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THE IMPACT OF URBAN CANOPY METEOROLOGICAL FORCING ON THE URBAN GAS-PHASE CHEMISTRY

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Abstract: The regional climate model RegCM4.4, including the surface model CLM4.5, was offline coupled to the chemistry transport model CAMx version 6.30 in order to investigate the impact of the urban canopy induced meteorological changes on the long-term summer photochemistry over central Europe for the 2001-2005 period. A strong urban canopy impact on temperature, wind speed and turbulence was modelled. These changes significantly affected the photochemistry as well as the transport of gaseous species. Their combined effect was characterized by increases in ozone concentrations up to 4-5 ppbv over urban areas. It is found, that the main contributor to this change is the enhanced vertical turbulent mixing while the contribution of decreased wind speed over cities and increased temperatures are less important. Process analysis technique is adopted to gain a more detailed insight of what drives the modelled chemical changes due to urban canopy meteorological forcing.

Key words: *summer photochemistry, urbanization, urban canopy effects, regional climate, air quality, turbulence.*

INTRODUCTION

Cities and urban areas, in general, represent a certain meteorological forcing owing to artificial surfaces they are covered with. These have specific properties and geometry greatly modifying the mechanical and thermodynamic properties of the air above. This leads effect like increases of urban temperatures in contrast with rural ones (Oke, 1982), decreases of humidity (Richards, 2004) and decreases of wind speeds and intensification of turbulence (Hou et al., 2013). These effects are moreover often not limited to the air above the cities themselves but have a regional fingerprint (Huszar et al., 2014) and show to be a very important component of the urbanization impact on the environment (Huszar et al., 2016b) These urban canopy induced meteorological perturbations must have impact on air-quality, as one of the main drivers of atmospheric chemistry are meteorological conditions. Elevated urban temperatures increase reaction rates resulting in faster chemical conversions. Higher temperatures further modify dry and wet deposition and influence wind by triggering urban-breeze circulation which can help the circulation of pollutants from- as well as to- urban areas depending on the daytime (Ryu et al., 2013). Wind stilling caused by drag over urban areas, on the other hand, can slow down pollution dispersion into larger scales. Increased turbulence over urban supports vertical transport of pollutants away from the urban canopy layer often leading to high gradients of primary and secondary pollutants resulting in elevated concentrations in upper layers of the planetary boundary layer (Stutz et al., 2004).

To evaluate an integrated 'chemical' effects of the urban induced meteorological changes, one however meets several difficulties. First of all, the individual impacts are often antipodal. For example elevated temperatures trigger higher reaction rates for reactions that are responsible for both ozone production and destruction at the same time. Slower winds keep primary pollutants closer to sources where they trigger formation of secondary pollutants, however, at the same time can contribute to their more effective chemical destruction. Enhanced vertical turbulence removes primary pollutants like NOx from urban areas, which can suppress ozone titration leading to increase of concentrations. Simultaneously, the secondary produced pollutants are subject to vertical eddy-removal which, consequently, lowers their concentrations.

To describe the complex nature of interaction between air chemistry and urban meteorology with many opposite effects requires modelling approaches and experimental strategies which are able to separate different pathways of this interaction. This study is motivated by this need and it analyses the long-term impact of urban canopy effects on air quality considering multiple years (2001-2005) covering a regional domain where a large number of medium to big cities is located, enabling to perform a more robust multi-city analysis instead of focusing on a particular urban area (as it is the case in many previous studies). The work further looks at the individual components of the overall impact and their partial contribution.

MODELS AND EXPERIMENTS

As a meteorological driver, regional climate model RegCM4 (version 4.4) was applied (Giorgi et al., 2012). Surface processes were modelled by the Community Land Model version 4.5 (Oleson et al., 2013). CLM4.5 offers a more detailed description of land surface processes compared to the simple BATS land-surface model originally coupled to RegCM model, including the CLMU urban canopy scheme implemented. The regional climate model RegCM4.4 has been offline coupled to chemistry-transport model (CTM) CAMx version 6.30 (ENVIRON, 2016). CAMx is an Eulerian photochemical CTM developed by ENVIRON Int. Corp. (http://www.camx.com). It includes multiple gas phase chemistry mechanism options (CB-IV, CBV, CBVI, SAPRC99). The CBV scheme was invoked in the present study.

