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A WRF-Chem modelling study to analyse the effect of urban greening and white roofs on urban air quality

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Abstract

Cities are the predominant places for human beings to settle down, thus becoming more vulnerable to extreme weather events aggravating phenomena like heat stress and decreasing air quality aroused by inner city pollution. The excessive warming of impervious surfaces and additional release of anthropogenic heat promotes urban heat island (UHI) formation. Human activities lead to an increase of emissions of air pollutants which in turn influences the chemical composition of urban air. In this study, the mesoscale chemical transport model WRF-Chem is used for the urban area of Stuttgart to simulate the effect of UHI mitigation strategies such as urban greening and high albedo materials on the concentration of primary and secondary pollutants.

2. Introduction

In 2050, the fraction of global urban population is supposed to increase to over 69%, which means that around 6.3 billion people are expected to live in urban areas (United Nations 2012). Cities are concentrations of humans, materials and activities, thus exhibiting the highest levels of pollution and largest targets of impacts concerning air quality and climate change.

Urban Heat Island (UHI) describes the tendency for an urbanized area, because of its radiative and geometrical features, to remain warmer than its rural surroundings and thus generating its own microclimate (Oke, 1982). Specific urban planning strategies like green roofs or facades and highly reflective materials are able to reduce the negative effects of the UHI and mitigate future problems (Taha 1995). The urban atmosphere can be described as a reaction chamber within which chemical reactions between anthropogenic pollutants and biogenic compounds take place under specific urban conditions such as higher temperature, higher turbulence, less humidity and modified radiation. Altering the characteristics of the urban surface promote changes in the energy and radiation budgets which modify the accumulation and dilution of primary compounds and the formation of secondary compounds. This study aims to investigate the feedback of the abovementioned mitigation strategies on urban air quality by using the mesoscale chemical transport model WRF-Chem on regional scale, coupled to a multi-layer urban canopy parameterization scheme (Chen, 2011). The urban area of Stuttgart acts as test bed for the modelling of a case scenario of the 2003 European Heat Wave.

3. Data and methods

For representing urban sub-grid scale processes in WRF-Chem, the multi-layer urban canopy model BEP is applied (Martilli, 2002). By using a 33 classes CORINE data set, urban land cover is divided into three sub-classes (high- and low density residential and commercial). Each sub-class inherits specific geometrical and physical characteristics, which are to be defined within an urban parameter table (Fallmann et al. 2014). The innermost model domain covers an area of 600 x 450 km with a horizontal resolution of 3km and 36 vertical levels. Anthropogenic emissions are retrieved from the MACC 7 km emission inventory, biogenic emissions from the global MEGAN emission database. MOZART lateral chemical boundary conditions are used and the RADM2 scheme is applied for calculating the gas-phase chemistry, aerosol dynamics and chemistry is described with the module MADE/SORGAM. The modelled time period ranges from August 9 to August 18 2003. The full model setup is presented in Tab. 1.

Tab. 1: WRF-Chem model configuration

Parameter/Scheme	Specification	Parameter/Scheme	Specification	Parameter/Scheme	Specification
geographical input data	1km USGS land use	meteorological BC	0.5 Deg ERA-Interim	land surface model	Noah LSM
dx, dy	3km	urbanization scheme	BEP (Martilli 2002)	chemical option	RADM2, MADE/SORGAM aerosols
west-east [grid cells]	200	microphysics	Lin et al.		
south-north [grid cells]	150	longwave	RRTMG (Mlawer 1997)	emission inventory	7km MACC 2006
vertical layers	36	shortwave	RRTMG	chemical boundary	MOZART global data
time frame	8/9 - 8/18/03	cumulus (only 3rd domain)	Grell Devenyi ensemble	biochemistry	MEGAN global data
lowest model level	11m	land surface model	Noah LSM	photolysis scheme	FastJ

The urban area of Stuttgart acts as test bed for the modelling of a case scenario within the 2003 European Heat Wave. The location of the innermost model domain is presented in Fig. 1.

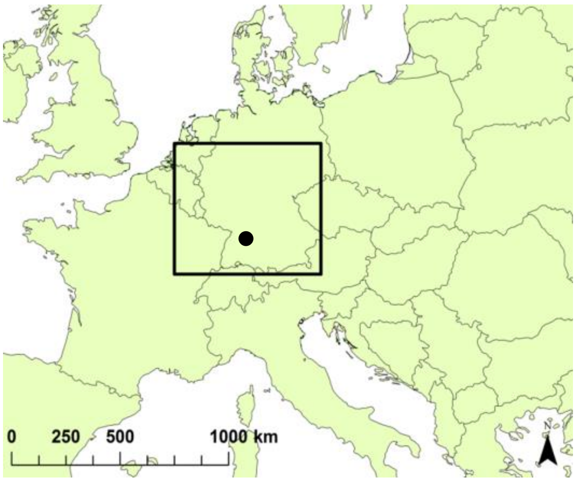

Fig 1 *WRF-Chem innermost model domain (black frame) and the location of the city of Stuttgart (black dot)*

