less demanding in computational resources unlike its multi-layer counterparts (Lee et al., 2010).

SLUCM considers the urban surface in a realistic way: it assumes street canyons with a certain width; in the street canyon, shadowing, reflection and trapping of radiation are considered. An exponential wind profile is prescribed. SLUCM treats surface skin temperatures at the roof, wall, and road and temperature profiles within roof, wall and road layers as prognostic variables. The heat fluxes from each surfaces are calculated using the Monin-Obuchov similarity theory and finally the canyon drag coefficient and friction velocity is computed using a similarity stability function for momentum. Fig. 1 presents the conceptual design of SLUCM. It shows the fluxes between street canyon air and the surrounding surfaces (road and walls) and the fluxes from/to the building roofs.

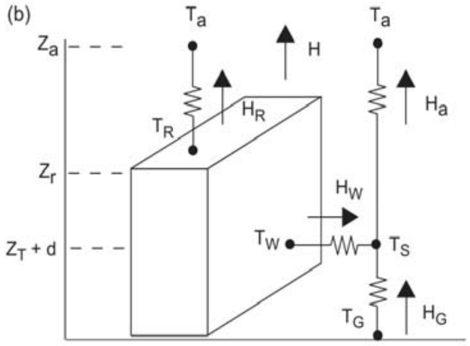

Figure 1. Energy fluxes in the SLUCM between the street canyon and the road and walls and from the buildings roof (T_a - air temperature at reference height z_a T_R - building roof temperature, T_W - building wall temperature, T_G - the road temperature, T_S - temperature defined at z_T+ d, H – the sensible heat exchange at the reference height, H_a is the sensible heat flux from the canyon space to the atmosphere, H_W - from wall to the canyon space, H_G - from road to the canyon space, H_R - from roof to the atmosphere).

The regional climate model used in this study is the model RegCM version 4.1 (hereafter referred to as RegCM4.1) from The International Centre for Theoretical Physics (ICTP), which is a three-dimensional mesoscale model. In terms of physical parameterizations it is nearly identical to RegCM3 (Pal et al., 2007). Major changes in the model from version 3 to version 4.1 include the following: the inclusion of the Community Land Surface Model v3.5 (CLM3.5) as an optional land surface parametrization, a new optional parametrization for diurnal SST variations, and a major restructuring (modularization) of the code base. RegCM4.1 and its evolution from RegCM3 is fully described by Giorgi et al. (2012).

RegCM4.1 includes a two land-surface models: BATS (Giorgi et al., 2003b) and the CLM model (Oleson et al., 2008). Both land-surface models can work in mosaic-type mode where the model grid is divided into sub-grid boxes for which the calculation of fluxes is carried out separately and the fluxes are then aggregated back to the large scale model gridbox (for BATS scheme reffered as SUBBATS, see Pal et al., 2007). An improvement can be achieved by implementing more sophisticated urban parameterizations lying under these land-surface models that better represent for the urban land-use type most urban features like building morphology, street geometry, variability of the properties of artificial surfaces, as well as the description of radiation trapping in the street canyon. For this purpose, Chen et al. (2010) provide a Single Layer Urban Canopy Model (SLUCM), originally developed by Kusaka et al. (2001) and applied in Kusaka and Kimura (2004).

This SLUCM model has been implemented into RegCM4.1 by linking it to the BATS surface scheme, applying SUBBATS with 2 km x 2 km sub-grid resolution. SLUCM is called within SUBBATS wherever urban land-use categories are recognized in the land-use data supplied. The scheme returns the total sensible heat flux from the roof/wall/road to BATS, as well as the total momentum flux. The total friction velocity is aggregated from urban and non-urban surfaces and passed to RegCM's boundary layer scheme. However, as RegCM4.1 by default does not consider urban type land-use categories, we extracted the urban land-use information from the Corine 2006 (EEA, 2006) database and we have added this information to the RegCM4.1 land-use database. In those parts of the domain where this was not available in Corine data, the GLC2000 (GLC, 2000) database was used. We considered two categories, urban and suburban. See Fig. 2 for the urban land-use coverage for the SUBBATS 2 km x 2 km subgrid module.

The domain for the present study has been selected to cover most of Central Europe with a spatial resolution of 10 km × 10 km. It is divided into 23 vertical levels reaching up to 5 hPa. For convection, we have used the Grell scheme (Grell, 1993). RegCM4.1 is initialized and driven by the ERA-Interim reanalysis (Simmons et al. 2007). The time step for the integration is 30 s.

