reviewed paper

Developing Effective Measures for Reduction of the Urban Heat Island based on Urban Climate Model Simulations and Stakeholder Cooperation

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1 ABSTRACT

The climate change projections for the Austrian cities indicate that the observed warming trend, including frequent occurrences of extreme heat events, is expected to continue in the coming decades. Due to the Urban Heat Island (UHI) effect, caused by modification of energy balance in the built-up environment, the cities are warmer than their rural surroundings and therefore more exposed to negative impacts of climate change. During prolonged heat wave events, the excess in heat combined with reduced night-time cooling, decreased ventilation and possible air pollution can cause severe health impacts on the urban population. Developing measures for reduction of the UHI effect is important in the context of sustainable urban development and climate sensitive urban planning. Number of counteracting measures such as increase in vegetation, green open spaces, green roofs, unsealing of paved surfaces, decreasing absorption of solar radiation by increasing the reflectiveness of buildings and paved surfaces, are considered in the scope of climate change adaptation strategies. Nevertheless, the effectiveness of these measures, as well as their applicability in the existing urban structure, especially in the densely-built environments is not well known. Moreover, the expected cooling effects need to be quantified and the possible application should be communicated and appropriately planned with the relevant stakeholders in order to anticipate a large-scale implementation.

This study investigates the effective methods for application of climate adaptation measures to reduce the UHI effect in a densely built-up environment on an example of the residential and business district of Jakomini in the city of Graz/Styria. The current local climate conditions are simulated with the urban climate model MUKLIMO_3 of the German Weather Service (DWD) using meteorological, geomorphological and land use data from the city of Graz. The simulations with altered land use characteristics corresponding to application of different UHI counteracting measures are calculated and compared to the reference simulation. The gradual increase in green areas, existing potential for green roofs implementation, modification in reflectivity of roofs and façades as well as unsealing of paved surfaces is considered. The resulting difference in heat load is evaluated as the potential cooling effect for the area of the Jakomini district and its surroundings. Based on the model results, a set of measures with optimal climatic impact is identified in close cooperation with the city's planning department and in accordance with already existing concepts, plans and projects. This information is communicated with the relevant stakeholder groups both from private and public sectors to get their commitment to definitely undertake measures in the test-district. Considering the respective interests and role of action of different stakeholder groups a set of target measures is selected for further technical, financial and administrative planning of implementation.

The study is supported by the Austrian Research Promotion Agency (FFG) and the Climate and Energy Fund (KLIEN) within the Smart Cities project "JACKY_cool_check" (Project Nr. 855554).

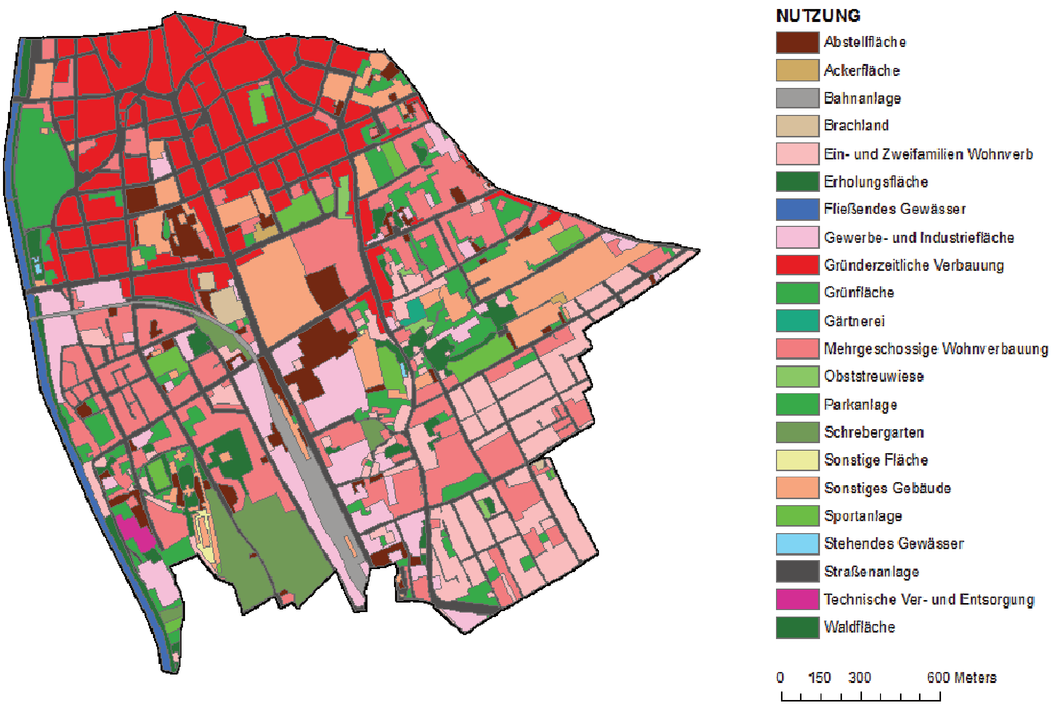
Keywords: stakeholder cooperation, cooling effect, climate adaptation measures, green roofs, urban heat island

