PUBLIZIERBARER ENDBERICHT

A) Projektdaten

Kurztitel:	FOCUS-I Future Of Climatic Urban heat Stress Impacts
Langtitel:	Adaption and mitigation of the climate change impact on urban heat stress based on model runs derived with an urban climate model
Programm:	ACRP, 2nd Call for Proposals
Dauer:	24 months
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Projekt- und KooperationspartnerIn (inkl. Bundesland):	
Schlagwörter:	urban climate, future climate scenarios, dynamical climate modeling, heat load, urban planning, adaptation strategies, urbanization
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Klimafonds-Nr:	B060373
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B) Projektübersicht

1 Executive Summary

The urban heat load in Vienna shows a significant increase in the past decades. The increase in urban heat can be attributed to a warming trend in the regional climate and changes in urban morphology. Based on future climate projections the maximum summer temperatures in southern and central Europe are likely to increase by the end of the 21st century. Possible expansions of urban area would additionally contribute to the already extensive formation of the Urban Heat Island (UHI) in Vienna. The health risks related to the extreme heat pose a considerable problem for the urban population in the future. At this point, urban planning strategies to mitigate or adapt to future changes need to be considered.

We have used the dynamical urban climate model MUKLIMO_3 (DWD) to analyze the development of the urban heat load in Vienna and to evaluate the efficiency of possible adaptation strategies to mitigate the excessive heat stress. The model simulates the daily cycle of temperature, wind and relative humidity within the urban area based on the topography and land use data with 100 m resolution and background weather conditions from a reference station outside the city. We focus our investigation on the spatial gradients of temperature during calm, hot daytime conditions to identify thermally sensitive areas within the city. The model has been evaluated against climatological data from monitoring stations and mobile measurements taken on a multi-vehicle bicycle tour. Both model and in-situ measurements show strong gradients in temperature, which can be attributed to the different land use and partially to the topographical characteristics.

An ensemble of future climate projections for Vienna was calculated based on multi-model, multi-scenario regional climate model runs. The results show an increase in the mean annual number of summer days in the next decades. For the period 2021-2050, mostly moderate increase is expected ranging from 0 up to 25 days compared to the reference simulation (1971-2000). For the period 2071-2100 a strong increase is expected ranging from about 20 to 50 additional summer days per year. However, large uncertainties in future climate signal are found. The evaluated trends are similar to previous climate studies for Vienna. Analysis based on an ensemble of model runs pointed out a much wider range of possible future climate scenarios with large deviations especially in the first half of the 21st century. Differences between future climate scenarios mostly originate from the regional climate data used in the analysis. Moreover, the differences in signal between different regional modelling setups (spatial resolution, choice of the global model, initialization) are often larger than the expected development for different emission scenarios. These results point out a large temporal variability of the local climate. Further progress in reduction of uncertainties in downscaling techniques from global to regional scale needs to be achieved, prior to appropriate quantification of the future climate signal on the local scale.

Modelling experiments related to urban planning strategies show that adaptation measures should be applied on large-scale in order to reach substantial reduction in urban heat load for the entire city. If only particular areas are considered, the adaptation measures could be optimized through targeted and combined implementation. With minor, but joint application of several adaptation measures (decrease in building density and pavement, enlargement in green and water surfaces, albedo increase), it is possible to achieve substantial cooling effects in critical areas, which could partly compensate the expected climate warming.

Modelling results demonstrate that equal adaptation measures might have different effects at different locations due to the influence of topography, prevailing atmospheric circulation and characteristics of the immediate environment. Neighbouring surfaces could amplify or damp the efficiency in heat reduction and the efficiency of the mitigation strategy could non-linearly depend on the size of the applied area. As an example, fragmentation of modified areas could bring limited local effects, while agglomeration of areas could lead to possible intensification. Therefore, for a designated urban planning project it is recommended to conduct a

specialized study in order to appropriately quantify the expected results, rather than using standard values or defining parameters for integration into urban planning policies.
Analysis of long-term urban development (comparison of land use distribution in Vienna at the end of the 18th century, current land use survey and future urbanization trends) and modelling experiments show a consequent expansion of areas with excessive urban heat load, emphasizing the importance of implementation of adaptation measures in urban planning and the necessity of sustainable urban development in order to ensure life-quality for the city inhabitants in the future.
The urban model results should help to develop urban planning strategies and can be expected to provide guidelines for policy making in city management. During the project several emerging issues and required scientific developments related to urban climate in Vienna were brought to attention. Further research investment is recommended in field of model development to provide reliable and robust numerical solutions for a broader scope of applications regarding different temporal scales and meteorological parameters (minimum temperature, wind speed and direction, relative humidity, radiation) in urban environment; coupling of the urban climate modelling results with other indices related to human comfort and risk assessment; comparison with different city case studies; integration of realistic future urban designs in modelling setup and further sensitivity studies in cooperation with city administration and urban planners; organization of additional measurement campaigns; development of cost-effective solutions and use of potential of new technologies for data acquisition; dissemination of results especially education of young professionals in fields of climate impact research and urban planning; rising awareness of problems related to heat hazards, climate change and urban climate among public and institutional stakeholders.

2 Hintergrund und Zielsetzung

Urban heat load in Vienna shows a significant increase in the past decades. The increase in urban heat can be attributed to the warming trend in regional climate (Auer et al., 2007) and changes in the urban morphology (Böhm, 1979; 1998, Auer et al. 1989). According to future climate projections by IPCC AR4 (Christensen et al., 2007), the maximum summer temperatures in southern and central Europe are likely to increase by the end of the 21st century. Possible expansions of the urban area would additionally contribute to the already extensive formation of the UHI in Vienna. The health risks related to the extreme heat might pose a considerable problem for the urban population in the future (Schär et al. 2004; Fischer und Schär, 2010; Souch and Grimmond, 2004). At this point, the urban planning strategies to mitigate or adapt to the future changes need to be considered.

The production of excessive heat in urban areas through UHI phenomenon is well known. However, possible future trends in local development coupled to the changes in the background climate have not yet been thoroughly investigated. Large differences in urban heat load can be observed dependent on the location of the monitoring station in Vienna and its surroundings.

Regional climate projections based on dynamical climate models do not take into account or have a rather simplified representation of the urban processes. Furthermore, the effective resolution of the existing regional model simulations (Hollweg et al., 2008; Lautenschlager et al., 2008; Jacob et al., 2008; Loibl et al., 2011) is not sufficient to untangle the details of urban development. Therefore, regional climate models cannot be used directly in urban planning. There is a necessity of a new generation of climate models that can simulate processes in the urban area on a finer spatial scale.

Several urban heat load mitigation concepts have been developed to moderate the thermal stress in urban areas, such as customizing urban vegetation for shading and evaporative cooling areas that moderate thermal and moisture conditions, planning of built structures that support ventilation by choosing an appropriate geometry and size of buildings and street areas; applying suitable materials and colours for buildings to reduce the heat storage and the absorption of solar radiation. Although these measures bring a benefit to the population on a micro-environment scale, the real efficiency in reduction of heat stress on a city scale has not been quantified yet.