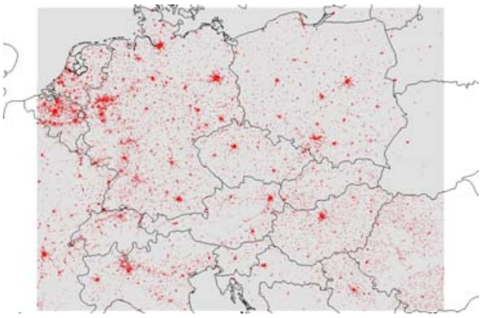

Figure 2. Urban and suburban land-surface categories on 2 km x 2 km resolution.

RESULTS

Fig. 3 presents the change of selected meteorological parameters between experiments SLUCM (the urban canopy model turned on) and NOURBAN (urban canopy not considered) averaged over years 2005-2009. Shaded areas represent significant changes on the 95% confidence level. We show only winter (left panels) and summer (right panels) seasons, actually, the effect is well expressed in spring and autumn as well, but summer signal is stronger.

For temperature, there is an evident increase with urban canopy introduced in summer, for winter only slight signal can be seen for big cities like Berlin and Vienna, similarly for urban and industrial areas like Rhine-Ruhr region and Po-valley. In summer, this temperature increase can be of 1K over urbanized areas (effect of cities like Budapest, Vienna, Prague, Berlin are well seen), but it is statistically significant elsewhere with up to 0.4K increase even over non-urban areas. Opposite effect can be seen for specific humidity. Urban surfaces can absorb less water vapor than other surfaces and they represent a sink for the precipitated water as well. Therefore the evaporation from the urban surfaces is reduced as well which leads to the lower humidity over urban areas as seen in Fig. 3. Again, this decrease is highest above cities (up to -0.8 g/kg), but significant decrease is simulated over non-urbanized areas as well, up to -0.3 – -0.4 g/kg. Signal is quite strong in summer, but similar patterns, although much slighter, can be seen in winter. For wind speed, introducing the urban canopy parameterization leads to stronger wind over the surface (Fig. 3). This increase is limited mainly over urban areas where it can reach 0.4 – 0.6 m.s^{-1} in summer, much less it is expressed in winter, when for Po-valley there is even decrease. However, the signal is rather small in winter and not so much significant in all the domain. The increase above the cities in summer has to be further studied, one possible reason might be support of convection above the city with stronger winds in the bottom. Finally, we assess the effect of urban canopy parameterization on the height of planetary boundary layer from the model, which leads to statistically significant increase in summer above most of the domain, with quite strong signal above the cities and industrial regions (Fig. 3) of about 100-150 m, mostly negligible and not significant in winter.