2 METHODS AND DATA

2.1 Urban Morphology

The geomorphological data for the Jakomini district were provided by the city administration of Graz, (Stadtplanungsamt and Stadtvermessungsamt der Stadt Graz). The data include land use and land cover data, digital surface model (DOM) and the green roof potential for the Jakomini district. The orography data are based on the EU-Digital Elevation Model (DEM) of 25 m horizontal resolution provided by Copernicus Land Monitoring Services of European Environmental Agency (EEA). Additional information on tree density per land use class was calculated from the Pan-European High Resolution Layers of Copernicus Land Monitoring Services.

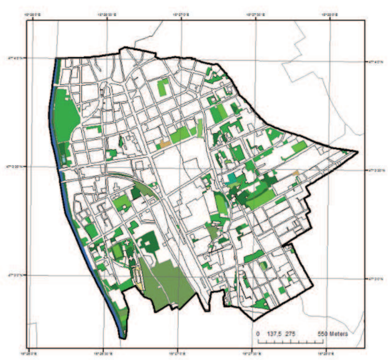
Based on the availble data from the time period 2011/2012, the Jakomini district covers an area of 406.1 ha, of which 64% or 259.9 ha are paved and built-up surfaces. The paved surfaces cover 136.3 ha and the building area is 101.9 ha of which 11% of roofs (11.2 ha) are adequate for greening. The transportation infrastructure accounts for 16.2 % of the Jakomini area or 65.7 ha. Green surfaces cover 74.3 ha or 18.3% of the district area and water surface amount to 1.5% or 6.2 ha. The land use distribution, including built-up, paved and green areas is given in Fig. 1. The land use dataset has 23 different land use types. For each land use type a set of parameters is defined to describe urban structures and surface properties: fraction of built area, mean building height, wall area index, fraction of pavement, fraction of tree cover, fraction of low vegetation, tree height, height of the low vegetation, albedo of roofs, walls and paved surfaces and fraction of green roofs. The land use parameters calculated for the Jakomini district are applied in the model for the district surroundings as well, assuming that the typical characteristic of the building types do not differ significantly.



(a)

(b)

(c)



(d)

Fig. 1: Land use distribution in the district Jakomini, city of Graz/Styria (a). In the lower panel are shown buildings (b), paved areas (c) and green surfaces (d). The data are provided by the city administration of Graz (Stadtplanungsamt and Stadtvermessungsamt der Stadt Graz).

2.2 Urban Climate Model Simulations

In this study, the urban climate model MUKLIMO_3 (in German: 3D Mikroskaliges Urbanes KLImaMOdell) developed by the German Weather Service (DWD) is used to simulate the urban heat load in the Jakomini district with focus on day-time conditions during the summer period. The MUKLIMO_3 model (Sievers and Zdunkowski, 1985; Sievers, 1990; Sievers, 1995; Sievers, 2012; Sievers, 2016) is a micro-scale z-coordinate model based on Reynolds-averaged Navier–Stokes (RANS) equations, which was designed to simulate atmospheric flow fields in presence of buildings. The thermo-dynamical version of the model (Sievers, 2016) includes prognostic equations for air temperature and humidity, the parameterization of unresolved buildings using the porous media approach (Gross, 1989), short-wave and long-wave radiation, balanced heat and moisture budgets in the soil (Sievers et al., 1983), vegetation model based on Siebert et al. (1992) and calculation of short-wave irradiances at the ground level, the walls and the roof of buildings in an environment with unresolved built-up ass described by Sievers and Früh (2012). The model takes into account the cloud cover and its effects on the radiation. However, it does not include cloud processes, precipitation, horizontal runoff nor anthropogenic heat (e.g. traffic or heat generated from air conditioning). The vegetation in the canopy model has three vertical layers and a 15-layer soil model is included in the simulations. The model differentiates between four main land use types: buildings, trees, free surfaces and water. The grid cells with buildings do not include trees, but it is possible to define the percent of the low vegetation, which is also considered in the simulations with green roofs. The fraction of sealed and unsealed surfaces is taken into account in all grid cells except water. The modelling approach takes into account complex terrain and land use distribution including a detailed register of green roof potential. The model domain covers the Jakomini district and its immediate surroundings with a domain size of 138 x 135 x 25 grid points. The horizontal grid spacing is 20 m. The vertical resolution of 1D model with 52 levels varies from 10 to 100 m with higher resolution near ground level and lower resolution at the maximum height of about 2000 m.

