


Modelling reduction of urban heat load in Vienna by modifying surface properties of roofs

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Abstract The study examines the potential of urban roofs to reduce the urban heat island (UHI) effect by changing their reflectivity and implementing vegetation (green roofs) using the example of the City of Vienna. The urban modelling simulations are performed based on high-resolution orography and land use data, climatological observations, surface albedo values from satellite imagery and registry of the green roof potential in Vienna. The modelling results show that a moderate increase in reflectivity of roofs (up to 0.45) reduces the mean summer temperatures in the densely built-up environment by approximately 0.25 °C. Applying high reflectivity materials (roof albedo up to 0.7) leads to average cooling in densely built-up area of approximately 0.5 °C. The green roofs yield a heat load reduction in similar order of magnitude as the high reflectivity materials. However, only 45 % of roof area in Vienna is suitable for greening and the green roof potential mostly applies to industrial areas in city outskirts and is therefore not sufficient for substantial reduction of the UHI effect, particularly in the city centre which has the highest heat load. The strongest cooling effect can be achieved by combining the green roofs with high reflectivity materials. In this case, using 50 or 100 % of the green roof potential and applying high reflectivity materials on the remaining surfaces have a similar cooling effect.

1 Introduction

High temperatures in summer months reduce human thermal comfort and can have severe impacts on public health, which can lead to increased mortality rates of the population (Souch and Grimmond 2004). According to the IPCC climate projections (Christensen et al. 2007, 2013), the duration and frequency of heat waves in southern and central Europe are very likely to increase by the end of the twenty-first century (Schär et al. 2004; Fischer and Schär 2010). Hence, higher health risks related to the extreme heat can be expected, especially in densely populated urban areas (Basu and Samet 2002; Martiello et al. 2007), where the phenomenon of the urban heat island (UHI) leads to excess in heat compared to the rural environments (Landsberg 1981; Oke 1982; Oke et al. 1991). The studies from large central European cities (Dessai 2003; D'Ippoliti et al. 2010; Barriopedro et al. 2011; Paci 2014) indicate observed records in extreme temperatures and project further increase in frequency and intensity of heat waves. In Vienna, the heat-related mortality could increase by more than 100 % in the forthcoming decades (Muthers et al. 2010). Even without the most dramatic impacts, exposure to prolonged periods of heat can have various negative effects on the human health and well-being, increasing risk of heat-related illnesses and reducing mental concentration lowering the work productivity and efficiency (Koppe et al. 2004). The energy demands for cooling and ventilation are expected to increase as well (Eliasson 2000; Gago et al. 2013), and the urban planning strategies to reduce the UHI effect are gaining importance when sustainable development of the cities is considered (EEA 2012). Currently, residential buildings in Austria do not require active cooling. However, if projected warming trend is considered, a dramatic increase in energy demand is to be expected (Orehounig et al. 2014).

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Among many concepts that have been developed to mitigate the heat load in urban areas, increasing reflectivity of roofs in order to reduce the absorption of solar radiation is one of the simplest and potentially highly effective measure (Hamdi and Schayes 2008; Krayenhoff and Voogt 2010; Santamouris 2014). Santamouris et al. (2011) found that an increase in solar reflectivity ranging from 0.08 to 0.42 decreases the surface temperature from 4.2 to 11 °C depending on the colour of the material. The estimated magnitude of change for the air temperature 2 m above ground level is nevertheless lower ($\Delta T_{\text{air}} = 1.9$ °C for $\Delta T_{\text{surface}} = 12$ °C, Santamouris et al. 2012). Many studies have examined the sensitivity of UHI effect to the urban albedo using experimental setup and meso-scale meteorological models with varying surface properties (Sailor 1995; Rosenfeld et al. 1998; Savio et al. 2006; Taha 2008; Lynn et al. 2009; Zhou and Shepherd 2010; Millstein and Menon 2011; Fallmann et al. 2014; Li and Norford 2016). Based on the analysis of the existing studies from various cities, Santamouris (2014) estimated the expected decrease of the average urban ambient temperature per 0.1 increase in the roof reflectivity. The temperature change varies between 0.1 and 0.33 °C, with the mean value close to 0.2 °C and a higher UHI mitigation potential in the sunny climates. The cooling effects were most pronounced during the peak daytime period.

Another effective strategy to mitigate the heat load is to maintain and increase the vegetated surfaces (so-called green infrastructure) in urban areas. The green surfaces are of particular interest for urban planners due to the multiple functionality and benefits of vegetation for the environment (Akbari et al. 2001; Wilby and Perry 2006; Gill et al. 2007). Green areas have relatively low reflectivity (albedo of 0.2 found by Gaffin et al. 2009) but produce a cooling effect due to the shading and evapotranspiration. Analysis of satellite images for Paris indicates that the surface temperature is 2–3 °C lower in small parks than in their built surroundings and 4–5 °C lower in large ones (Douset et al. 2011). However, in the densely built-up environment, few surfaces at the ground level are available for greening and the building roofs provide unused potential for implementation of new vegetation (Susca et al. 2011). A number of studies using simulation techniques aiming to evaluate the UHI mitigation potential of green roofs on a city scale were performed (Savio et al. 2006; Rosenzweig et al. 2006; Smith and Roeber 2011; Chen et al. 2009; Li et al. 2014; Fallmann et al. 2014; Li and Norford 2016). The results indicate that the vegetative roofs are able to produce the cooling effect of similar magnitude as the high-reflective roofs. Green roofs with relatively abundant soil moisture have comparable effect in reducing the surface and near-surface UHI effect to cool roofs with an albedo value of 0.7 (Li et al. 2014). However, the reduction in ambient temperature is dependent on the location, building height and geometry, type of vegetation, soil characteristics and particularly the soil water content (Wong et al. 2003; Chen et al. 2009; Coutts et al.

2013; Santamouris 2014). The estimated values for latent heat released by green roofs during the peak period vary considerably as a function of the water content on the roof and the leaf area index (LAI) (Santamouris 2014).

In Vienna, a maximum of 45 % of the roofs are appropriate for planting low vegetation based on their geometrical properties (source: City of Vienna, MA22—Environment Protection Department). However, only 2–3 % of this surface is actually used as green roofs. The implementation of green roofs is technically demanding and more costly compared to the changing of the colour of the roof. For construction of new buildings, there is, in general, no significant cost difference between implementing high or low reflective roof material. In addition to the implementation of green or reflective roofs, urban planning strategies for sustainable development consider extensive employment of renewable energy, such as implementation of photovoltaic (PV) systems on roofs, as a suitable way to meet high energy demands in the cities. Solar panels have high absorption of short-wave radiation and could therefore have a warming effect, which can enhance the UHI. However, the combination of PV and vegetation on roofs could be a promising long-term mitigation strategy offering environmental and economic benefits, especially in warm climates (Lamnatou and Chemisana 2014). The combination of PV and low vegetation could have positive synergies such as enhancing the maximum power output of the PVs due to lower surface temperatures and reduction of dust and pollutants from solar panels (Chemisana and Lamnatou 2014).

In order to provide an appropriate base for urban planning, these combined effects need to be analysed in the context of a real city application. In this study, we use the City of Vienna as an example and we investigate which modification of roofs leads to the most effective cooling, to which extent do these measures need to be implemented to have a substantial cooling effect on a city scale and what is the realistic application of adaptation measures considering the existing urban structure. We consider the combined application of different types of roofs, and we evaluate which combination can provide an optimal cooling effect and what is the resulting effect when green roofs are combined with low reflective surfaces such as solar panels. The results are based solely on the model simulations.