The project FOCUS-I is intended to rate the impact of a changing climate on the UHI in Vienna by applying the dynamical urban climate model MUKLIMO_3 (DWD) to simulate possible changes in urban heat load taking into account regional climate projections and urban morphology. The goal of the modelling study was to identify critical areas within the city that are exposed to heat stress, as well as potential areas that may be affected in the future. Furthermore, the sensitivity simulations with the urban climate model for possible reduction of the UHI effect were intended to quantify the efficiency of envisaged adaptation and mitigation strategies in urban planning. The aim of the project was to provide a climatological base which can serve as a supporting tool for sustainable urban planning and which can be used as a guideline for policy making in city management to reduce negative impacts of climate change and enhance the well being of the city population. The presented project is accomplished with support from the DWD and the Vienna city administration (MA18).

3 Projektinhalt und Ergebnis(se)

Urban climate model simulations based on observational background data

The mean annual number of summer days (T_{max}≥25°C), hot days (T_{max}≥30°C) and warm nights (T_{min}≥17°C) for the reference period 1981–2010 calculated with the MUKLIMO_3 model using the “cuboid method” are shown in Figure 1. The modelling results indicate a complex spatial structure of the heat distribution, which is strongly dependent on the surface characteristics.

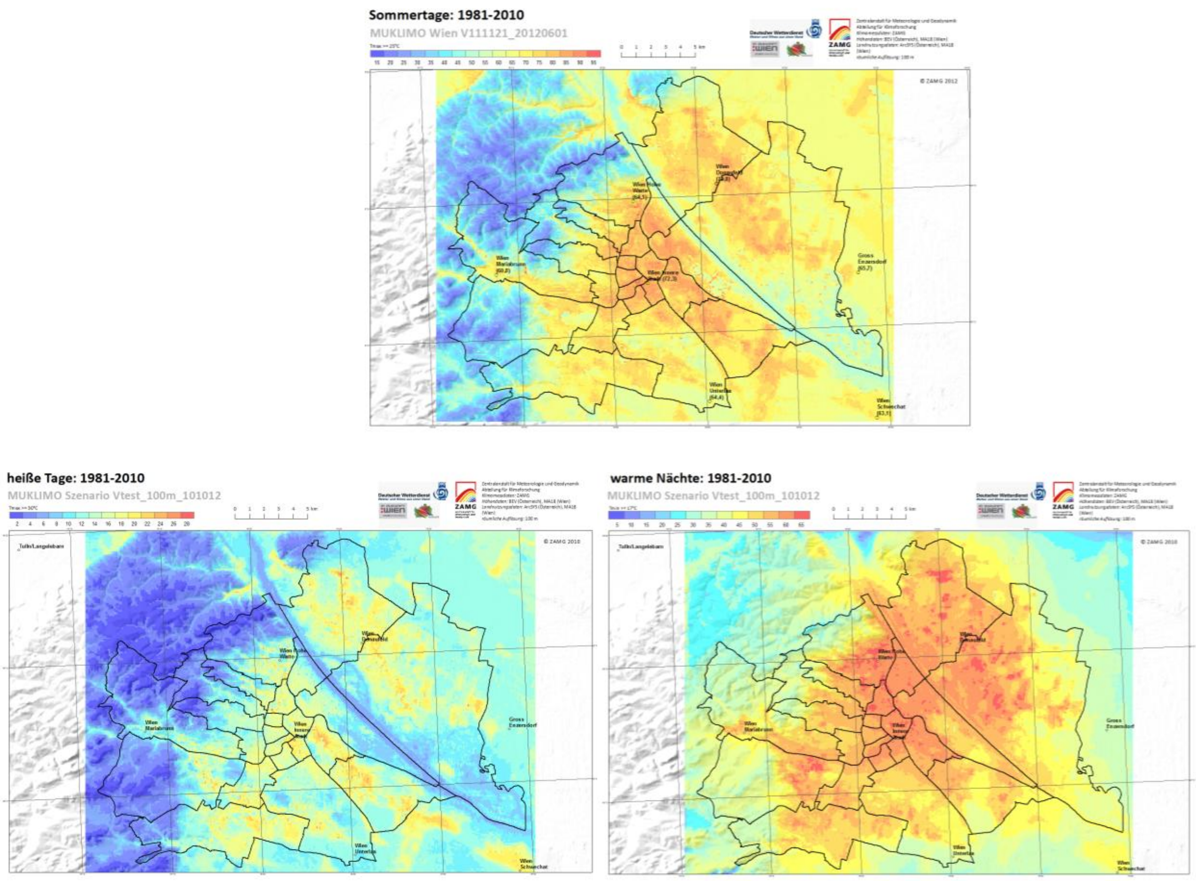


Figure 1 Mean annual number of summer days (top) and hot days (bottom left) and warm nights (bottom right) in Vienna for the time period 1981–2010.

Validation of model results

Modelling results have been evaluated against several observational datasets. The simulated climate indices (e.g. mean annual number of summer days, hot days and warm nights) have been compared to the observational data from the monitoring stations, which have more than 10 years of measurements. The evaluation was carried out for 3 climatological periods 1961–1990, 1971–2000 and 1981–2010. Best agreement with observational data was found for the evaluation of the mean annual number of summer days for the most recent climatological period (1981–2010) where modelling values in most cases differ less than 5% from the observed values at the individual stations (Table 1). Evaluation of hot days yielded to somewhat underestimated values (3–6 days less than observed), while warm nights were strongly overestimated (>30%). Better agreement with monitoring data for the recent climatic period could be associated with application of land use data in the model, which represents current land use distribution (land use survey 2007/2008) and better quality of observational data.

Table 1 Comparison of observed and modelled values of mean annual number of summer days for the climatic period 1981–2010 at the nearest point (NN), representative land use class (RLU), in the radius of 150 m (R150) from the monitoring station.

Station	**Obs.**	**Model**			**Difference**		
		NN	**RLU**	**R150**	**NN**	**RLU**	**R150**
Wien Donaufeld	**79.8**	73.8	73.8	73.1	-7.5%	-7.5%	-8.4%
Groß Enzersdorf	**65.7**	63.6	63.6	62.1	-3.2%	-3.2%	-5.5%
Wien Schwechat	**63.1**	66.0	66.0	64.4	4.6%	4.6%	2.1%
Wien Hohe Warte	**64.1**	63.2	64.8	63.0	-1.4%	1.1%	-1.7%
Wien Innere Stadt	**72.3**	72.2	72.9	72.9	-0.1%	0.8%	0.8%
Wien Mariabrunn	**60.8**	62.6	49.9	56.5	3.0%	-17.9%	-7.1%
Wien Unterlaa	**64.4**	58.3	60.2	59.4	-9.5%	-6.5%	-7.8%

The simulated spatial distribution of temperature extremes has furthermore been validated against the temperature measurements collected during a mobile measuring campaign on a single hot day in July 2011. 11 bicycle routes have been planned according to the modelling results with duration of each tour of about 2 hours in which more than 16000 temperature measurements where collected over 300 km distance. The data loggers with thermocouples (iButton) and GPS devices logged the temperature and geographic coordinates every 5 seconds. Additionally, the daily cycle of temperature has been measured at fixed locations in 10-minute intervals on 3 monitoring stations (near water channel, in a park and densely built-up area). The measurements showed strong gradients in temperature between build-up areas and green surroundings (up to 9°C at 15:00) with highest temperatures measured on streets and lowest temperatures found in forest area of Wienerwald and nature reserve Lobau. Similar spatial gradients in temperature could be simulated with the MUKLIMO_3 model given initial conditions representative for the atmospheric situation on a given day (Figure 2).