The models were run at 10 km x 10 km horizontal resolution centered over Prague, Czech Repubic with 160x120x23 (in x, y, and z direction) gridboxes for the 2001-2005 period. The uppermost level for the climate is at 50 hPa, while the chemistry was integrated only on the lowermost 16 levels (approximately up to 300 hPa). The regional climate model was forced by 50 km x 50 km resolution experiment carried out with the RegCM4 model in the framework of the EURO-CORDEX initiative (Vautard et al., 2013), denoted REGCM–CUNI42 in the mentioned study. This coarse experiment was driven with the ERA-Interim reanalysis. This set-up is identical to Huszar et al. (2016a,b). Urban landunit percentage was extracted from the 0.05° x 0.05° resolution LandScan2004 data that is based on census, night-time lights satellite observation and road proximity as described by Jackson et al. (2010). They provide urban canyon parameters and surface characteristics as well.

We made two runs with the RegCM model, one with the urban landunits considered (experiment URBAN) and one where urban landunit was disregarded replaced by rural (usually crops) landunit (experiment NOURBAN). For the CAMx, four experiments were performed differing with the meteorological driving fields taken from the both RegCM runs. In the first run, meteorology for CAMx is taken completely from the RegCM's NOURBAN experiment and regarded as a reference chemical experiment. In the 2nd run, only the temperature effects were considered. The 3rd run with CAMx considered temperature and wind changes and finally, the 4th run considered changes in turbulence as well (changes in the vertical eddy diffusion coefficient). These CAMx runs were denoted NOURBAN, URB_t, URB_t+uv and URB_t+uv+kv. Only summer months (JJA) are analyzed, when photochemistry plays important role over the area of focus.

RESULTS

In Fig. 1., the summer average urban meteorological impact on near surface temperature, wind speed and vertical eddy diffusion is plotted. The impact on temperature is, as expected, positive and maximum values up to 2-3 K are simulated. Cities such as Berlin, Budapest, Vienna etc. are clearly distinguishable. Values are statistically significant (95% level) even over rural areas further from cities, reaching about 0.1–0.2 K. There is further a clear surface wind speed reduction due to the presence of urban surfaces. The decrease is expectedly largest over cities, reaching 1 m s^{-1} (e.g. over Berlin, Budapest). Statistically significant reduction is, however, modelled over rural areas as well with decreases up to 0.2 ms^{-1}. For the maximum (in vertical) vertical eddy diffusion, the impact is, again, greatest over urban areas, usually exceeding 10-20 m^2s^{-1} with peaks around 60-70 m^2s^{-1}.

As mentioned earlier, the presented impacts are not distributed across the day equally but there are clear diurnal cycles for each of three components. We therefore plotted in Fig. 2 the JJA average diurnal cycle of the near surface temperature over Berlin as selected city (solid line) and its vicinity (dashed line). Our analysis showed very similar cycles for other cities as well.

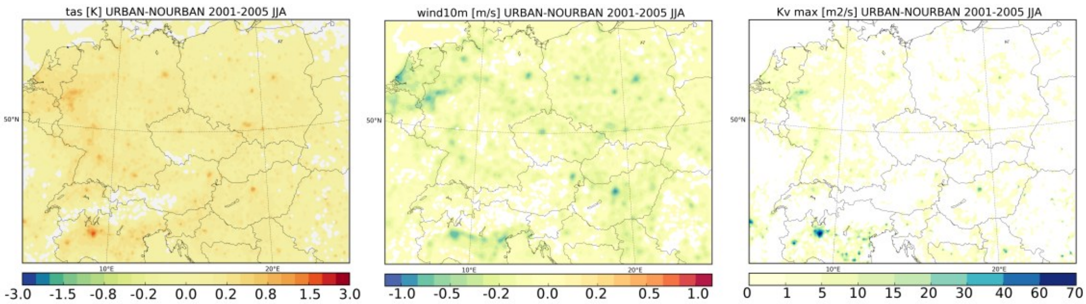

Figure 1. The urban canopy meteorological effects: impact on near surface temperature (K), on wind-speed (m s^{-1}) and on the coefficient of the vertical eddy diffusion (m^2 s^{-1}).