Number of micro-scale studies has been performed for different urban typologies in Vienna (Loibl et al. 2011; Pollak et al. 2011; Stiles et al. 2014; Vuckovic et al. 2016), which are valuable asset for urban planning. However, they do not include cumulative cooling effect of climate adaptation strategies when applied on a large scale. In this study, we focus on relative change in heat load between the reference simulation and the climate adaptation scenarios on a city scale. The model setup takes into account that the total sum of the roof area corresponds to actual values for different building types. The study uses the urban climate model MUKLIMO_3 (Sievers and Zdunkowski 1985; Sievers 1990; Sievers 1995; Sievers

2012; Sievers 2016) developed by the German Meteorological Service (DWD) to evaluate the potential of urban roofs to reduce the UHI effect in Vienna. The focus of the investigation is on long-term changes in urban heat load in the daytime during the summer period. In comparison to previous investigations (Žuvela-Aloise et al. 2014, 2016), in this study, the colouring and roof types as well as the roof vegetation are based on realistic values for surface albedo and roof materials in Vienna which is determined by a point sampling approach based on aerial imagery. The effectiveness of adaptation measures when applied to a large area of the city is investigated. The study analyses the effect of increased as well as decreased roof reflectivity and puts it in relation with possible application scenarios for Vienna. The modelling approach allows simulations of the urban boundary layer at very high resolution (horizontal distance of 100 m) taking into account complex terrain and land use distribution and including a detailed register of green roof potential. The changes in urban heat load are evaluated using the method for calculation of climate indices called the “cuboid method” (Früh et al. 2011). The method has been recently developed in order to perform analysis of heat load changes on a longer temporal timescale to achieve a robust analysis of climate signals.

2 Methodology

2.1 MUKLIMO_3 model setup for Vienna

The urban climate model MUKLIMO_3 (in German: 3D Mikroskaliges Urbanes KLImaMOdell) is a micro-scale z -coordinate model based on Reynolds-averaged Navier–Stokes (RANS) equations. The model is designed to simulate atmospheric flow fields in presence of buildings (Sievers and Zdunskowski 1985; Sievers 1990; Sievers 1995), and the thermodynamical 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) and a vegetation model based on Siebert et al. (1992). The numerical method for the calculation of short-wave irradiances at the ground level, the walls and the roof of buildings in an environment with unresolved built-up is described by Sievers and Früh (2012). The MUKLIMO_3 model uses a simple first-order closure of the turbulence scheme based on the Monin-Obukhov similarity theory (MOST) and the Prandtl mixing length approach (Sievers et al. 1987, 2012). The model takes into account the effects of cloud cover on radiation, but it does not include cloud processes, precipitation, horizontal runoff or anthropogenic heat (e.g. heat generated from air condition units). The vegetation in the canopy model has three vertical layers: tree

crown, tree trunk and low vegetation. Grid cells with buildings do not include tree fraction, but low vegetation (< 3.5 m).

To initialize and drive the 3-D simulation, a 1-D model version of MUKLIMO_3 is used. The 1-D simulation is initialized by atmospheric profiles of air temperature, humidity and wind, as well as estimated values for soil temperature and moisture at the reference station outside the city. In order to calculate climate indices for a 30-year period (e.g. mean annual number of summer days SU: $T_{\max} \geq 25$ °C, based on Expert Team (ET) on Climate Change Detection and Indices (ETCCDI); Zhang et al. 2011)), the dynamic-statistical downscaling approach called the cuboid method is applied (Früh et al. 2011; Žuvela-Aloise et al. 2014). The cuboid method refers to a trilinear interpolation of meteorological fields deriving from single-day 3-D simulations from the urban climate model MUKLIMO_3. Eight simulations representing the cuboid corners with duration of 24 h for the two prevailing wind directions are calculated. Calculation of mean annual SU for the 30-year period is based on interpolated T_{\max} fields from the eight single-day simulations using daily time series of the mean air temperature (T), relative humidity (rh) and wind speed (v), including hourly wind direction from a reference station as input. It is important to note that these are idealized simulations that represent a range of weather situations which could occur on a summer day. The cuboid range for Vienna is defined as $T_{\min} = 15$ °C, $T_{\max} = 25$ °C, $rh_{\min} = 42$ %, $rh_{\max} = 80$ %, $v_{\min} = 0.7$ m/s and $v_{\max} = 4$ m/s, and the prevailing wind directions are northwest and southeast. The climatological data show that when the regional daily mean air temperature is below $T_{\min} = 15$ °C, the T_{\max} in the city centre will rarely exceed 25 °C. Therefore, these situations can be excluded from the calculation of the number of SU.

The model domain covers the City of Vienna and its surroundings with a domain size of $310 \times 240 \times 39$ grid points. The horizontal grid spacing is 100 m. The vertical resolution varies from 10 to 50 m with higher resolution near ground level (150 masl) and lower resolution at the maximum height of about 1000 masl. The model uses the terrain and land use data as input. The digital elevation model (DEM) for Vienna is provided by the “Bundesamt für Eich- und Vermessungswesen” (BEV—Federal Office of Metrology and Surveying). The land use dataset is obtained by merging the satellite-based ARCSYS dataset with a raster resolution of 100 m (Steinnocher 1996) and the high-resolution dataset with 32 land use categories and minimum polygon size of 0.2 ha that is provided by the local authorities (City of Vienna, MA18—Urban Development and Planning) as shown in Fig. 1a. Land use types are divided into four main categories: built-up areas, transportation infrastructure, vegetation and water. For each land use type, a set of parameters is defined to describe urban structures and surface properties. The list of land use parameters for Vienna is given in Table 1. An initial estimate for the land use parameters is derived from a technical description of typical building structures

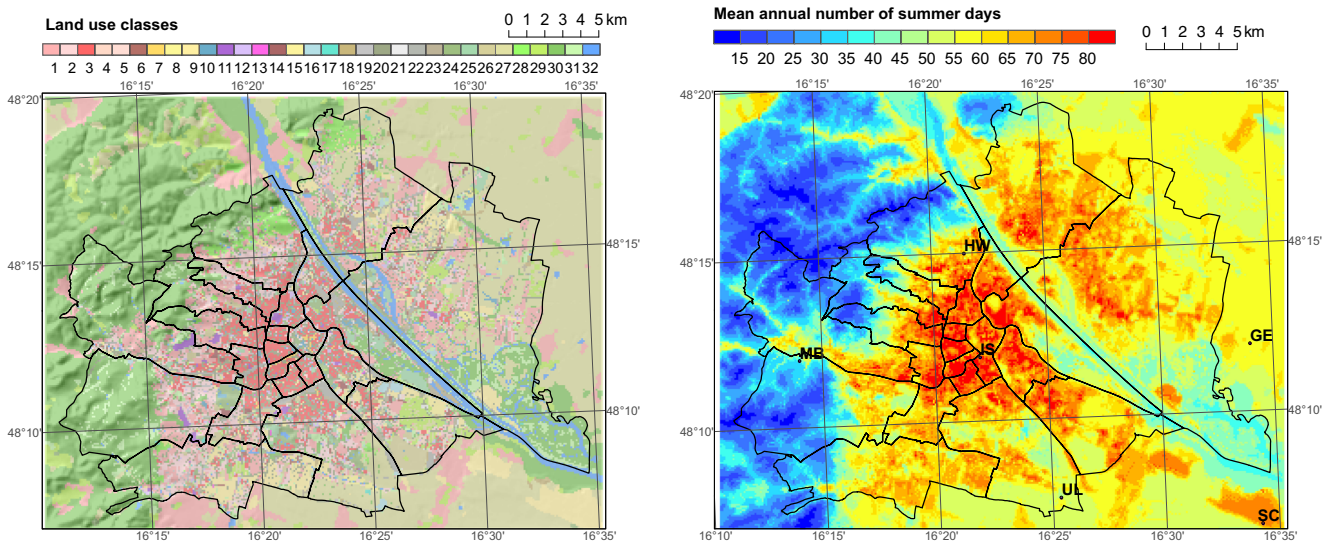


Fig. 1 Orography and land use distribution (*left*) in Vienna and its surroundings provided by the Vienna city administration (Wien MA18) and combined with the satellite-based land use dataset for Austria (Steinnocher 1996). Mean annual number of summer days ($T_{\max} > 25$ °C) in Vienna calculated with the urban climate model