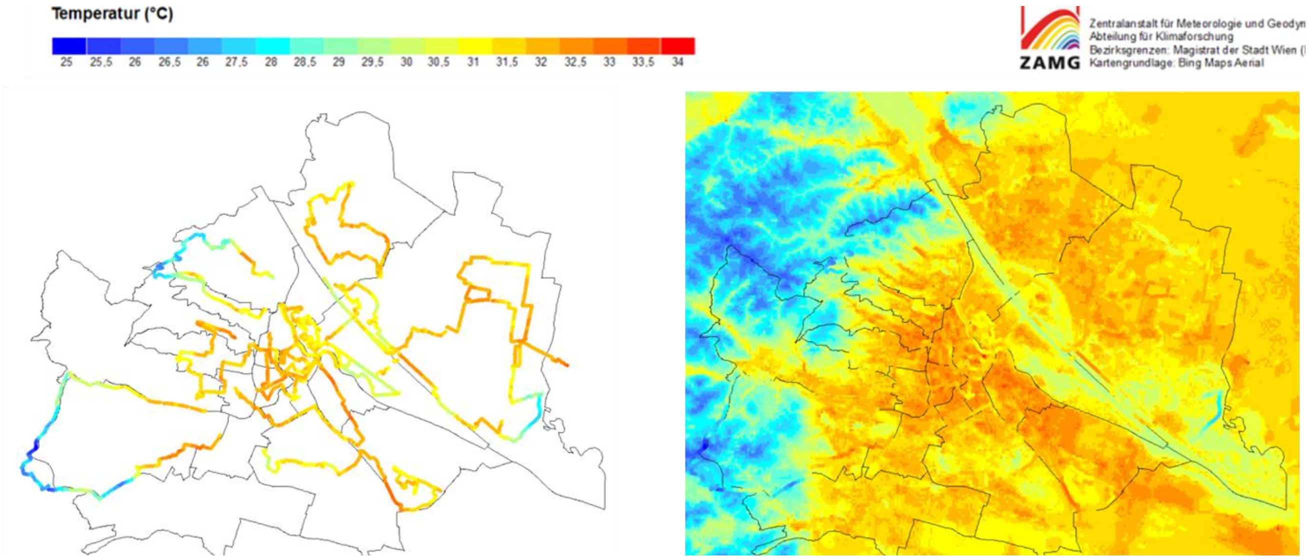


Figure 2 Temperature distribution in Vienna as measured on the bicycle tour on 07.07.2011 (left) and simulated with the urban climate model (right).

Collected temperature data have been further employed to validate the temperature distribution for typical land use types (Figure 3) in order to adjust the modelling setup. It must be emphasized that both the measurement technique and the modelling approach have limitations and require further consideration in order to directly compare the modelling results with measurements at single points.

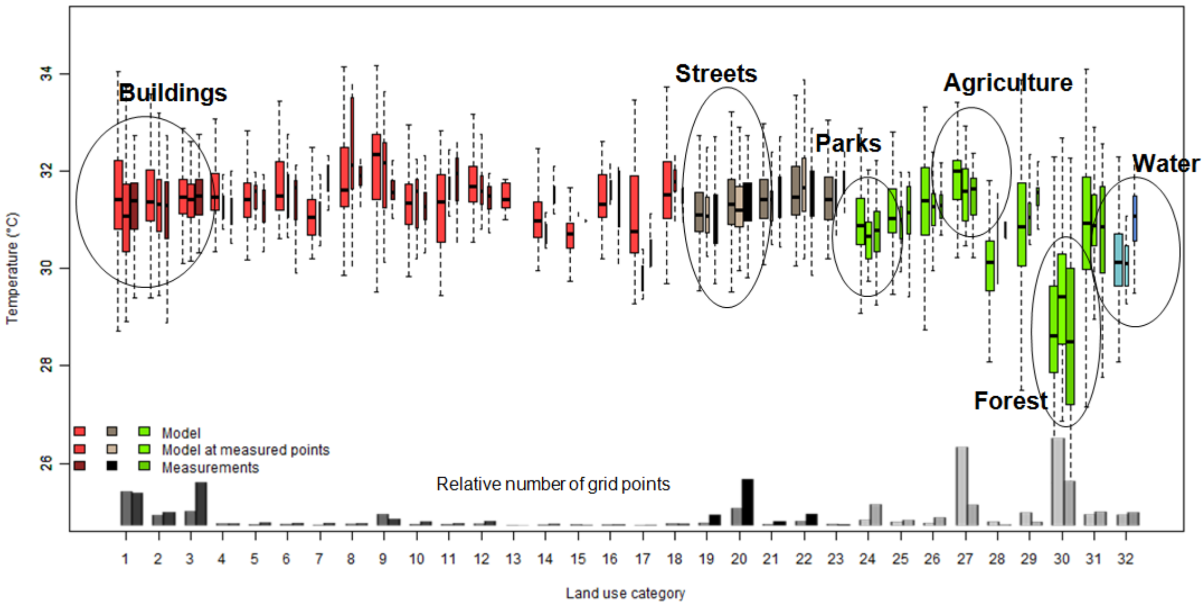


Figure 3 Comparison of modelled and measured temperatures for each land use category.

Remote sensing data (satellite and thermal images) have been used for qualitative comparison of spatial gradients in surface temperature.

Future climate projections

An ensemble of future climate projections for Vienna was calculated based on multi-model multi-scenario regional climate model runs. The results show an increase in the mean annual number of summer days in the next decades (Figure 4). For the period 2021-2050, a moderate increase is expected ranging from 0 up to almost 25 days compared to the reference simulation (1971-2000). For the period 2071-2100 a strong increase is expected ranging from about 20 to 50 days.