The changes in urban heat load are evaluated using the method for calculation of climate indices called the "cuboid method" (Früh et al., 2011; Zuvela-Aloise et al. 2014), which allows analysis of heat load changes on a longer temporal timescale. The cuboid method refers to a tri-linear interpolation of meteorological fields deriving from single-day 3-D simulations from the urban climate model MUKLIMO_3. Eight idealized simulations representing the cuboid corners with duration of 24 hours for the two prevailing wind directions (northwest and southeast) are calculated. Calculation of climate indices for a 30-year period is based on interpolated Tmax fields from the eight single-day simulations using climatological data from a reference station as input. The time series of daily mean temperature, relative humidity, wind speed and hourly wind direction for the period 1981–2010 from the monitoring station Graz Flughafen are used as input meteorological data. The mean annual number of summer days (SU: Tmax≥25°C), based on ETCCDI indices (Expert Team (ET) on Climate Change Detection and Indices; Zhang et al., 2011) is taken as index for evaluation of the urban heat load. For further information on model initialization and the description of the boundary conditions please refer to Zuvela-Aloise et al. (2011; 2014; 2016; 2017).

2.3 Methods for Stakeholders Cooperation

The project JACKY_cool_check is following an innovative approach and explores and elaborates on the necessary requirements for measures against Urban Heat Islands not only from a technical side but also from the side of urban planning as well as the social viewpoint. Basic assumption of this approach is that public and private stakeholder groups are able to identify and use their own scope of action to set measures against Urban Heat Islands, if they are provided with prior technical information ("informed stakeholders") and are supported by a targeted communication process.

Although Urban Heat Islands are causing measurable negative physical and mental effects, approaches to decrease these effects are opposing other interest (e.g. trees vs. parking lots, green surfaces vs. façade protection). Therefore, it is the key to adapt technical measures to the social system they are designed for. The Urban Heat Island Strategy Plan for Vienna (UHI 2015) showed that information and communication, within the city departments and beyond, public relations and the opportunity for citizens to actively participate in the identification, planning and implementation of Urban Heat Island measures is fundamental.

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For the project JACKY_cool_check, all relevant stakeholders in the district of Jakomini were identified in a first step. Special attention was set on the inclusion of all different kinds of stakeholders, public and private ones:

- Old and young people;
- People who have been living there for a long time, new residents and immigrants (which account for almost a quarter of the population in this district);
- Associations, collectives and parishes
- Enterprises, especially those with big potential concerning (free) surfaces
- Big housing complexes
- City departments linked to the topic, like urban planning, environment, transport planning, etc.
- The district administration

This list is complemented by additional stakeholders who are being mentioned within the interviews and group meetings.

All these stakeholders have been contacted at the beginning of the project and have been provided with information on the project, its goals and different activities and the possible role of the stakeholders. In interviews and group meetings, all different interests, their attitude to Urban Heat Islands and already existing engagement and initiatives were surveyed.

3 RESULTS

A reference simulation based on the current urban morphology of the Jakomini district using climatological data for the period 1981-2010 is shown in Fig. 2. The modelling results indicate higher heat load in densely built-up areas in the northern and central part of the district and lower heat load in the areas with higher fraction of vegetation or water. Unfortunately, no climatological monitoring station in the period 1981-2010 is available in the Jakomini district and the results for mean annual number of SU cannot be directly validated. A dense network of monitoring stations would be required for a detailed quantitative analysis of the modelling results. However, the resulting mean annual number of SU is in expected range of variation for the City of Graz (Graz Flughafen: 66.6 SU; Graz UNI: 63.0 SU). Due to the spatial grid resolution and porous media modelling approach, the micro-scale processes on the level of buildings in the model are parameterized. Therefore, the model results are not necessarily accurate on a level of single building and a micro-scale modelling approach with resolved buildings and individual building geometry is required for more detailed analysis.