Next to a base case run ('Control'), two scenarios are conducted with WRF-Chem representing urban greening ('Park') and increased albedo of roofs and facades ('Albedo'). With regard to the urban greening scenario, four urban grid cells in the center of Stuttgart, accounting for 15 % of the total urban area, are replaced to grassland. This aspect mainly changed the surface hydrological properties within the land surface model and the roughness length calculation within the boundary layer scheme. The use of high reflective building materials is simulated by changing the albedo of roofs and facades in the urban canopy parameter table from 0.2 to 0.7 for the entire urban area, not distinguishing between different urban classes. Dry deposition models have to be adapted in WRF-Chem in order to account for the three urban classes.

4. Results and discussion

a) Effect of reduced temperature

Changing the radiative or geometrical properties of urban surfaces has an effect on the dynamic structure of the urban boundary layer, thus resulting in a modification of turbulent mixing. Model results show, that a temperature reduction leads to a decrease of secondary compounds such as ozone and to an increase of primary compounds such as NO and CO. Results are discussed on the basis of simulated mixing ratios [ppb] for the lowest model level (~15 m) for a WRF grid cell in the urban center as mean values for the time period Aug 10 – Aug 18 2003.

Mean ozone concentration can be reduced by about 1.7 ppb (~4%) for the 'Albedo' scenario and about 3.2 ppb (~8%) with regard to urban greening ('Park'). These reductions are equivalent for about 1 °C temperature- or UHI- reduction respectively. With regard to the primary compounds CO and NO, the strongest effect is found for the 'Albedo' case. The increase of mean NO concentration amounts to 26 %. NO2 and CO show an increase of 13 % and 8 % respectively. NO2 however originates from both primary and secondary processes (Tab.2)

Tab. 2 *Effect of UHI mitigation scenarios on modelled runtime mean 2 m potential temperature Tmean and concentrations of NO, NO2, CO and O3 in the urban center showing absolute values. A decrease is presented in italics and the maximum effect is presented in bold. Normal formatting reveals an increase.*

Scenario	Control	Albedo	Park
NO[ppb]	4.69	**5.84**	4.92
NO2[ppb]	20.57	**23.37**	22.02
CO [ppb]	366.74	**398.84**	381.95
O3 [ppb]	40.10	*38.40*	***36.92***
Tmean [°C]	26.81	25.64	25.50

Results from Tab. 2 show the effect for one single urban grid cell. With regard to the average for the whole urban area, the resulting differences are smaller, with ozone reduction accounting for 0.9 ppb and 1.1 ppb and CO increase by 4.3 ppb and 21.2 ppb for the 'Park' and 'Albedo' scenario respectively.

The effect of reduced temperature on the concentration of primary and secondary pollutants can be quantified by the difference between scenario run and base case ('Control'). Results are presented for an area of 13 x 13 grid cells for the lowest model level (~15m) (Fig. 2).

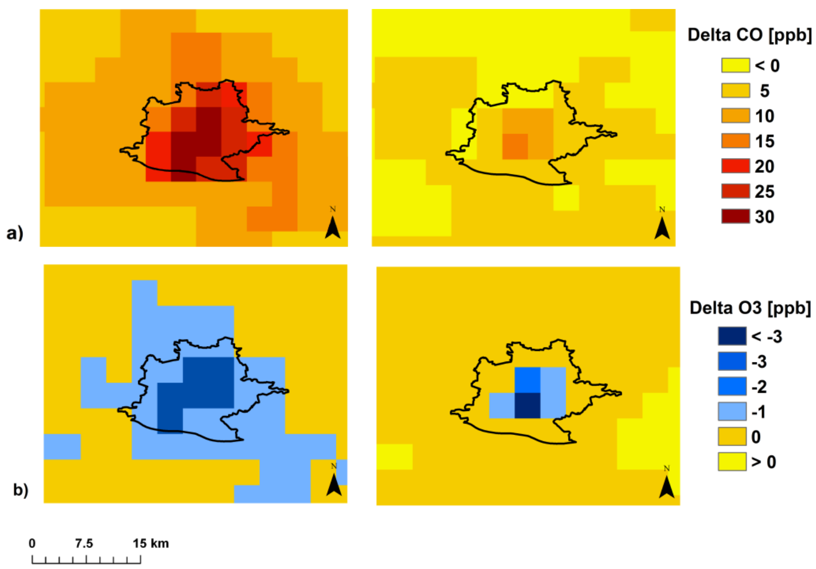

Fig 2 *Difference between scenario run and base case for simulated mean CO (a) and ozone (b) in the lowest model level. The 'Albedo' scenario is shown on the left and the 'Park' scenario on the right of each figure. Values are displayed in mean modelled concentration differences [ppb] with red colors representing an increase, blue colors a decrease.*

While the effect on primary pollutants is most pronounced for the albedo scenario (Fig.2a), with a maximum mean concentration increase of 32 ppb (8.7 %) the situation is reversed for ozone (Fig. 2b) with a maximum mean decrease of 3.7 ppb (9.2%) for the 'Park' scenario. For ozone, the urban greening scenario locally has the bigger impact on average concentrations.