MUKLIMO_3 and the “cuboid method” based on the climatic data for the period 1981–2010 (*right*) with indicated locations of monitoring stations: Wien–Donaufeld (*DF*), Groß Enzersdorf (*GE*), Wien–Hohe Warte (*HW*), Wien–Innere Stadt (*IS*), Wien–Mariabrunn (*MB*), Schwechat (*SC*), Wien–Unterlaa (*UL*)

in Germany (BMBAU 1980). These values were then adjusted based on the GIS data provided by the City of Vienna and the Austrian Institute of Technology. The values for albedo are based on the satellite imagery and are calculated per land use class according to Liang (2001). The fraction of roof types is determined by systematic point sampling based on visual interpretation of aerial imagery. The existing registry of the green roof potential from the City of Vienna (MA22—Environment Protection Department) is used to calculate the fraction of available green roof area for each building type. The green roof registry of the City of Vienna differs between flat ($<5^\circ$) and inclined ($<20^\circ$) roofs, which are adequate for intensive or extensive vegetation, respectively. In the model simulations, the roofs are flat and the total green roof potential includes all roofs that have an inclination less than 20° . In that case, only low vegetation without trees is assumed with vegetation height of 0.1 m and LAI of 1.0. The roof soil type is loamy sand with approximate depth of 0.25 m (Sievers 2016). The soil moisture is initialized with different water content for different weather situations varying between very dry soil (stage 1) and moist soil (stage 4). The soil stages (maximum six stages, where stage 6 is very humid soil) refer to the soil type characteristic wilting point and saturation moisture of the volumetric soil water content (Pielke 2013; Sievers 2016). During a single-day simulation, no watering is applied. A comparable 1D-version of the green roof model has been validated with observational data on short- and long-term timescale by Gross (2012).

Time series of (T , rh , v) for the period 1981–2010 from the monitoring station Groß Enzersdorf located in the rural environment eastward of Vienna is used to calculate the climatic indices for all simulations. For the initialization and the description of the

model boundary conditions and further model details, please refer to Zuvella-Aloise et al. (2014, 2016).

In the model setup, the City of Vienna covers an area of 41,572 ha, of which 50 % (20,614 ha) is a built-up area including transportation infrastructure (14.4 % or 6000 ha), city parks (2.8 % or 1157 ha) and water surfaces (4.6 % or 1915 ha). The remaining land surfaces are covered by forest or agriculture. The roof area covers 5187 ha, of which 2358 ha is adequate for greening. The land use distribution for built-up areas transportation infrastructure, roof surfaces and available green roof potential per land use category is given in Fig. 2. The land use parameters calculated for the City of Vienna are applied for the city surroundings as well, assuming that the typical characteristic of the building types does not differ significantly.

3 Results

3.1 Reference simulation and model validation

A reference simulation based on the current urban morphology of Vienna (Fig. 1b) using climatological data for the period 1981–2010 represents well the main characteristic of the urban heat load found in previous climate studies (Auer et al. 1989). The results for mean annual number of SU show agreement with less than 10 % deviation from the observational values from the monitoring stations in the period 1981–2010 (Table 2). Due to the large inhomogeneity in the land cover, better agreement with observational data is found when comparing the model values at the grid point with representative

Table 1 Parameters for land cover properties in MUKLIMO_3 model: fraction of built area (γ_b), mean building height (h_b), wall area index (w_b), fraction of pavement (v), fraction of tree cover (σ_t), fraction of low vegetation (σ_c), tree height (h_t), height of the low vegetation (h_c), observed roof albedo ($albd_r$) and fraction of potential green roof area in Vienna ($grant_{pot}$)

Land use class	γ_b (%)	h_b (m)	w_b	v (%)	σ_t (%)	σ_c (%)	h_t (m)	h_c (m)	$albd_r$	$grant_{pot}$
1 Low-density residential (mix) buildings	0.19	5	1.20	0.17	0.00	0.61	0	0.5	0.150	0.378
2 Medium dense residential (mix) buildings	0.28	8	1.80	0.19	0.00	0.47	0	0.5	0.150	0.378
3 Dense built-up area	0.55	15	2.10	0.17	0.00	0.22	0	0.4	0.140	0.310
4 Large volume, solitary residential (mix) buildings	0.33	17	2.75	0.23	0.00	0.38	0	0.4	0.150	0.598
5 Offices, administrative buildings	0.58	17	2.75	0.17	0.00	0.15	0	0.4	0.160	0.549
6 Solitary business structures	0.5	9	1.30	0.23	0.00	0.16	0	0.4	0.180	0.765
7 Commercial, business and mixed zones	0.74	20	3.20	0.10	0.00	0.10	0	0.4	0.150	0.346
8 Mixed usage less dense/old city	0.33	6	1.30	0.18	0.00	0.35	0	0.5	0.153	0.352
9 Industry	0.37	8	0.90	0.28	0.00	0.25	0	0.4	0.170	0.787
10 Culture, leisure, religion, fairs	0.36	12	1.90	0.24	0.00	0.30	0	0.4	0.153	0.462
11 Health and emergency organizations	0.28	13	2.30	0.24	0.00	0.34	0	0.4	0.150	0.596
12 Education	0.38	11	2.58	0.20	0.00	0.25	0	0.4	0.160	0.582
13 Sport and pools (indoor)	0.62	10	2.40	0.14	0.00	0.12	0	0.4	0.202	0.741
14 Military facilities	0.22	9	2.30	0.29	0.00	0.32	0	0.3	0.158	0.559
15 Wastewater treatment, waste disposal	0.07	6	0.50	0.60	0.00	0.14	0	0.4	0.152	0.612
16 Energy supply, broadcasting	0.17	10	1.50	0.31	0.00	0.34	0	0.3	0.170	0.743
17 Water supply	0.05	5	0.90	0.15	0.00	0.77	0	0.4	0.163	0.557
18 Transformation surfaces	0.09	6	0.90	0.48	0.00	0.22	0	0.4	0.180	0.604
19 Streets, green	0.00	0	0.00	0.35	0.42	0.19	9	0.4	0.000	NA
20 Streets, few vegetation	0.00	0	0.00	0.49	0.22	0.17	9	0.5	0.000	NA
21 Parking areas, garages	0.15	9	1.60	0.45	0.00	0.21	0	0.4	0.162	0.762
22 Railroad stations and tracks	0.33	7	1.30	0.38	0.00	0.13	0	0.5	0.147	0.685
23 Transport and logistics including deposit	0.21	8	0.40	0.42	0.00	0.14	0	0.4	0.163	0.796
24 Park, green areas	0.00	0	0.00	0.25	0.28	0.44	10	0.4	0.000	NA
25 Sport and outdoor pools, camping	0.00	0	0.00	0.24	0.14	0.41	10	0.3	0.000	NA
26 Cemetery	0.00	0	0.00	0.19	0.25	0.51	9	0.6	0.000	NA
27 Field, agriculture	0.00	0	0.00	0.07	0.03	0.82	7	0.5	0.000	NA
28 Vineyard	0.00	0	0.00	0.06	0.07	0.80	7	0.6	0.000	NA
29 Gardens, orchards	0.00	0	0.00	0.36	0.06	0.40	7	0.4	0.000	NA
30 Forest	0.00	0	0.00	0.00	0.90	0.10	20	1.0	0.000	NA
31 Green field, meadow	0.00	0	0.00	0.00	0.25	0.59	11	0.5	0.000	NA
32 Water	0.00	0	0.00	-1.00	0.00	0.00	0	0.0	0.000	NA