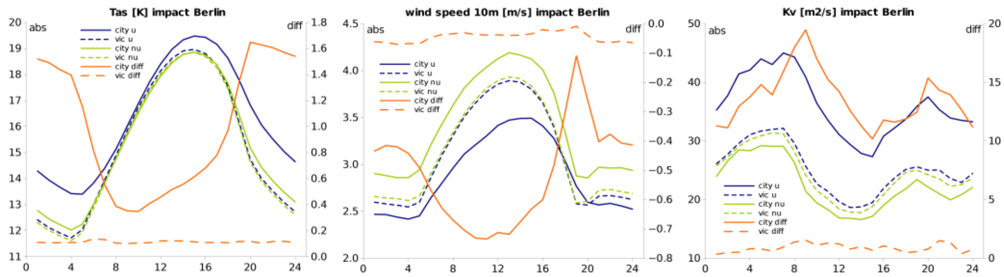

Figure 2. Diurnal cycle of the modelled near surface temperature (K), wind speed (m s^{-1}) and the coefficient of the vertical eddy diffusion (m^2 s^{-1}) in UTC for Berlin: blue - values from the URBAN (”u”) experiment, green - values from the NOURBAN (”nu”) experiment; red - difference of URBAN and NOURBAN simulations; solid line - city averaged values, dashed line - values from the city vicinity.

The URBAN experiment predicts higher temperatures over the cities, while the difference is smallest during morning to noon (reaching nearly zero). Maximum values are higher by about 0.5 to 1 K if urban surfaces are considered. The largest impact is modelled for late afternoon and evening hours, as expected. It is seen that the diurnal temperature range (DTR) is decreased by about 1.5-2.5 K. As expected, daytime wind speeds are higher compared to those during night with a daily amplitude about 1–1.5 ms^{-1}. The urban induced reduction is clear over cities themselves but it is evident for the vicinity as well, in accordance with the spatial figure above. Looking at the diurnal cycle of vertical eddy diffusion, the systematic increase by 10-20 m^2s^{-1} due to urban surfaces is evident throughout the whole day with maximum impact during morning hours. Unlike the maximum, the timing of the minimum of the impact is not unique over the cities and occurs during afternoon to late evening hours. The impact over the city’s vicinity is almost negligible.

Urban canopy impact on ozone concentrations

The impact of individual components of the urban canopy meteorological forcing (temperature, wind and turbulence) as well as the impact of their combined effects on ozone is plotted in Fig. 3. Due to higher temperatures, ozone decreases reaching -0.4 ppbv as JJA average (e.g. Berlin, Budapest). This decrease is usually limited to the area of the city. Over rural areas, the impact is of opposite sign and reaches 0.1-0.2 ppbv.

The response of O_3 to urban induced wind changes (i.e. decreases over cities) is characterized by a clear suppression of concentrations up to -1 ppbv over many cities (Budapest, Berlin, the Ruhr area in Germany, Milan etc.). For rural areas, a slight increase up to 0.3 ppbv is modelled.

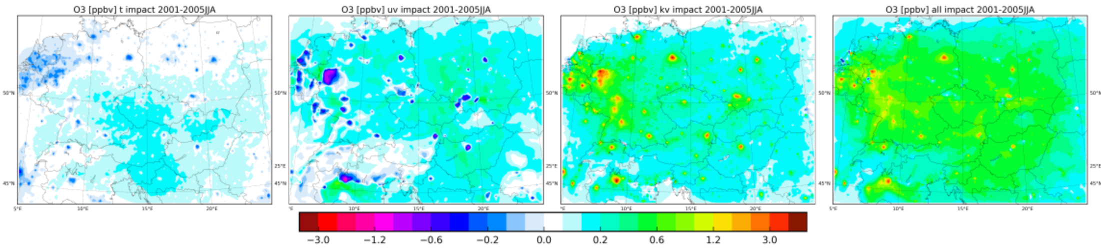

Figure **3.** Impact of urban canopy meteorological forcing on O_3 surface concentrations in ppbv for the 2001-2005 JJA period for the temperature (t), wind (uv), turbulence (kv) and total impact (all).