The different impact of reduced temperature on primary and secondary compounds as shown in Fig. 2 can be explained by two basic mechanisms. A decrease of turbulent kinetic energy (TKE) due to a lower temperature leads to a lower rate of turbulent mixing and a decrease of the mixing layer height (Fig. 3a), thus slowing down the removal rate of primary pollutants such as CO (Fig 3a). The decrease of the mean ozone concentration is related to the temperature dependency of photochemical reaction rates (Seinfeld 2012) which increases ozone formation (Fig. 3c).

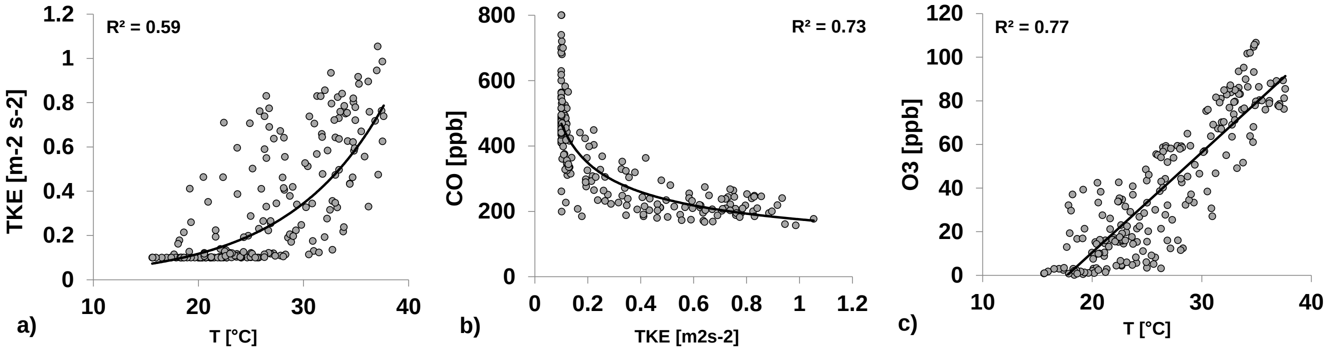

Fig. 3: *Correlation between grid cell simulated hourly mean values of temperature and turbulent kinetic energy TKE [m-2s-2] (a), TKE and CO (b) and temperature and ozone (c) in the lowest model level with regard to an urban grid cell.*

The reversed scenario's impact as presented in Figure 2 can be explained by the additional part of reflected short wave radiation when increasing the albedo from 0.2 to 0.7 for the building roofs and facades (Fig. 4a). Compared to the urban greening scenario, the 'Albedo' case shows an increase of reflected shortwave radiation of 170 %. This additional amount of energy accelerates photochemical reactions and by this triggers ozone formation (Fig. 4b). Fig. 4c supports this aspect, indicating a positive relationship between reflected shortwave radiation (SW_UP) and the photolysis reaction rate [min-1].

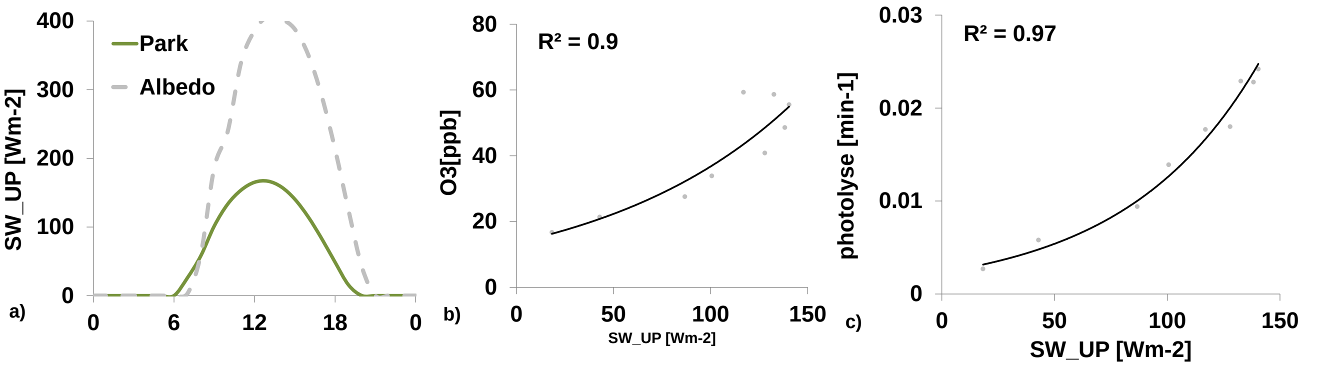

Fig. 4: *Mean diurnal profile of short wave upwelling radiation SW_UP [wm-2] for 'Albedo' and urban greening scenario (a), correlation between SW_UP and ozone concentrations [ppb] (b) and photolysis rates [min-1] (c).*