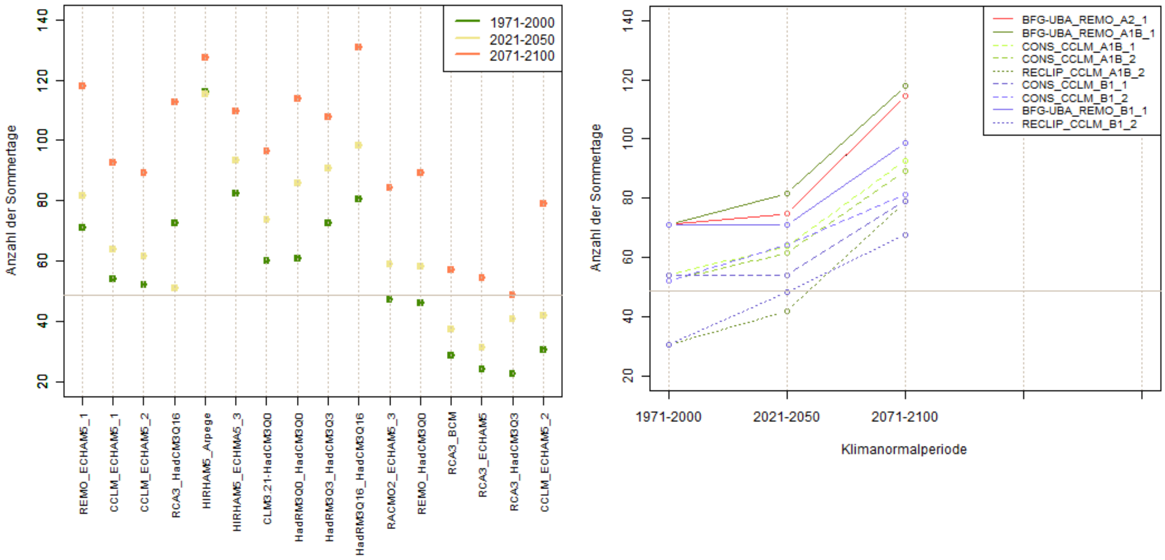


Figure 4 Mean annual number of summer days for Vienna for the periods 1971-2000, 2021-2050 and 2071-2100 calculated with an urban climate model based on an ensemble of regional climate projections for the IPCC scenario A1B (left) and different IPCC scenarios for selected regional climate models (COSMO-CLM, REMO) (right). Note: lines between the climatic means are indicated only for illustration purposes; no linear transition between the climatic periods is implied.

The strength of the warming signal and the temporal development is mainly dependent on the results of the regional climate model used in the evaluation. An example of spatial distribution of urban heat load for future climate scenarios based on regional climate projections from UBA-BFG project with regional climate model REMO (Jacob et al., 2008) for different IPCC scenarios are shown in Figure 5.

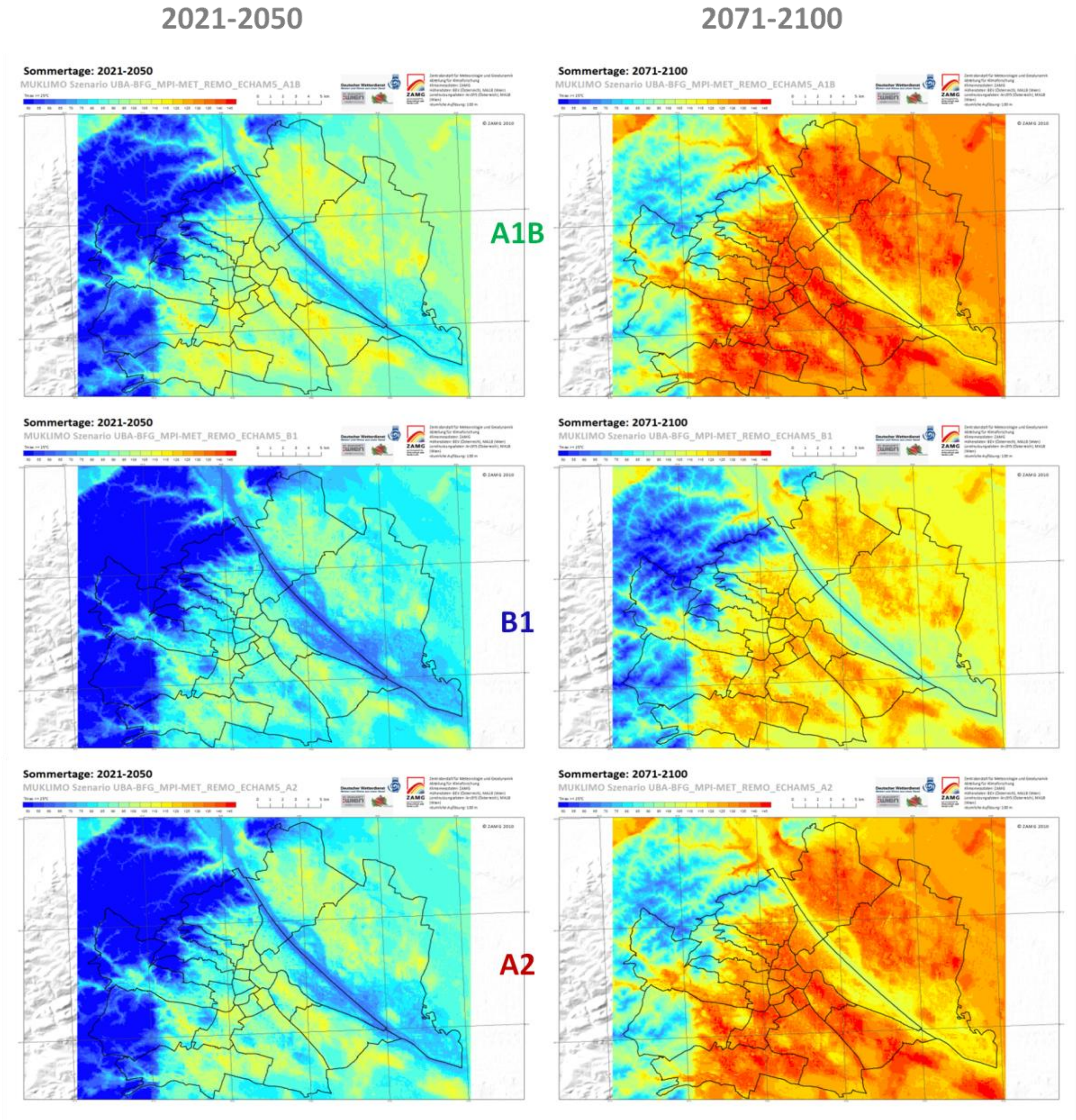


Figure 5 Future climate scenarios for Vienna calculated with the urban climate model MUKLIMO_3 and the cuboid method driven by the input data from the UBA-BFG_REMO_ECHAM5 regional model simulation.

Implementation of urban planning strategies in model setup

In order to evaluate the efficiency of urban planning strategies to mitigate excessive heat load in urban areas, a set of experiments with altered land use characteristics in the modelling setup was designed. The modifications include an increase in vegetation, albedo and water areas, changes in building geometry and hypothetical urban growth as opposite to heat load mitigation (Table 2).

Table 2 Overview of modelling experiments for urban planning strategies. Model parameters: fraction of built area (vg), mean building height (h), fraction of pavement (vsx), fraction of tree cover (sbm), fraction of low vegetation (sigma), roof albedo (albd), wall albedo (albw).

Experiment	Test	Modification
Green City	fraction of buildings	vg: -10%, 10%, 20%
	fraction of vegetation	sigma: -10%, -20%
	fraction of pavement	vsx: -10%, -20%, 10%
	green corridors	vg<0.1 vsx<0.2, sigma>0.2, sbm>0.2
	green corridors + built-up	vg<0.1 vsx<0.2, sigma>0.2, sbm>0.2
	parks instead of buildings	10%, 30%, 100%;
		inner and outer districts
		larger parks vs. new parks
		scattered vs. joint parks
	forest instead of agriculture	rural areas
White City	roof albedo	albd: 0.3 – 0.9
	wall and roof albedo	albd+albw: 0.3 – 0.9
Shaded City	height of buildings	inner and outer districts: + 5m
Blue City	water instead of new parks	inner and outer districts: 30% - 100%
	water temperature	18°C, 23°C
Grey City	urbanisation	planned projects, virtual city growth, densification

Modified heat load distribution is expressed in difference in mean annual number of summer days compared to the reference simulation. In order to evaluate the modelling results in terms of impact on local climate, we define a scale that relates difference in mean annual number of summer days with qualitative modification of urban heat load (Table 3). The scale is defined under consideration that the observational data from Vienna for monitoring stations in distinct micro-environments (urban versus suburban or rural) show a difference between 6.6 and 11.5 summer days per year in mean. Another measure for comparison is the correlation between the annual number of summer days and mean summer temperature (June, July, August). Linear regression between the two variables based on temperature data from the homogenized dataset of the station Vienna Hohe Warte for the time period 1872–2011 indicates that change in mean summer temperature of 1°C corresponds to a difference of 12.2 summer days per year. These scales are based on empirical values for Vienna and are not necessarily applicable for other urban environments.