All fractions are relative to the total grid cell area, except the $grant_{pot}$, which is relative to the built-up area. No green roof potential (NA) is assigned to streets, green surfaces and water

Fig. 2 Land use distribution, roof area and green roof potential of built-up (LU = 1–18) and transportation infrastructure (LU = 19–23) in the City of Vienna calculated on the 100-m horizontal resolution model grid. Source: Stadt Wien—ViennaGIS (2011)

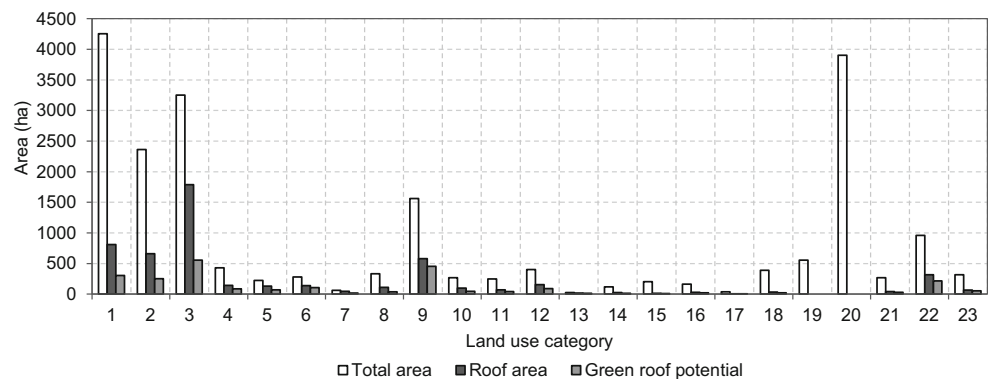


Table 2 Comparison of the mean annual number of SU ($T_{\max} \geq 25^\circ\text{C}$) at the monitoring stations in Vienna for the climatic period 1981–2010

Station	Obs.		Model			Δ (Model-Obs.)			RMSE		MAE		d		
	H (m)	YY	SU	LU _{NN}	SU _{NN}	LU _R	SU _{RLU}	NN	RLU	NN	RLU	NN	RLU	NN	RLU
DF	161	14	79.9 ± 13.6	12	79.2 ± 14.1	12	79.2 ± 14.1	-0.8 %	-0.8 %	4.8	4.8	3.9	3.9	0.94	0.94
GE	153	30	65.7 ± 12.7	27	58.3 ± 14.2	1	62.5 ± 14.6	-11.3 %	-4.9 %	9.8	6.6	7.9	5.4	0.66	0.87
SC	183	30	62.8 ± 12.9	9	66.3 ± 14.5	9	66.3 ± 14.5	5.6 %	5.6 %	6.5	6.5	5.3	5.3	0.91	0.91
HW	198	30	64.1 ± 12.6	20	67.0 ± 14.8	5	62.4 ± 14.4	4.5 %	-2.6 %	7.2	7.1	5.5	5.5	0.89	0.86
IS	177	26	72.3 ± 12.8	3	76.3 ± 14.3	3	76.3 ± 14.3	5.5 %	5.5 %	8.0	8.0	6.1	6.1	0.88	0.88
MB	225	25	60.6 ± 12.5	31	48.0 ± 13.8	2	56.8 ± 14.1	-20.7 %	-6.3 %	15.4	8.9	13.4	7.2	0.25	0.77
UL	201	30	64.4 ± 12.7	27	53.9 ± 13.9	16	58.8 ± 14.1	-16.3 %	-8.6 %	12.7	8.9	10.5	6.6	0.42	0.73

The locations of the stations are indicated in Fig. 1. Model values are calculated at the nearest neighbour grid point (NN) and representative land use class (RLU). Observational values for the station IS are available for the period 1985–2010 and for the station DF for the period 1997–2010. For the station MB, observational data for years 1990, 1992, 1993, 1995 and 1996 are missing. Model performance is given by root mean square error (RMSE), mean absolute error (MAE) and index of agreement (d) as defined by Willmott (1981)

land use type than at the nearest neighbour grid point. These differences are evident for example at the station Wien–Mariabrunn (MB), which is located in a narrow residential area surrounded by forest. Compared to the previous modelling studies (Zuvella-Aloise et al. 2014, 2016), only minor changes in spatial distribution of heat load are found when using current values for surface albedo based on the satellite imagery instead of the standard values (roof albedo of 0.2). The reason is the mixed roof types and small difference in resulting surface albedo between different land use categories. The changes in roof albedo lower than 5 % do not show notable impact on the heat load. The validation of the meteorological fields provided by the high-resolution model remains a problem due to sparse and irregularly spaced observations, especially when long-term measurements are concerned. For the period 1981–2010, only seven monitoring stations with measurements longer than 10 years are available and a denser network of monitoring stations would be required for a detailed quantitative analysis. Nevertheless, the map of urban heat load derived by the modelling approach is similar to the characteristic spatial pattern of the UHI in Vienna provided by differ independent methods including remote sensing and satellite data analysis (City of Vienna, MA22; Pongrácz et al. 2010) and statistical methods (Stiles et al. 2014).

Due to the spatial resolution of the model (100 m in horizontal and 10 to 50 m in vertical), the micro-scale processes on the level of buildings are parameterized. Therefore, the results of the model that can be considered representative on a district scale are not necessarily accurate on a building level and micro-scale modelling approach with resolved buildings, such as applied in Pollak et al. (2011) and Stiles et al. (2014), is required to account for the individual building geometry. For this reason, the validation of the model with the point-wise measurements on specific locations is also limited.

The change in heat load is expressed in difference in mean annual number of SU when compared to the reference

simulation. Using long-term monitoring time series of daily T_{\max} and mean monthly temperature, the annual number of SU can be correlated with the mean temperature in summer months (June, July and August). In Vienna, the change in mean summer temperature of 1 K corresponds to a difference of 12.2 SU (Zuvella-Aloise et al. 2014). The reduction of heat load by -6 SU in annual mean is, therefore, equivalent to a cooling effect in mean summer temperature of approximately -0.5 K. The heat load difference of less than 1 SU (equiv. to approximately 0.1 K) is considered to be below model accuracy.

3.2 Modelling simulations with altered albedo and green roofs

A set of simulations with altered roof albedo and fraction of roof vegetation is performed (Table 3). The simulations are intended to demonstrate the effect of increasing the roof albedo in comparison with implementing vegetation on roofs (Albd25+, Albd50+ and Green100). They also show the maximum cooling potential of green roof implementation in Vienna (Green_{pot}100) and effects of combining the vegetation with materials of different reflectivity (Green_{pot}50PV, Green_{pot}100PV, Green_{pot}50White, Green_{pot}100White). The high reflectivity roofs have an albedo value of 0.68, which is the value for white ceramics (Prado and Ferreira 2005). Theoretical higher albedo values were tested in the model simulations but were not considered valid for practical applications. The sensitivity simulations with low reflectivity (PV, albedo value of 0.1) are intended to investigate cooling effects of possible combined implementation of solar cells with vegetation on roofs. The warming effect due to the decrease in albedo is compared to the cooling effect due to the evapotranspiration of vegetation. The waste heat from the solar cells, as well as inclination of solar panels, is not included in the simulations.