b) Tendency terms

In order to quantify the scenario impact on atmospheric chemical composition in the simulations, the contributions of different processes to the temporal change of NOx and CO is analyzed. WRF-Chem calculates accumulated tendency terms, which allow for the calculation of hourly budgets for each compound in order to quantify the impact of chemical and dynamical tendencies on altered atmospheric composition. The Albedo scenario is used as an example to illustrate the interrelations.

The budget terms for the chemical species, which are provided by WRF-Chem output are: chemical production/loss tendency (CHEM), turbulent vertical mixing tendency (TURB) and advective tendency (ADV). The term EMIS describes the emission as given in the emission inventory and the term Gain/Loss can be calculated by adding up the different budget terms, including the hourly emission.

The hourly budgets are shown in Fig. 5 for the time of maximum concentrations of CO, NO and NO2 which is between 0007 h and 0008 h for both Control Run and 'Albedo'. Following the methods shown by Sarrat et al. (2006), hourly averaged budget terms are calculated from model output which can be used to quantify the contributions of chemical and dynamical mechanisms on net urban concentrations. Negative values indicate a loss and positive values a gain [ppbv h-1] with regard to the respective term (Fig. 5). For the turbulence term (TURB) all values are negative, indicating a net loss. For each of the three chemical compounds presented in

Fig. 5 this value is decreased for the Albedo scenario, whereas CO shows the highest relative impact with almost 70 % decrease of ‘turbulent transport’.

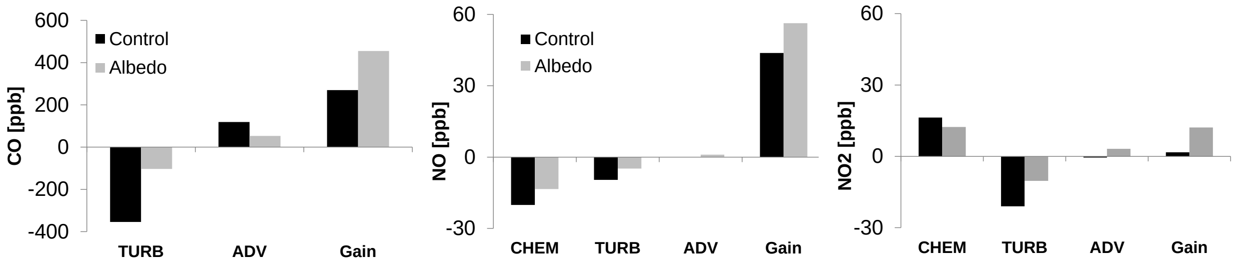

Fig. 5 *Hourly budget between 0700h and 0800h with respect to turbulence (TURB), advection (ADV) and chemistry (CHEM) for two scenarios and for CO (left), NO (middle) and NO2 (right). Gain is calculated from the sum of the tendency terms.*

Fig. 5 particularly indicates the dominating role of turbulent mixing for primary pollutants (CO). The opposed direction of the chemistry bars (CHEM) for NO and NO2 well indicate their interrelation within the NOx cycle, were NO is titrated to NO2.

Conclusion

This study shows that common urban planning strategies to mitigate UHI formation can have both positive and negative impacts on the urban air quality. Model results reveal that the concentration of primary pollutants is largely dependent on the dynamical structure of the urban boundary layer, being responsible for turbulent exchange and vertical mixing. Ozone formation instead is mainly driven by temperature and intensity of shortwave radiation.

With a mean reduction of 5-8 %, the results from this study acknowledge the positive effect of green areas and increased albedos on near surface ozone concentration. Reducing the urban temperature in the model however entails several side effects which negatively affect local urban air quality.

With regard to CO or NOx, the positive effect of reduced temperatures is reversed. Model results show, that a temperature reduction has a significant effect on the dynamical structure of the urban boundary layer. A decrease of turbulent kinetic energy (TKE) due to a lower temperature leads to a lower rate of turbulent mixing and a decrease of the mixing layer height, thus slowing down the removal rate of pollutants.

Finding sustainable strategies for future urban planning has to consider both, meteorological and air chemical aspects. It should further be accounted for both primary and secondary compounds and impacts.

Acknowledgment

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