Table 3 Evaluation scale for heat load modification.

Difference in mean annual number of summer days	Impact on urban heat load
<1	below model accuracy
1 – 3	minor
4 – 9	moderate
≥10	strong

Green City

Due to the important role and multiple benefits of green infrastructure in urban environment, a large part of the investigation was focused on experiments that examine the impact of increased vegetation in amelioration of the local climate. The experiments included systematic change in fraction of vegetation in urban area, increase in vegetation only on specific locations such as traffic corridors and residential districts and placement of new parks on defined locations in zones of interest.

Systematic change of fraction of vegetation in the model setup was achieved by altering the percentage of low vegetation directly or by decreasing the fraction of buildings and pavement, which indirectly enlarges green areas. The results indicate that both decrease in building density and reduction of pavement have a cooling effect. However, lowering the building density has higher impact on reduction of heat load than decreasing the fraction of pavement by the same amount (Figure 6).

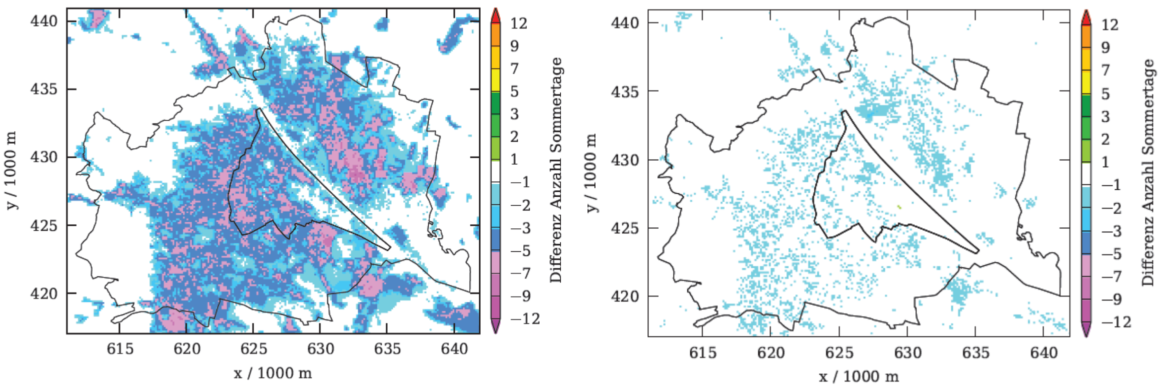
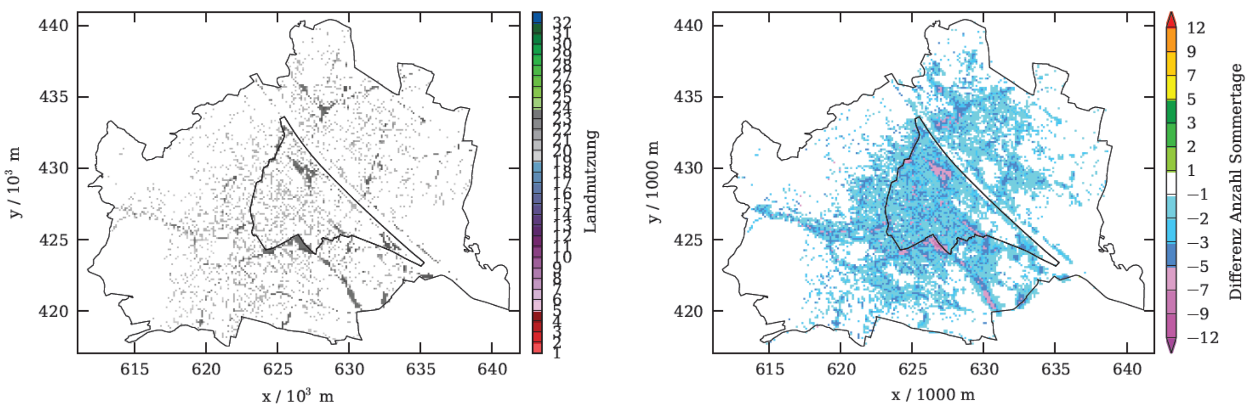


Figure 6 Difference in mean annual number of summer days in the experiment with reduced building (left) and pavement fraction (right) by 10% compared to the reference simulation.

Considering that extensive application of adaptation measures on a large scale is technically difficult and cost intensive, we examined the possibility of achieving the cooling effects by combining different adaptation measures on targeted areas. Moderate cooling effects could be achieved when applying minor but several joint adaptation measures (lowering building density by 10%, fraction of pavement by 20% and increasing tree and low vegetation percentage by 20%) on traffic corridors (Figure 7, top); strong cooling effects when modifications are applied in residential areas as well (Figure 7, bottom). The cooling effect is not only evident on surfaces with altered land use characteristic, but in the surrounding areas as well.



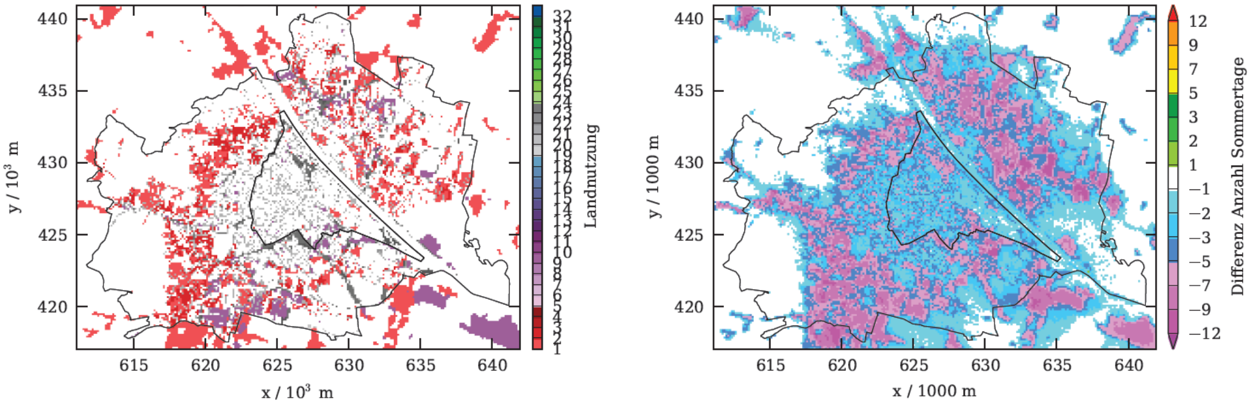


Figure 7 Modified land use (left) and difference in mean annual number of summer days (right) in the experiment with green traffic corridors (top) and green residential and traffic areas (bottom) compared to the reference simulation.