Table 3 Overview of modelling simulations

Simulation	Description	albd	grant
Ref	Reference simulation	$albd_r$	0.00
Albd25+	Increase in roof albedo by 0.25 from the reference value	$albd_r + 0.25$	0.00
Albd50+	Increase in roof albedo by 0.50 from the reference value	$albd_r + 0.50$	0.00
Green100	Vegetation implemented on all roofs	$albd_r$	1.00
Green _{pot} 100	Realization of green roof potential by 100 %	$albd_r$	$1.00 \times grant_{pot}$
Green _{pot} 50PV	Realization of green roof potential by 50 % and implementation of solar cells on the remaining roof surface	0.10	$0.50 \times grant_{pot}$
Green _{pot} 100PV	Realization of green roof potential by 100 % and implementation of solar cells on the remaining roof surface	0.10	$1.00 \times grant_{pot}$
Green _{pot} 50White	Realization of green roof potential by 50 % and implementation of white roofs on the remaining roof surface	0.68	$0.50 \times grant_{pot}$
Green _{pot} 100White	Realization of green roof potential by 100 % and implementation of white roofs on the remaining roof surface	0.68	$1.00 \times grant_{pot}$

Model parameters: roof albedo (albd), fraction of vegetation on the roof surface (grant), observed roof albedo $albd_r$ and green roof potential in Vienna ($grant_{pot}$) as defined in Table 1

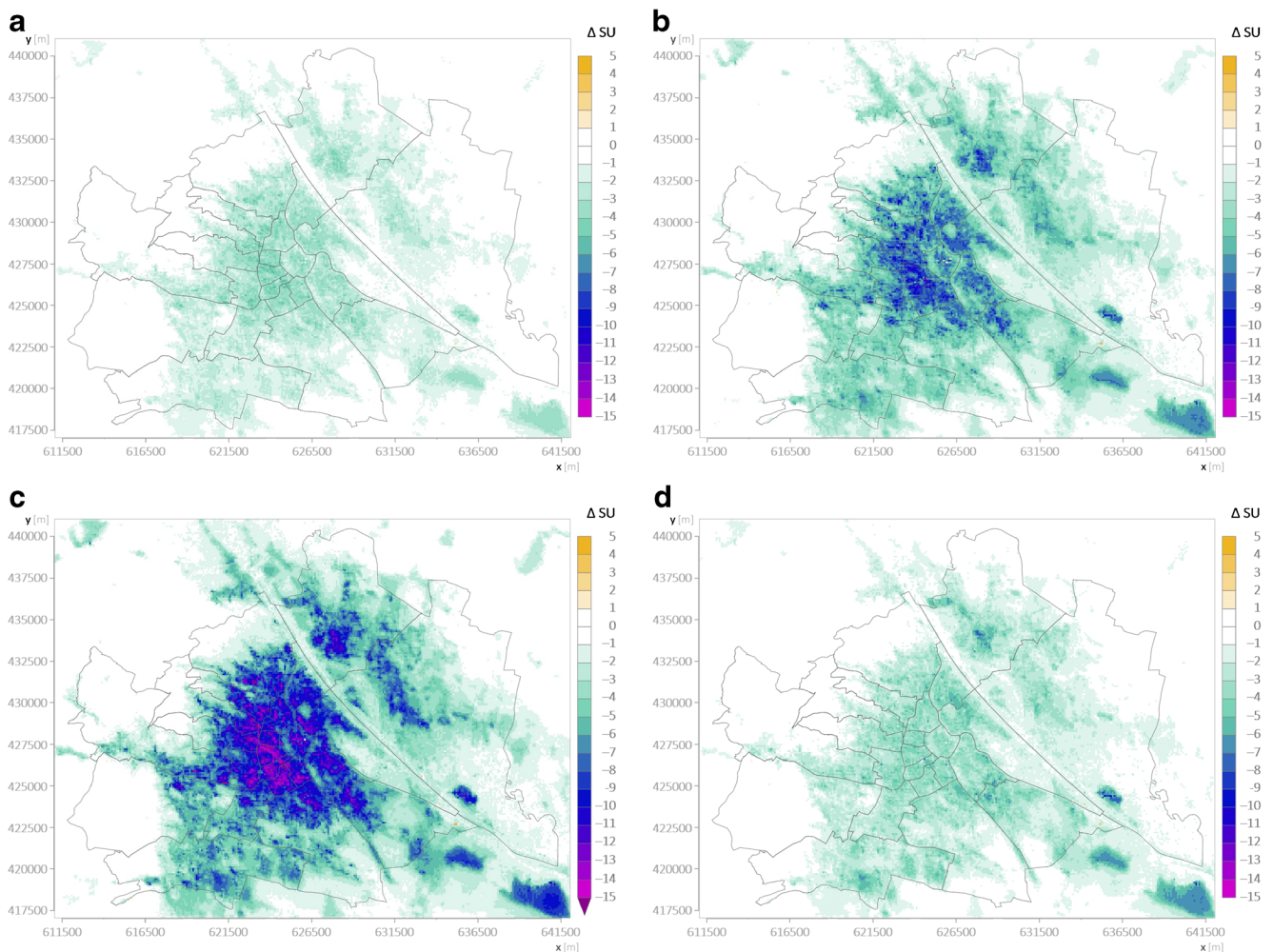


Fig. 3 Difference in mean annual summer days (ΔSU) compared to the reference simulation in the simulations with increased albedo by +0.25 (a) and +0.50 (b) from the reference value and implementation of green roofs on all buildings (c) and only on adequate surfaces (d)

The simulations Albd25+ and Albd50+ (Figs. 3a, b and 4), in which roof albedo is increased from reference value by 0.25 and 0.50, respectively, show a reduction of heat load over a large area of Vienna. A decrease in heat load by more than 1 SU is modelled for 52 % of the city area in the simulation Albd25+ and for 72 % of the city area in the simulation Albd50+. The strong cooling ($\Delta\text{SU} \leq -12$) is found only in the simulation Albd50+, whereas the intensity of cooling in the simulation Albd25+ is low (average cooling in the built-up and traffic areas is -2.0 SU, with maximum below -7 SU). The highest cooling effect is found in the city centre in densely built-up areas due to the high fraction of roofs (Fig. 5). In the simulation Albd50+, 3840 ha shows moderate cooling ($\Delta\text{SU} \leq -6$), which is 9 % of the total city area. Increasing the roof albedo to values higher than 0.7 leads to even stronger cooling effects; however, these values are assumed to be unrealistic for the existing roof materials.

Very strong cooling effects can be seen in the simulation Green100 where all roofs are covered with vegetation (Fig. 3c). The maximum cooling is found in the city centre with 627 ha

(3 % of the built-up and traffic surfaces) having decreased heat load by 12 SU or more and 9682 ha (47 % of the built-up and traffic surfaces) with heat load change of 6 SU or more. When vegetation is implemented only on the roof area equivalent to the available green roof surfaces in Vienna (simulation Green_{pot}100), the cooling effect is considerably reduced (Fig. 3d). Although 61 % of the city area shows a reduced heat load by at least 1 SU (compared to the 79 % in the simulation Green100), the intensity of cooling is much lower. Only 1 % of built-up and traffic surfaces shows a moderate reduction of heat load ($\Delta\text{SU} \leq -6$). Moreover, the strongest cooling effect is not found in the city centre but in the industrial areas in the suburban area, which have the largest fraction of roofs suitable for the implementation of greenery (Fig. 5).