Surface ozone values respond to increased vertical turbulent diffusion with increases, especially over cities, reaching 5 ppbv (over Milan, Berlin, the Ruhr area etc.). Ozone enhancement is modelled even over rural areas, up to 0.2-0.5 ppbv. Looking at the total impact, which, given the experimental design, is mathematically the sum of the previous impacts, O_3 responds with increases up to 4 ppbv over cities.

In order to gain a more detailed view of what controls the above presented changes, we selected one city, Berlin, as a representative one (relatively large city placed further from sea and located over flat geographical area). We adopted the Process Analysis capability of model CAMx to analyse the contribution of individual processes like chemical reactions, deposition, horizontal/vertical diffusion, horizontal/vertical advection etc. to the overall change caused by any of the considered component of the urban impacts. Results of this analysis is plotted in Fig. 4.

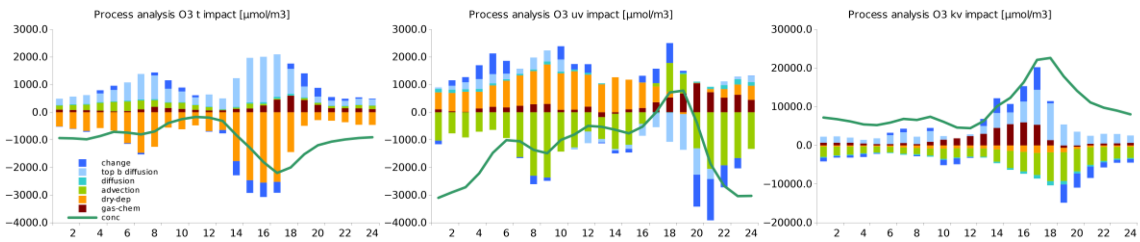

Figure **4.** Process analysis of the urban impact on air-quality for JJA over the city of Berlin: for the temperature (t, left column), wind (uv, middle column) and turbulence (kv, right column) impact on O_3 surface values. The plotted processes are gas-phase chemistry, dry deposition, advection (both vertical and horizontal), horizontal diffusion and top boundary diffusion.

Starting with the temperature impact on ozone, two competing processes are responsible for the change: top boundary diffusion and dry deposition. During the day, their magnitudes are similar, however during late afternoon dry deposition of ozone offsets the vertical diffusion and leads to decreased concentrations. Later, vertical diffusion becomes small and chemical production increases (which here means difference of two negative numbers, i.e. decreased destruction) and along with top boundary diffusion increases the difference (i.e. the temperature impact). Secondly, for the wind impact, the negative impact is a result of reduced through-top-boundary diffusion and also of reduced advection across side boundaries. The impact is then increasing (i.e. negative impact is getting smaller in magnitude) across the night and day mainly due to reduced dry deposition (note deposition is always a sink). At last, the impact of enhanced turbulence on the afternoon O_3 enhancement is caused mainly by chemical production, i.e. decreased loss via titration along with increased top boundary diffusion contribution (from higher level towards lower). Then, advection becomes dominant reducing the impact again.

DISCUSSION AND SUMMARY

The modelled impact of urban canopy on meteorology characterized by increases of temperature, decreases of wind speed and increased turbulence follows the expectations and are well corresponding to results of previous studies (Struzewska and Kaminski, 2012; Vautard et al., 2013).

The induced response of ozone concentrations are greatly differing between the individual components, which shows the importance of separating the influences in order to better understand the overall impact. Temperature increases led to ozone decrease, which, according to the process analysis, is the result of mainly increased dry-deposition. Due to decreased wind speeds, advection inside cities is reduced and the process analysis showed that this leads to suppressed transport of ozone towards city from its vicinities. Finally, due to increased turbulence, the vertical transport of primary pollutants is increased. This, in case of NOx-saturated conditions (where NO titration dominates), leads to less effective ozone destruction leading to higher concentrations.

The combined impact on ozone is in line with previous studies, that also indicated ozone increases up to 10 ppbv (e.g. Civerolo et al., 2007). We further showed that the turbulence domintes the modulation of urban chemistry, while the increased urban temperatures play in average a much smaller role. Further investigation is however needed in order to better interpret the modelled changes, involving the analysis of other relevant gases as NOx, HNO_3 and radicals.

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