A set of simulations with altered land use characteristics is performed to evaluate the cooling potential of different climate adaptation strategies. The change in heat load is expressed in difference in mean annual number of SU when compared to the reference simulation. The reduction of heat load by more than -10 SU in annual mean is considered as strong cooling effect, while change of about -5 SU is taken as moderate cooling effect. The heat load difference of less than 1 SU (equiv. to approximately 0.1 K) is considered to be below model accuracy.

In Fig. 3 are shown selected simulations intended to demonstrate the cooling effect of climate adaption strategies applied on paved and built-up surfaces. The model sensitivity simulations include reduction of sealed surfaces by 50%, implementation of green roof on 50% of buildings and increase in wall and roof albedo from standard values, 0.3 for the walls and 0.2 for the roofs, to 0.7 which is approximately the reflectivity value of white ceramics (Prado and Ferreira 2005).

The simulation with reduction of sealed surfaces by 50% (Fig3.a) shows a reduction of heat load over a large area of Jakomini district. The cooling effect is of minor to moderate intensity. In the Jakomini district, about 70 ha of paved surfaces have been in this case replaced with low vegetation (48.5 ha) or free soil (21.1 ha). The strongest cooling effect is found in the transportation and densely built-up areas where the high fraction of paved surfaces is reduced. Moderate to strong cooling effects are found in the model simulations with increased wall (Fig3.b) and roof albedo (Fig3.c). The cooling effect of the increased wall reflectivity is stronger in intensity on a local scale in vicinity of buildings. However, the cooling effect on the surroundings is larger in the simulation with the increased roof albedo. The model simulations with green roofs indicate minor to moderate cooling effects if vegetation is implemented on 50% of the roofs (Fig.3.d). The cooling effect of green roofs is strongly dependent on the area to which the greenery is applied. The higher the fraction of green roofs, higher is the cooling effect. However, given the realistic values for the green roof potential in the Jakomini district of only 11%, the cooling effect is considerably reduced leading only to minor changes in heat load.

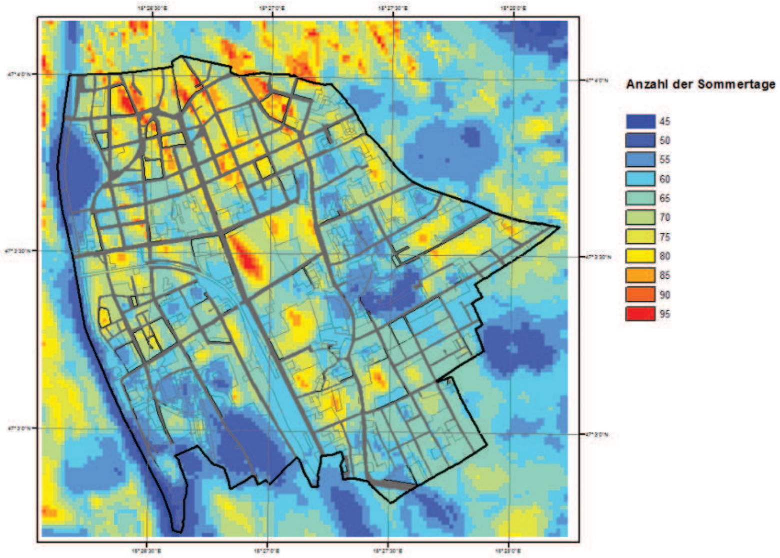

Fig. 2: Mean annual number of summer days (SU: Tmax ≥ 25°C) in Jakomini district calculated with the urban climate model MUKLIMO_3 (Sievers, 2016) and the cuboid method (Früh et al. 2011; Zuvela-Aloise et al. 2014) based on the climatic data for the period 1981–2010.