Figure 4 shows the heat load reduction in simulations where different amount of green roof potential is used and combined with the low (PV, albedo value of 0.1) and high-reflective (white, albedo value of 0.68) roof materials. Reducing the albedo of roofs by extensive implementation of solar cells has a negative effect on the heat load.

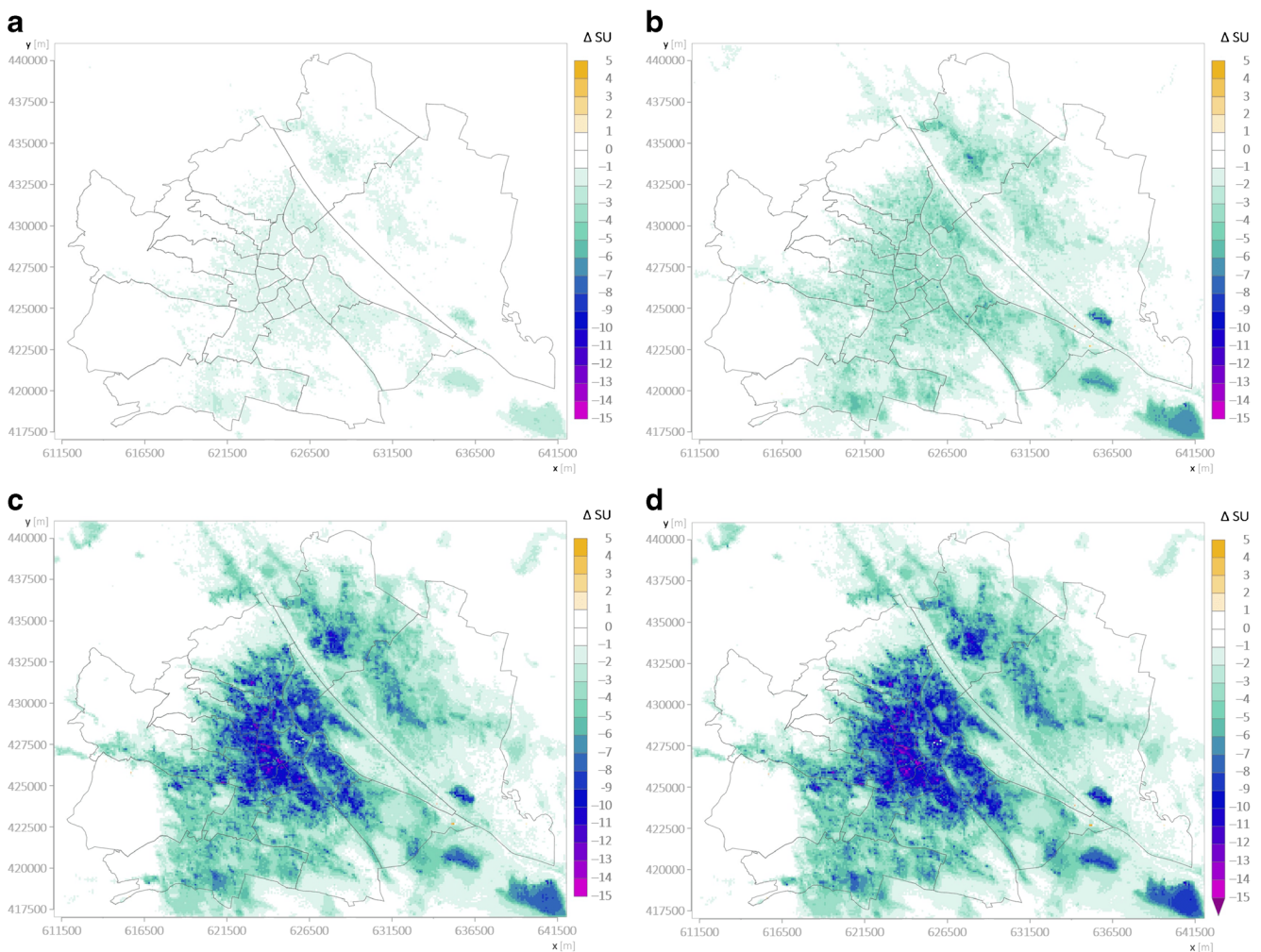


Fig. 4 Difference in mean annual number of summer days (ΔSU) compared to the reference simulation in the simulations with green roofs combined with dark (a, b) and white surfaces (c, d). Vegetation is implemented only on adequate roofs using 50 % (left) or 100 % (right) of the green roof potential

However, the change in albedo is small and, if combined with green roofs, the resulting cooling effect is nevertheless positive. If the total green roof potential is exploited and the remaining surfaces are covered by low reflective materials (simulation $Green_{pot}100PV$), the cooling effect ($\Delta SU \leq -1$) is found on 59 % of the total city area. If only 50 % of the green roof potential is used (simulation $Green_{pot}50PV$), the cooling effect is reduced to 24 % of the city area. These results refer only to changes in albedo when implementing solar cells, and no other material properties such as different heat capacity or energy transfer are taken into account.

Combining green roofs with the high-reflective materials produces a strong cooling effect, especially in the city centre. Whether the entire green roof potential is used (simulation

$Green_{pot}100White$) or only half the potential while the remaining roof surfaces are covered with light-coloured material ($Green_{pot}50White$), the resulting cooling effect is of the same order of magnitude. In the simulation $Green_{pot}100White$, the cooling effect with $\Delta SU \leq -6$ is found in 18 % (7463 ha) of the city area and 85 ha has a cooling of -12 SU or more. In the simulation $Green_{pot}50White$, 15 % (6092 ha) of the city area is cooled by 6 SU or more, while strong cooling of $\Delta SU \leq -12$ is modelled in 41 ha. Although the green roofs produce a stronger cooling effect than light-coloured roofs solely, this simulation illustrates the fact that in the areas where implementation of vegetation is not possible, a compensating cooling effect can be achieved with the high-reflective materials.