In the model setup based on the current land use survey, 1158 grid points with 100 m x 100 m horizontal spacing are defined as park areas. Random increase in the existing park area by 10% gives minor cooling effect, while moderate cooling can be found by increase of 30% (not shown). The cooling effects are mostly limited to the surfaces where land use modifications were applied. Strong cooling effects with moderate cooling of near-by surfaces is achieved when the total area of parks is doubled (not shown). Considering that implementation of over 1000 ha of new parks in densely build environment is out of practical reach, we investigated possibilities of positioning a smaller amount of new green areas that will produce highest cooling effects (new parks vs. enlargement of existing parks, small vs. large parks, scattering versus agglomeration).

An example in Figure 8 shows reduction of heat load by increasing the park area at different locations in the city. Two experiments were performed in which the park area was increased by 30%. In the first case, new parks were concentrated in the inner city (top). In the second case (bottom), the parks were scattered outside of the city centre. Both experiments show a reduction of heat load at the park locations. However, in the first experiment with neighbouring parks an amplifying effect was found as well as spreading of cooling on the near-by built-up areas. In contrast, the second experiment with scattered small parks showed mostly local cooling. Enlargement of existing parks versus creation of new parks did not yield to distinctive results. The strength of the cooling effect and possibility of spreading on the surrounding area depended on the size, location and previous land use characteristics. For example, large green area produced stronger cooling effects on the location of the park itself, but the distant effect on the surroundings was dependant on whether the modified area is in densely built environment or near green or water surfaces and whether there is a prevailing air circulation that would enhance cool air propagation. Positioning of small single parks in the densely built environment mostly yielded in minor local effects. These results demonstrate the importance of urban climate modelling as part of reasonable urban planning.

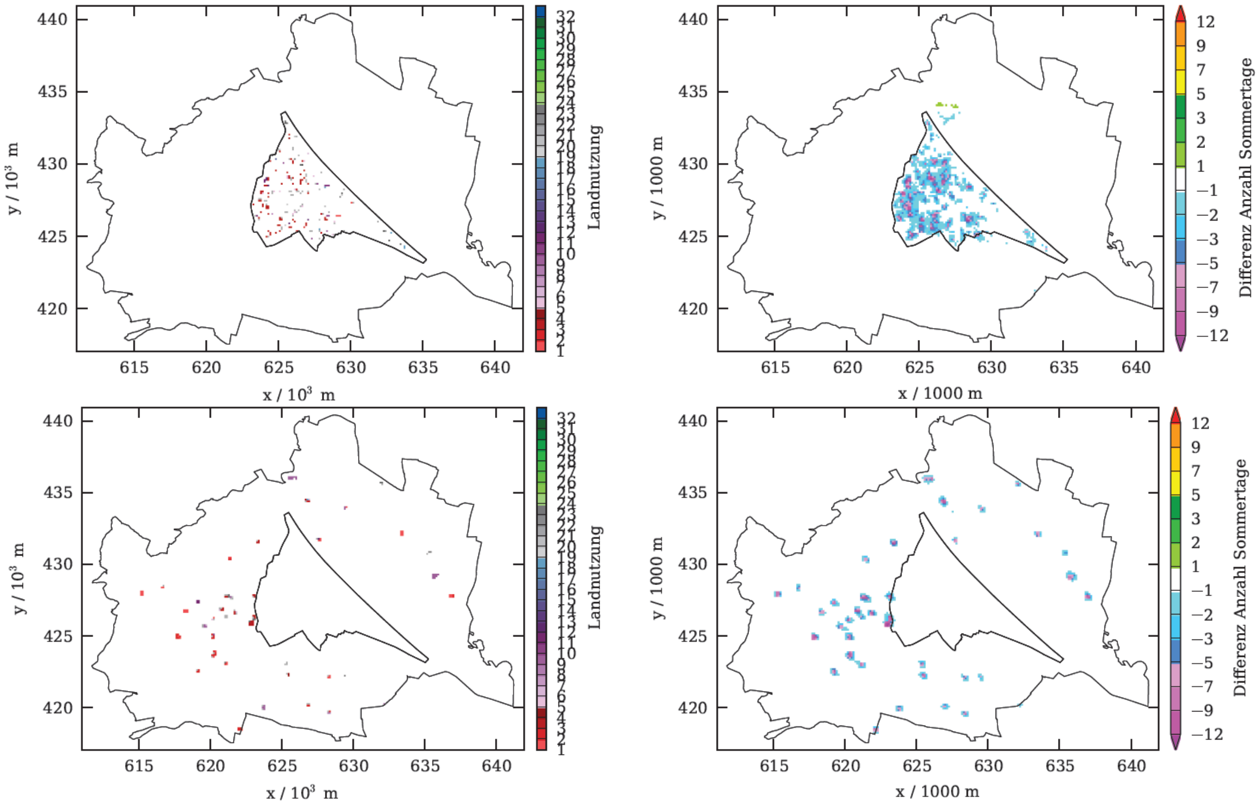


Figure 8 Modified land use (left) and difference in mean annual number of summer days (right) in the experiment with 30% increase of park areas in the city centre (top) and outside of the city centre (bottom) compared to the reference simulation.

As an example of extreme green scenario, we tested possible transformation of all agricultural areas surrounding the city into forest (Figure 9). The results demonstrate particularly strong cooling effects and reduction of heat load in remote areas as well. Due to the forestation, the built-up areas in the vicinity of the new forest are under influence of moderate to strong cooling. Largest spread of cooling effects is visible in areas lying in the directions of prevailing winds (Northwest and Southeast).

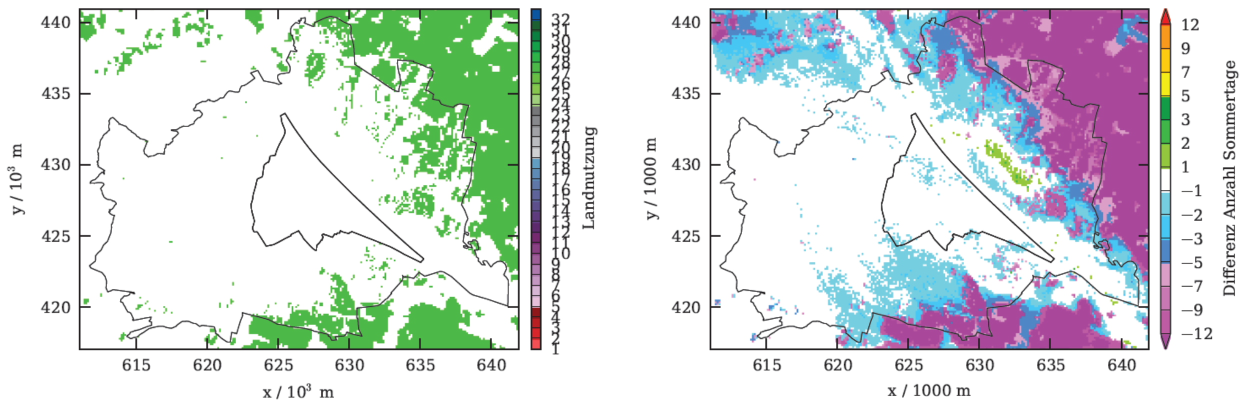


Figure 9 Modified land use (left) and difference in mean annual number of summer days (right) in the experiment where agricultural areas have been modified into forest compared to the reference simulation.

