AIR-QUALITY CHANGES INDUCED BY URBAN LAND SURFACE FORCING IN CENTRAL EUROPE

Peter Huszar[1], Tomas Halenka[1], Michal Belda[1] and Katerina Zemankova[1,2]

[1]Charles University, Prague, Faculty of Mathematics and Physics, Dept. of Meteorology and Environment Protection, V Holesovickach 2, 180 00 Prague, Czech Republic
[2]LATMOS, IPSL, Paris, France

Abstract: Air-quality climate interactions in urban environment have many aspects. First of all, concentrated emissions lead to considerable abundance of primary and greatly influencing secondary pollutants, affecting not only the local but the regional and global scale. Secondly, the modified concentrations lead to modified radiative forcing leading to temperature changes. Thirdly, as air quality is greatly influenced by the meteorological forcing, urban land-surface represented by many artificial objects changes the meteorology, in turn impacts the air quality as well. This study will focus on this aspect.
Using a regional climate model RegCM4 coupled with Single Layer Urban Canopy Model (SLUCM) and CAMx regional chemical transport model, we will examine the impact of urban meteorological effects on air quality. It is expected the the urban heat island effect introducing higher temperature lead to increased chemical reactions rates changing the photochemistry. Further the surface heterogeneities introducing modified circulation, vertical mixing affect the advection and diffusion of pollutants.

To capture these effects, annual simulations are performed using the RegCM4/SLUCM/CAMx couple for year 2005 for a 10 km x 10 km European domain. The surface parameterization uses the SUBBATS option in the model allowing calculation of surface fluxes at much higher resolution – 2 km x 2 km in our case, which is a reasonable resolution to resolve larger cities in central Europe.

We find considerable summer impact on concentration of the policy relevant pollutants due to urban land surface effects, especially on ozone formation over urbanized areas that is connected mainly to the urban heat island effect but also to the modified distribution of the primary pollutants due to changed circulation patterns.

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

INTRODUCTION

Cities have significant environmental impact that follows primarily two pathways. They emit large amount of gaseous species and aerosols into air, having direct impact on the composition and chemistry of the atmosphere (Timothy et al., 2009) and harmful effect on the cities' population (Gurjar et al., 2010). This pathway has, indirectly, impact on the meteorology and climate as well. Certain gases and aerosols interact with radiation in the atmosphere, modifying the radiative and consequently the thermal balance resulting in temperature changes. Aerosols further interact with the cloudiness, changing its micro-physical and optical properties.

Secondly, urban surfaces affect meteorological conditions and therefore the climate: they are largely covered by artificial objects and are often paved, therefore clearly distinguished from natural surfaces (e. g. grassland, forest) by mechanical, radiative, thermal, and hydraulic properties. 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).

These meteorological changes triggered by the urban land surface characteristics can further influence the air-quality. Recently, Ryu et al. (2013), investigated these connection for the Seoul metropolitan area and found significant impact on the ozone day and night-time levels especially due to circulation pattern changes.

In this study, we will focus on this aspect of climate air-quality connections in urban environment and will investigate, how is the summer air quality perturbed due to the urban meteorological forcing using a coupled regional climate and air quality model. We will focus on the region of Central Europe.

Treatment of urban land-surface requires additional parameterizations as the spatial scale involved in urban meteorological influence is much smaller than the scale resolved by the mesoscale model. The most common parameterizations providing such a treatment are the slab models (bulk parameterization) where the soil constants (e.g., surface albedo, roughness length, and moisture availability) are varied to better describe those of the real urban surfaces. This treatment however ignores the three-dimensional character of the urban meteorological phenomena. A more accurate approach is the use of urban canopy models (single layered –

SLUCM or multi-layered MLUCM) coupled to the driving mesoscale model (Chen et al. 2011). Our study includes the implementation of such a SLUCM into our regional climate chemistry modelling system.

Models and experimental setup

The regional climate model used in this study is the International Centre for Theoretical Physics' (ICTP) regional climate model, RegCM version 4.1 (hereafter referred to as RegCM4.1). 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 model code. RegCM4.1 and its evolution from RegCM3 is fully described in Giorgi et al. (2012).

RegCM includes a two land-surface models: BATS (Giorgi et al., 2003b) and the CLM model (Oleson et al., 2008). Both land-surface model are mosaic-typed models were the grid is divided into subgrid-boxes were the calculation of fluxes is carried out separately and the fluxes are aggregated back to the large scale model gridbox. An improvement can be achieved by implementing more sophisticated urban parameterizations lying under these land-surface models that represent more realistically the urban features like building morphology, street geometry, variability of the properties of artificial surfaces as well as 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). We implemented SLUCM into RegCM4.1 as a sub-layer of BATs surface scheme at 2 km x 2 km subgrid resolution. Within BATS, SLUCM is called whenever urban landuse categories are found in the landuse data supplied for the model. RegCM4.1 by default does not consider urban type landuse categories. We extracted the urban landuse information from the Corine 2006 (EEA, 2006) database and those parts of the domain where this was not available, the GLC2000 (GLC, 2000) database was used. We considered two categories, urban and suburban.