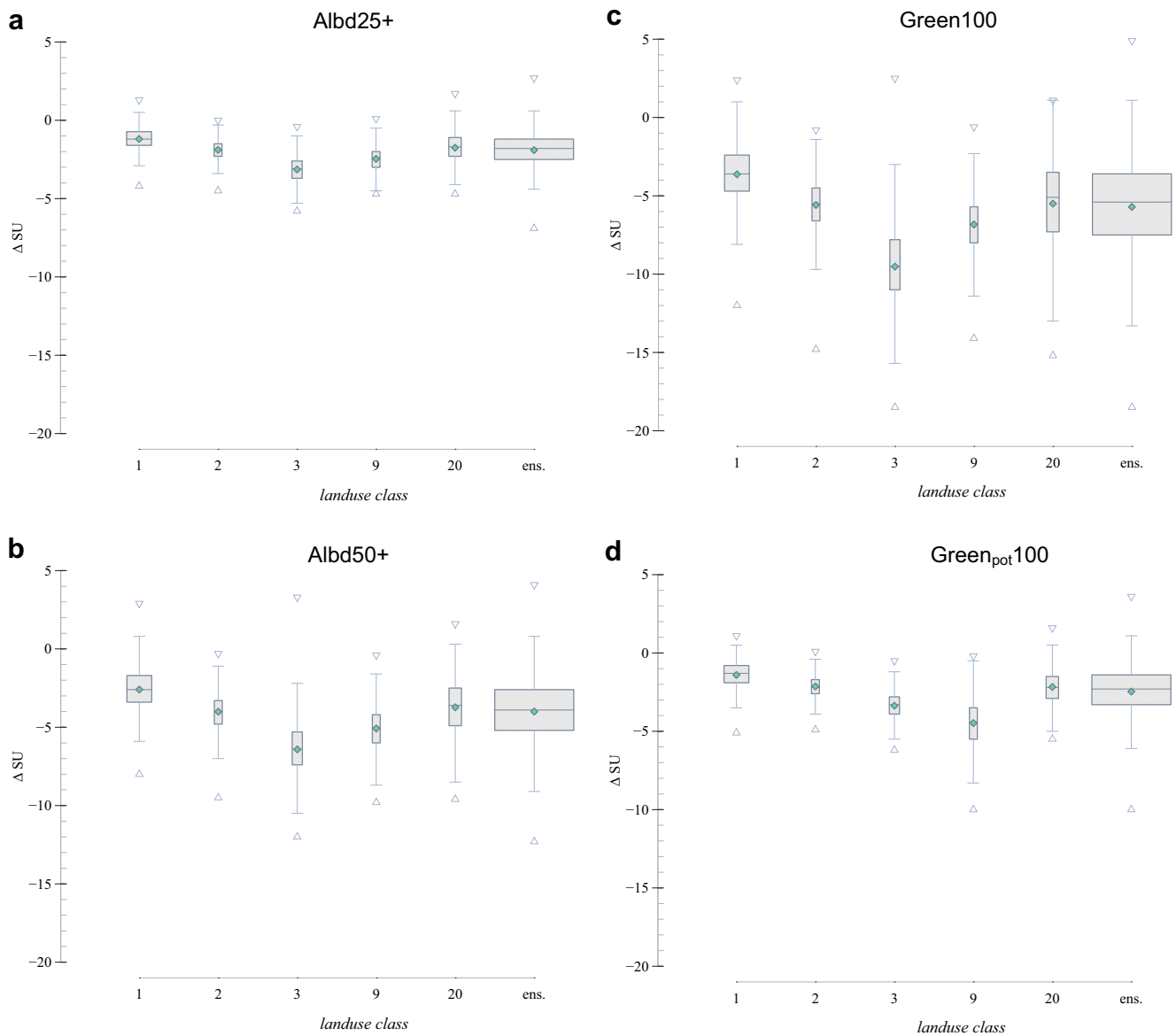


Fig. 5 Box-whisker plot of the change in mean annual number of summer days (ΔSU) calculated for the individual land use classes: main building types (LU = 1, 2, 3, 9), streets without vegetation

(LU = 20) and combined for all built-up and traffic surfaces (ens.). The plot shows median value (*horizontal line*), the lower and upper quartile (*box range*) and the 1.5 interquartile range (*whiskers*)

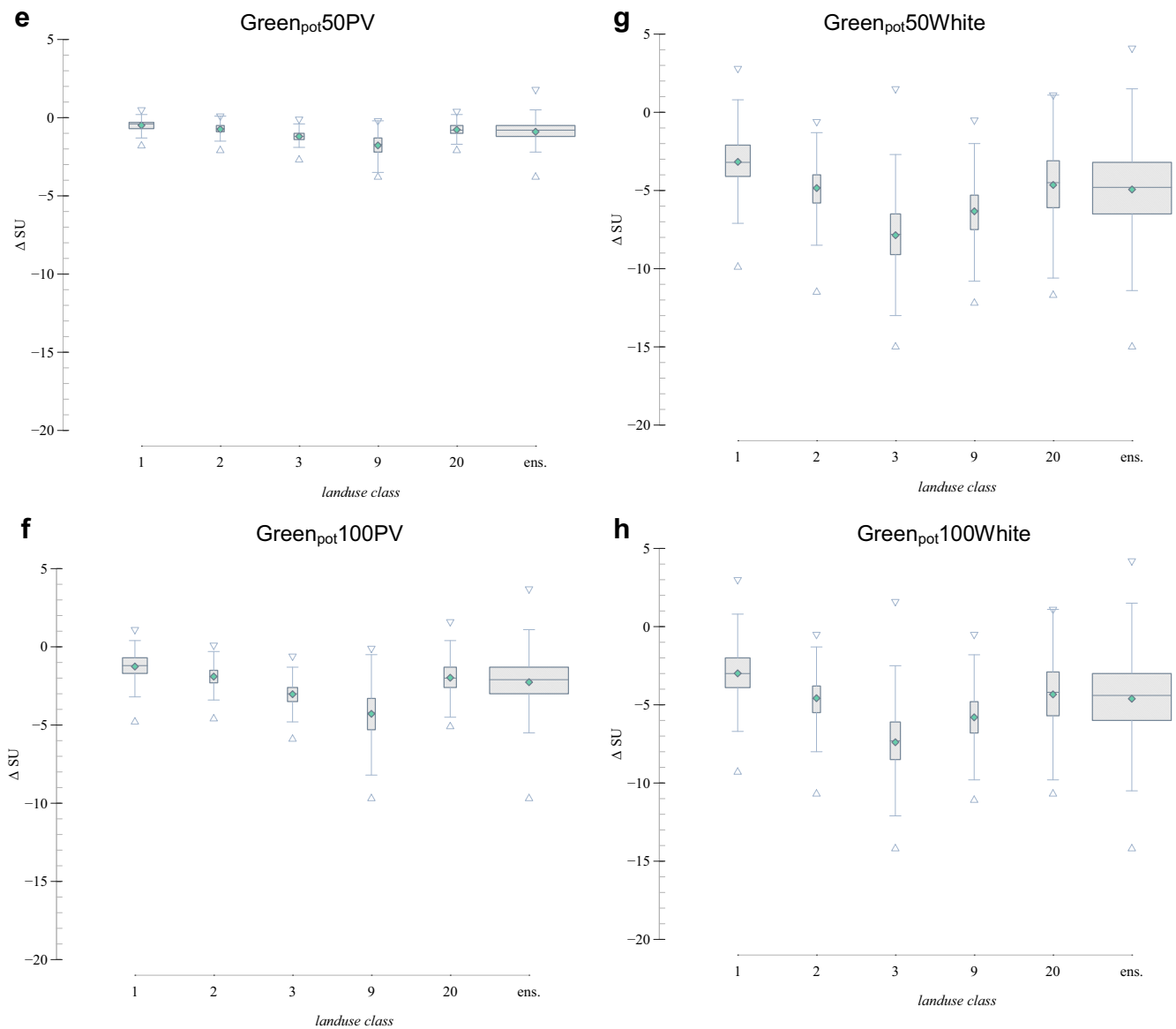


Fig. 5 (continued)