White City

An increase of building reflection has been tested by changing the reference roof and wall albedo from default values of 0.2 and 0.3, respectively to values of 0.3, 0.5, 0.7 and 0.9. In all cases considerable cooling effect could be found with stronger cooling in case both roof and wall albedo increase is applied (Figure 10 and Figure 11). Moderate and strong cooling effects are simulated only when albedo values exceed 0.5. Real values and spatial distribution of the roof and wall albedo in Vienna is not known. Hence, the question to which extent their values could be modified remains uncertain.

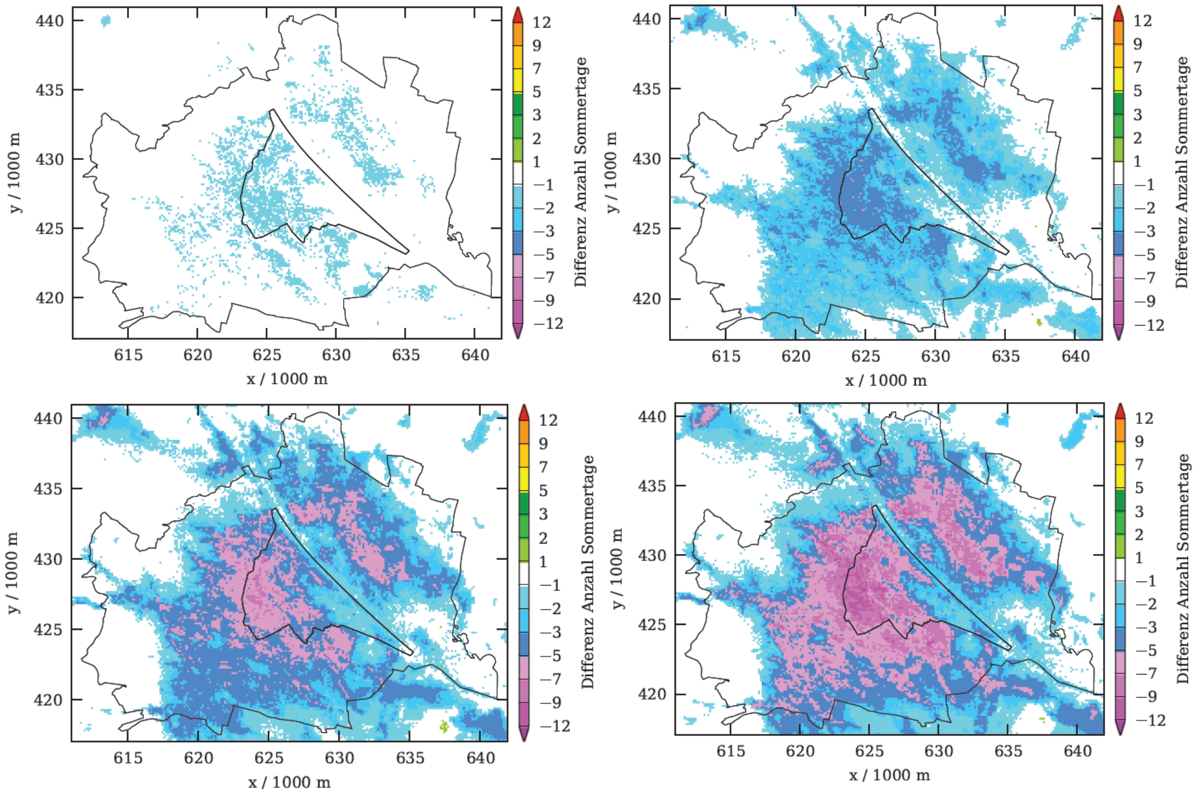


Figure 10 Difference in mean annual number of summer days in the experiment with roof albedo increase to albd=0.3 (upper left), albd=0.5 (upper right), albd=0.7 (lower left) and albd=0.9 (lower right) compared to the reference simulation (albd=0.2).

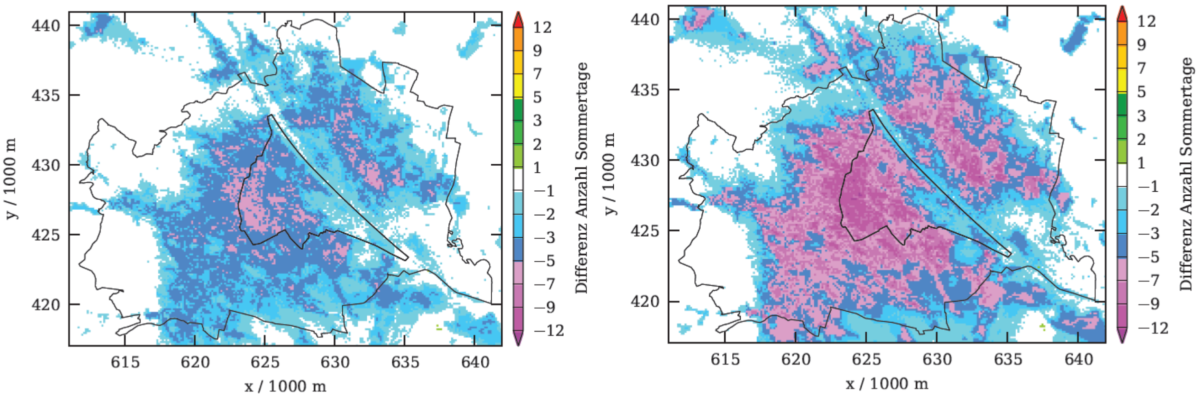


Figure 11 Difference in mean annual number of summer days in the experiment with roofs and walls albedo increase to albd=albdw=0.5 (left) and albd=albdw=0.7 (right) compared to the reference simulation.

Blue City

Similar experiments as for the Green City (Figure 8) were performed in which the modified park areas were replaced with water. Existing water surfaces were left unchanged. The modelling results show strong cooling effect (Figure 12).