We offline coupled RegCM4.1 to the chemistry transport model (CTM) CAMx version 5.4 (ENVIRON, 2011). The coupling technique is very similar to that in Huszar et al. (2011), only the participating models are of newer version. The RegCMCAMx coupler module remains the same, serving to translate the RegCM4.1 meteorological fields to CAMx meteorological input. Two-way interaction introduced in Huszar et al. (2012), i.e. accounting for the radiative impact of the gases/aerosols is not considered in this study.

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 invoked the Grell scheme (Grell, 1993). RegCM4.1 is initialized and driven by the ERA-Interim reanalysis (Simmons et al. 2007). The time steps for the integration are 30 s for the climate model and 5 min for the chemistry model. In CAMx, 16 vertical levels are defined, matching the first 16 levels of RegCM reaching up to about 8000 m. For chemical calculations, the SAPRC99 chemistry package has been invoked. For aerosols, we have activated the ISORROPIA scheme with static 2-mode particle size treatment.

Anthropogenic emissions used are from the MEGAPOLI year 2005 emissions (Butler et al., 2011) using the same temporal allocation factors and chemical speciation as in Katragkou et al. (2010). Biogenic emissions of hydrocarbons (isoprenes and monoterpenes) are calculated following the approach of Guenther et al. (1993). Chemical boundary conditions where extracted from the MOZART-4 global CTM (Emmons et al., 2010).

Using the RegCM/CAMx offline couple, we performed two experiments over years 2005-2009. One without any treatment of urban surfaces (denoted as NOURBAN, practically assuming as there were no urban surfaces) and one with the SLUCM urban canopy model turned on (SLUCM). We examined the summer mean changes in the most important meteorological parameters and the change in the ozone concentration.

Results

Meteorological impact of urban land surface

Fig. 1. presents the summer 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% level of confidence.

There is and evident summer temperature increase when introducing urban canopy. This temperature increase can be as high as 1K over urbanized areas (effect of cities of Budapest, Vienna, Prague or Berlin well seen) but is statistically significant elsewhere with up to 0.4K increase over non-urban areas. Urban surfaces can absorb less water vapor than other surfaces and represent a sink for the precipitated water as well. Therefore the evaporation from the urban surfaces is reduced leading the smaller humidity over them as seen in Fig.2(b). This decrease is highest again above cities (up to -0.8 $g.kg^{-1}$) but again, significant decrease is modelled over non-urbanized areas as well, up to -0.3 – -0.4 $g.kg^{-1}$. Introducing the urban canopy parameterization leads to increased wind over the surface (Fig.2c). This increase is limited mainly over urban surfaces where it can reach 0.4 – 0.6 $m.s^{-1}$. At last, the urban canopy parameterization introduced leads to statistically significant decrease of precipitation at many areas (Fig.2d), which may be the results of reduced evaporation. The decrease is in general highest over western Germany and the Benelux states, but is high over cities in other parts of the domain (decrease up to 1mm $.day^{-1}$).

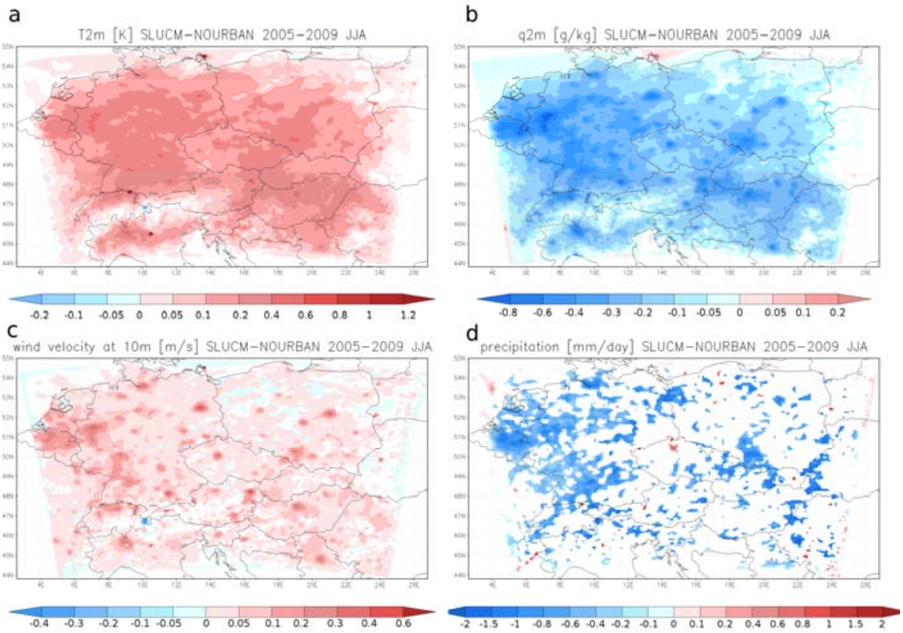

Figure 1. The mean summer differences of selected meteorological parameters between experiments SLUCM and NOURBAN averaged over years 2005-2009: (a) temperature at 2 m (K), (b) absolute humidity at 2 m as $g.kg^{-1}$, (c) wind speed at 10 m as $m.s^{-1}$, (d) summer precipitation as $mm.day^{-1}$. Shaded areas represent significant changes on the 95% level of confidence.