4 Discussion

Sensitivity simulations with the model are performed where the effect of different reflectivity of roof materials as well as the implementation of vegetation on roofs is tested and the reduction of heat load compared to the reference simulation is expressed as difference in mean annual number of SU. In the modelling simulations with high reflectivity of roofs (albedo increase by 0.25 or 0.50) and green roofs, the cooling effect varies between 1 and 18 SU, which is approximately the difference in mean summer temperature by 0.1 to 1.5 °C. This cooling effect applies to the near-surface temperature (2 m above the ground) and includes not only built-up areas but also neighbouring areas (e.g. traffic, parks) where no modifications on roofs are applied. Similar temperature reduction is

found in the mesoscale numerical simulations by Hamdi and Schayes (2008), Fallmann et al. (2014) and Georgescu et al. (2014). For a moderate increase in roof albedo (0.14 to 0.30) in Basel, Switzerland, Hamdi and Schayes (2008) found a maximum cooling effect of approximately 0.25 °C occurring during the day time. This is comparable to the simulation Albd25+ in which the albedo values for densely built-up (LU3) are increased from 0.14 to 0.39 and the resulting cooling effect is in average -3.1 SU or equivalent to 0.25 °C. Numerical simulations for Stuttgart in Germany (Fallmann et al. 2014) showed that changing the albedo for roof surfaces from 0.2 to 0.7 results in a decrease in air temperature by about 0.5 °C. This is similar to the simulation Albd50+ where average cooling for densely built-up area is -6.4 SU or equivalent to 0.5 °C. Applying high reflectivity for

other urban surfaces like walls and pavement can increase the total cooling effect. Taha (1997) summarized that localized afternoon air temperatures on summer days can be lowered by as much as 4 °C by changing the surface albedo from 0.25 to 0.40 in a typical mid-latitude warm climate. However, these scenarios are not considered for a realistic application in Vienna. In general, the modelling results suggest a mean cooling effect of approximately 0.1 °C per 0.1 change in albedo, which is in the range of ambient temperature changes estimated by Santamouris (2014) and similar to findings by Lynn et al. (2009) and Millstein and Menon (2011). The maximum cooling effect is found in the simulation with extensive implementation of green roofs (Green100), and it is comparable with the temperature decrease of 1.6 °C found in field measurements (Sun et al. 2012). The modelling studies report cooling effect of green roofs varying between 0.4 and 1.3 °C (Rosenzweig et al. 2006; Savio et al. 2006) which is similar to the average cooling of about 0.5 °C found in this study. The cooling effect is in average lower than temperature difference predicted by different studies (Gaffin et al. 2005; Susca et al. 2011; Smith and Roeber, 2011; Arabi et al. 2015) and is possibly related to usage of extensive type of roofs with low vegetation height (0.1 m) and relatively low LAI (1.0).

Comparative studies investigating UHI mitigation potential of both green and cool roofs indicate net cooling effects and positive synergies in application, where cool roofs seem to have a much higher mitigation potential during the peak day period (e.g. Takebayashi and Moriyama, 2007; Santamouris, 2014), while green roofs could have in general similar or higher cooling effect if sufficient watering and vegetative mass are available (Savio et al. 2006; Simmons et al. 2008; Santamouris, 2014). The presented study indicates similar cooling effect of albedo increase (up to 0.7) and extensive implementation of green roofs. The best cooling performance is found when combining the green roofs with high-reflective materials.

5 Conclusions

The study investigates the potential of urban roofs to mitigate the heat load in the summer period by changing their surface properties using the City of Vienna as an example. The modelling simulations are performed by using terrain, land use data and building characteristics based on the satellite images supplemented with detailed local geo-information from the city administration of Vienna and observational meteorological data.

A strong cooling effect (more than 12 SU or approximately 1 °C) can be achieved by applying materials with high albedo values (~0.7) but also by implementing the vegetation on roofs. In both cases, the mitigation measure should be applied to a large extent using the full potential of roofs to have a sizeable effect. The modelling simulations show that the cooling effect of the green roofs is of the same magnitude as

the temperature decreases induced by roofs with high solar reflectivity. This finding suggests that the implementation of white roofs can be equally efficient in reducing the UHI effect as the green roofs but with lower costs. However, when realistic application for Vienna is considered, implementation of both white and green roofs is limited by the available high reflectivity roof materials and existing green roof potential in the city. The roof materials with exceptionally high albedo (>0.7), which would induce strong cooling effect, are not permissible for cultural reasons in the current city structure (red tile roofs). Moreover, the ageing of roof materials (weathering, soot deposition, pollutants, smog) can pose a serious problem decreasing the reflectance of the roofs (Berdahl et al. 2002; Ferrari et al. 2014) and increasing the costs of maintenance on a long term. Economic evaluation of green roofs in comparisons to white and black roofs (Sproul et al. 2014), although suggesting high initial costs of implementation for the green roofs, on a longer time period indicates that the green roofs could have multiple compensating effects, which should be taken into account in urban planning. These effects include the longevity of green roofs, energy saving from additional insulation (Berardi, 2016; Silva et al. 2016; William et al. 2016), optimization of rain water management (Berardi et al. 2014; Hashemi et al. 2015), ecosystem services (Madre et al. 2014; Van Mechelen et al. 2015) and positive psychological effects (Tzoulas et al. 2007; Loder, 2014; Jungels et al. 2013).

However, more than 50 % of building in Vienna had a roof type and inclination that is not favourable for planting of vegetation. Therefore, an optimal solution could be found by combining the green roofs with high-reflective materials, preferably without changing the colour of roofs. Simulations Greenpot50White and Greenpot100White show that even using only 50 % of the green roof potential and applying the high reflectivity materials on the rest of surfaces, a similar cooling effect can be found as in the implementation of vegetation on 100 % of the potential green roofs.

Combining green roofs with low reflective surfaces, such as solar cells (simulations Greenpot50PV and Greenpot100PV), results in a cooling effect. This finding suggests that the extensive implementation of low reflectivity of solar panels may not influence the urban heat load substantially. The reason is the relatively small difference in albedo between the existing roofs (0.14–0.2) and the modified dark surfaces (0.1). Considering the large extent of application of vegetation (50–100 % of the green roof potential), the cooling effect of plants is sufficient to overcome the warming effect of the surfaces with high solar absorption. However, this study only considers the reflectivity of the surface material and possible heat that results from the energy production by the solar cells is not considered.

The numerical simulations presented in this study show not only magnitude of the cooling effect but also details of the spatial distribution of the urban heat load. Due to the interaction with the surroundings, the cooling effect can be found to a large

extent outside of the modified surfaces, for example on traffic corridors, especially if the mitigation measures are applied uniformly across the city. The characteristics of the built-up environment play an important role in the resulting cooling effect. The higher the fraction of roofs is, the larger is the intensity and spatial extension of the cooling effect. In most of the simulations, the highest cooling effect is found in the city centre, which is also the most affected area with excessive heat. However, when green roofs are considered, largest fraction of buildings with the green roof potential is located in the industrial areas outside the city. As a result, mostly local cooling effect is found that does not have large impact on the reduction of heat load on the city population. Nevertheless, the modelling results demonstrate large potential of urban roofs to mitigate the UHI effect. Both high reflectivity materials and roof vegetation show substantial impact on the urban heat load when applied extensively over the city.

The study does not take into account the technical feasibility of implementation of vegetation on buildings, which should be considered in the planning projects. Moreover, the extensive application of UHI mitigation measures can have secondary negative environmental impacts. One of them is the decrease in air quality, as reported by Fallmann et al. (2016), due to reduction in vertical mixing and reflected short-wave radiation which increases the near-surface pollutant concentration. As another example, the high reflection of solar radiation from buildings to the street level can decrease outdoor thermal comfort of pedestrians, therefore having a negative effect, even when positive impact on the UHI mitigation and energy savings are achieved (Yumino et al. 2015). Large-scale implementation of green roofs should consider the life cycle of waste materials used in installation in order to produce environmentally responsible roof systems (Chenani et al. 2015). Therefore, despite the available knowledge and evidence in efficiency of UHI mitigation measures, large difficulties still remain for policymakers and urban planners to select proper countermeasure techniques and to guarantee a sustainable urban transformation.

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