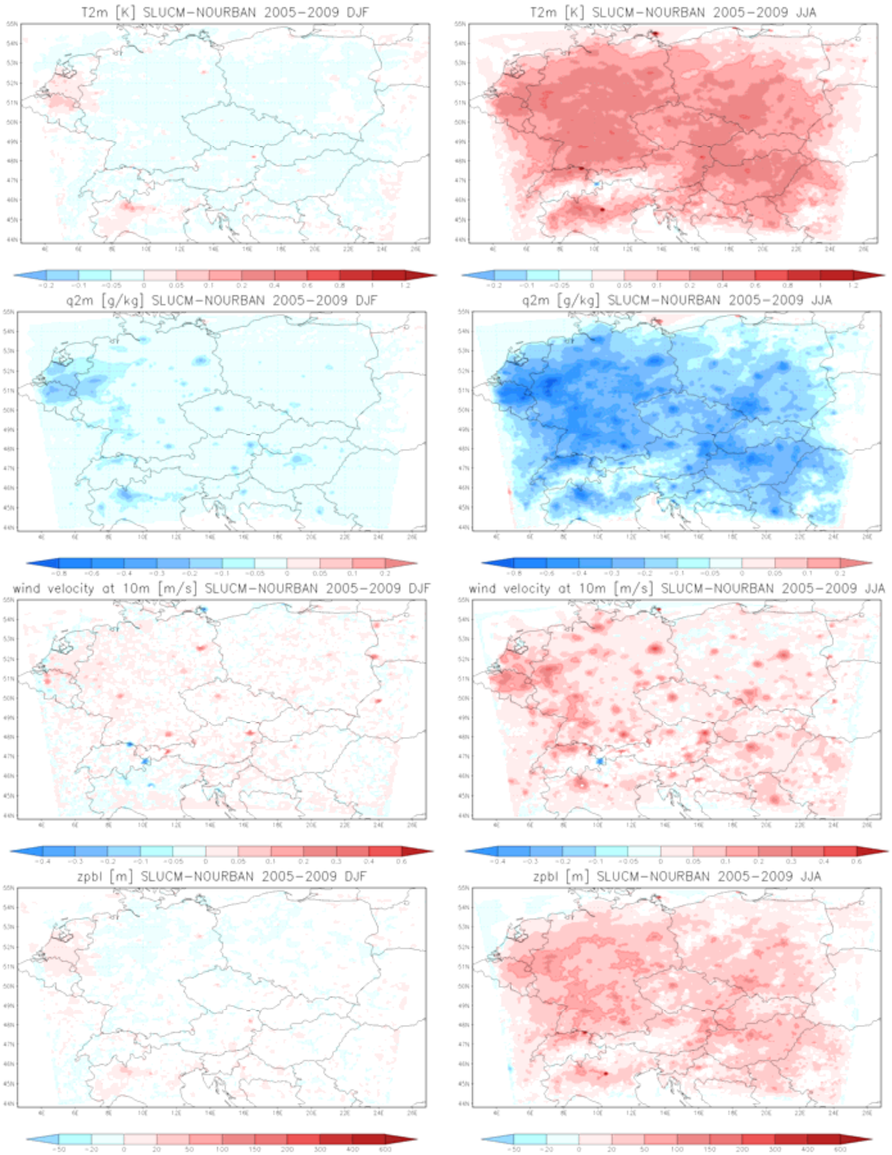

Figure 3. The mean differences of meteorological parameters between experiments with SLUCM against NOURBAN averaged over 2005-2009 for winter (left panels) and summer (right panels): from the top - temperature at 2 m (K), specific humidity at 2 m (g.kg^{-1}), wind speed at 10 m (m.s^{-1}), and planetary boundary height (m). Shaded areas represent significant changes on the 95% level of confidence.

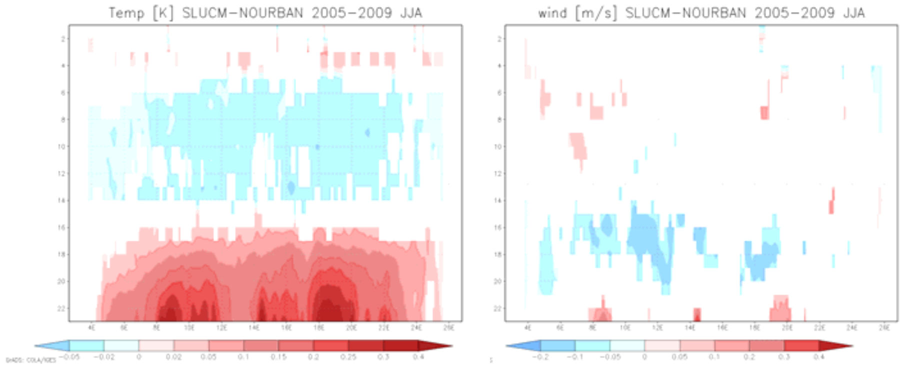

Figure 4. The mean differences in summer between experiments with SLUCM against NOURBAN averaged over 2005-2009 for vertical cross-section on 50N of temperature (K, left panel) and wind speed (m.s^{-1}, right panel). Shaded areas represent significant changes on the 95% level of confidence.

Fig. 4 presents the more detailed analysis of significant patterns of vertical structure of the urban parameterization effects in summer. The increase of temperature in the boundary layer is accompanied with temperature decrease above, concerning the humidity there is no effect in the free atmosphere (not shown). Stronger wind can be seen only at surface level, the effect throughout the boundary layer is rather negative.

SUMMARY

The presented study evaluates the effect of urban environment on the climate conditions, which can further play significant role in forcing on air quality. We successfully implemented a single layer urban canopy parametrization into the regional climate model RegCM4.1. Preliminary assessment is based on present day conditions simulation for 5 year long period with and without urban canopy parameterization included. Our simulations have shown that the impact on meteorological parameters is significant not only over urbanized areas but also over rural ones far from cities. The most important impact is the increase of surface temperature (up to 1 K), decrease of humidity, increase of surface wind speed, decrease of precipitation (not shown here) and increase of boundary layer hight.

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