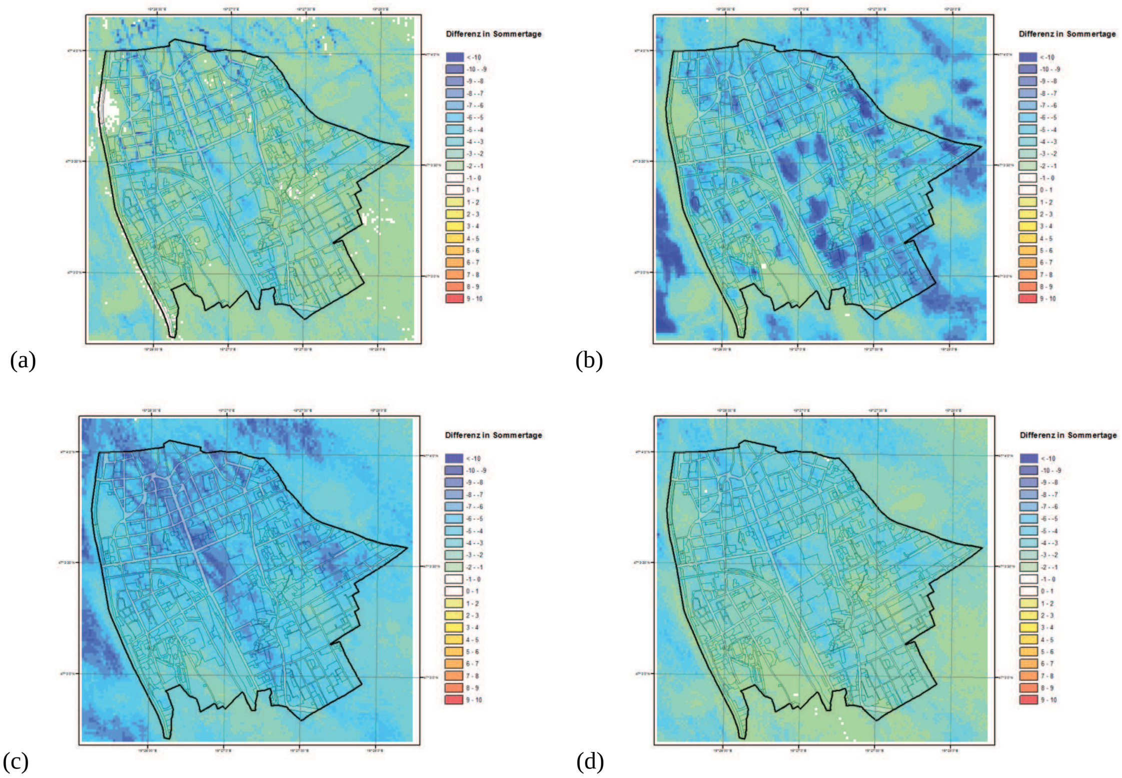

Fig. 3: Difference in mean annual summer days (ΔSU) compared to the reference simulation (Fig. 2) in the simulations with reduction of paved surfaces by 50% (a), increased wall reflectivity (b) and roof albedo to 0.7 (c) and implementation of green roofs on 50% of buildings (d).

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4 DISCUSSION AND CONCLUSIONS

This study investigates the potential for implementation of climate adaptation strategies in existing densely built-up environment of Jakomini district in Graz based on the urban climate model simulations and cooperation with the relevant stakeholders. The analysis of the urban heat load is focus on day-time conditions during the summer period and the climate index mean annual number of summer days (SU: Tmax≥25°C) is used for the evaluation of thermal changes.

The modelling simulations show that a strong cooling effect (more than -10 SU) can be achieved by applying materials with high albedo values (~0.7) on building's walls and roofs and also by significantly (more than 50%) reducing fraction of pavement or increasing vegetation on roofs. The mitigation measures should be applied extensively to have a sizeable effect. However, the potential for implementation of green roofs in Jakomini district is limited. Therefore, the best cooling performance could be achieved by combining different adaptation measures on the available surfaces.

To find appropriate measures that provide a good cooling performance in the test-district as well as fit into the already existing cityscape is a big challenge. As no large-scale new city developments will be possible in the areas of the inner city, measures will focus on the adaptation of the current building stock. As this is also an intervention with the social environment of the people living in these areas, a good communication process is necessary throughout the whole project. The urban climate model simulation provided a basic scenario that shows the maximum local cooling potential that is possible in theory. This scenario, together with the results from the first interaction with the stakeholders was discussed with the department of urban planning and will result in a "realistic" scenario that shows what is really possible in terms of measures, taking into account the Land Utilization Plan, the Urban Development Plan, building regulations, Green Space Service Planning and other regulation and guidelines of the city of Graz, influencing climate adaptation measurers.

In a next step, this realistic scenario is presented to the different stakeholder groups, initiating the communication and discussion process on concrete and practical ideas where stakeholders can bring in their own ideas. As the stakeholder groups will be quite diverse, different, tailor-made methods will be used (e.g. workshops, world-café, discussion forum, etc.) in this phase. The overarching goal of this step is the identification of concrete measures and the commitment of the stakeholders to these measures that will be implemented in a demonstration project, following JACKY_cool_check.

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