Chemical changes due urban land surface meteorological forcing

Fig. 2. presents the surface summer concentrations of ozone and nitrogen oxides (NOx) averaged over 2005-2009 (upper row) and their change when introducing urban land surface effects, i.e. the difference between SLUCM and NOURBAN experiments.

As seen on previous figure, urban surface increases the surface temperature. This could impact the ozone production trough increased reaction rates. Fig. 2. (bottom left) suggest however that the connections between urban meteorological effects and air quality are more complex. The surface ozone is increasing only over Poland and certain areas in Slovakia, Hungary and Croatia (by up to 0.6 ppbv). Over the Czech Republic, Germany the Benelux states a decrease of surface ozone is modelled. The modelled ozone change (especially over the areas of decrease) well corresponds to the surface NOx change (bottom right) which is represented by an increase up to 1-5 – 2 ppbv over the western part of the domain (about 5 % increase). The reason for the modelled air-quality changes can lie in the combined effect of temperature increase, the decrease of humidity and precipitation and the increase of wind over urban areas. E.g. The ozone decrease modelled is limited to areas where ozone titration dominates (in NOx saturated air). Here, increased reaction rates accelerate titration reactions (reaction of NO with O_3 etc.). Further, decreased precipitation decrease the deposition of NOx leading to increased concentrations causing further ozone destruction.

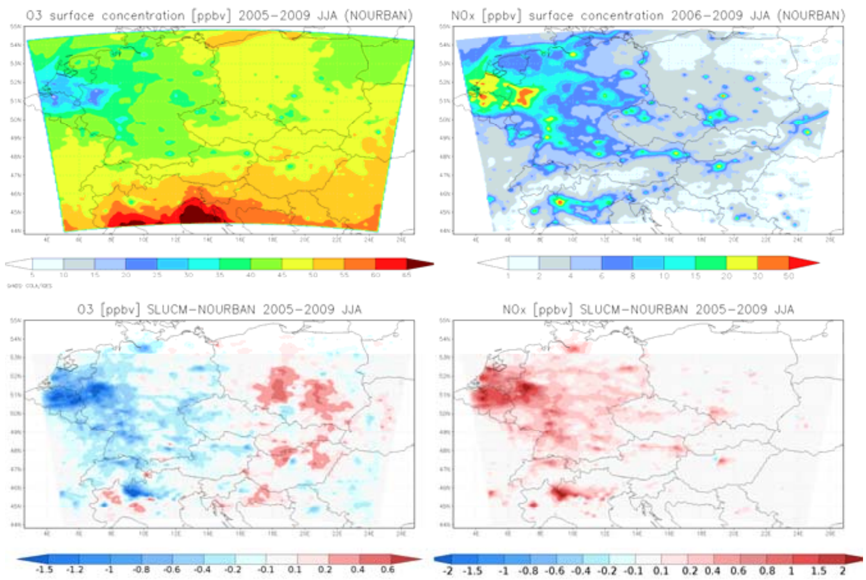

Figure 2. The mean summer surface ozone and NOx concentrations (upper row) and the differences between SLUCM and NOURBAN experiments for years 2005-2009 in ppbv.

Summary

The presented study dealt with one aspect of the urban land-surface impact on the environment: the impact of urban land surface meteorological forcing on air quality. Within the study, we successfully implemented a single layer urban canopy parametrization into the RegCM4.1 regional climate model offline coupled with the CAMx chemistry transport model. We performed two 5 year long simulations for present day conditions, one with no treatment of urban surfaces and one with the urban canopy model turned on.

Our simulations showed 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 wind speed, decrease of precipitation and increase of boundary layer height (not presented here). The changes in chemistry triggered by changed meteorological parameters encompass increase of ozone over the eastern part of the domain (up to 0.6 ppbv) and a more pronounced decrease over Germany and the Benelux states (up to -1 ppbv). Here, a small increase of NOx is also modelled.

The changes in O_3 and NOx suggest that the mechanisms that role the connections between urban land-surface meteorological effects and air-quality are more complex and far not unique. These connections include opposite effects on the pollutants concentration changes and this requires further investigation for better understanding the details of these connections.

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