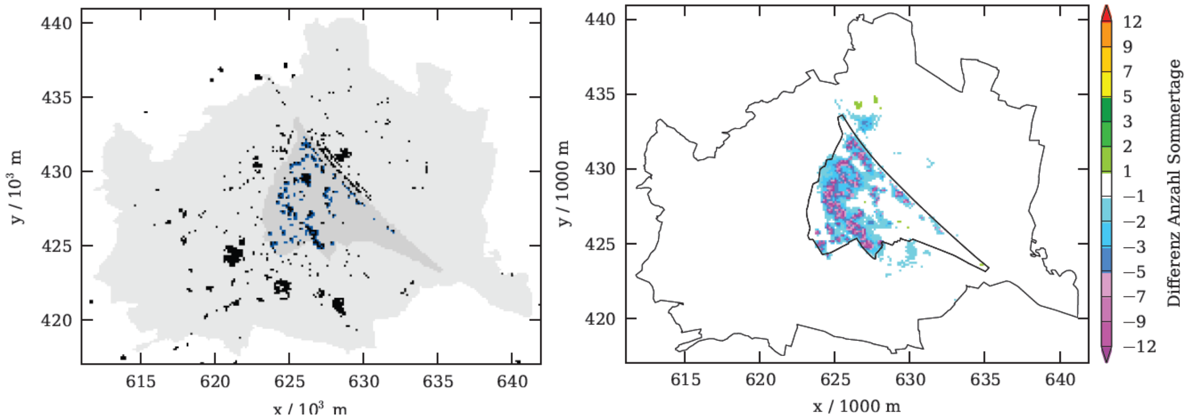


Figure 12 Modified land use (left) and difference in mean annual number of summer days (right) in the experiment with 30% increase of water areas water in the city centre compared to the reference simulation.

However, the results should be regarded with caution since the surface water temperature was relatively low (18°C) and held constant in the simulations. In the experiment with higher water temperatures the cooling effects was lower (Figure 13). Moreover, the cooling refers to the heat load during the day and the influence of water areas on nocturnal cooling needs to be additionally considered.

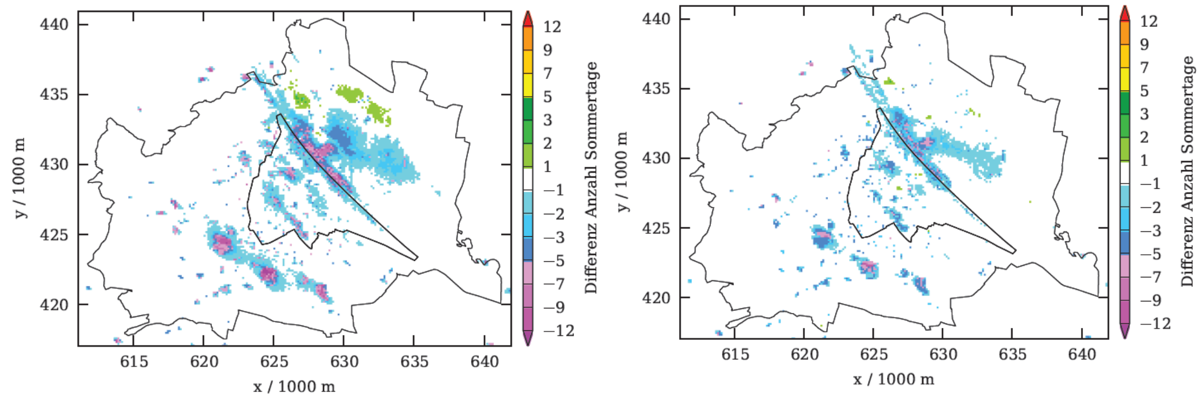


Figure 13 Difference in mean annual number of summer days compared to the reference simulation in the experiment with all park areas modified into water and water temperature set to 18°C (left) and 23°C (right).

Urbanization

The city of Vienna is expected to grow in the future. Urbanization trends already present in Vienna include densification of the existing built-up areas and sprawl of the city to the near-by rural surroundings in Northeast and Southeast direction. The urbanization induces spreading and intensification of the UHI effect, which in the future is expected to superimpose on the regional climate warming. We investigated the impact of the city growth on the formation of UHI and possible remote effects in order to differentiate between amplification and extension of the UHI. The urbanization experiments consider hypothetical growth of the city and are based only on general trends in urbanization and not on actual urban plans. The virtual city is defined with land use types corresponding to mixed built-up areas.

An example of the impact of the city growth in Southeast districts is illustrated in Figure 14. Strong increase in heat load is found in newly urbanized surfaces in modelling simulations with moderate to minor impacts on the surroundings.

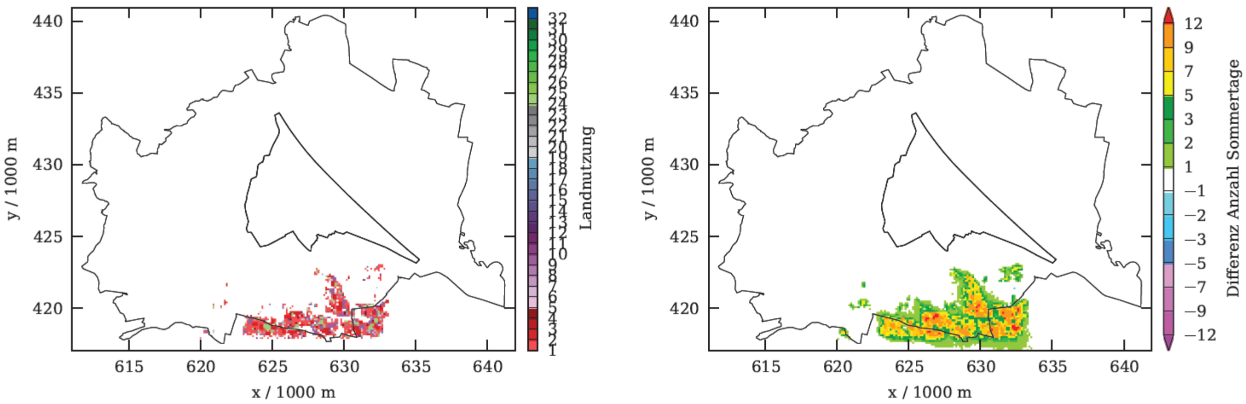
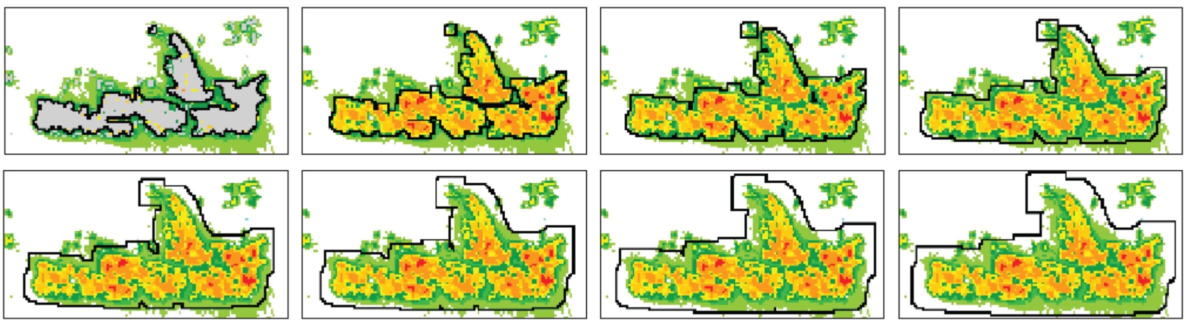


Figure 14 Modified land use (left) and difference in mean annual number of summer days (right) compared to the reference simulation in the experiment with hypothetic growth of the city in the South-East rural area.

Although urbanization induces strong heat load in newly built-up areas the remote effects of urbanization are limited. Analysis of the distant effect for newly urbanized area in Southeast region shows exponential decrease of the heat load with distance. In a distance of several hundreds of meters from the urbanized area, almost no difference in heat load is found (Figure 15).



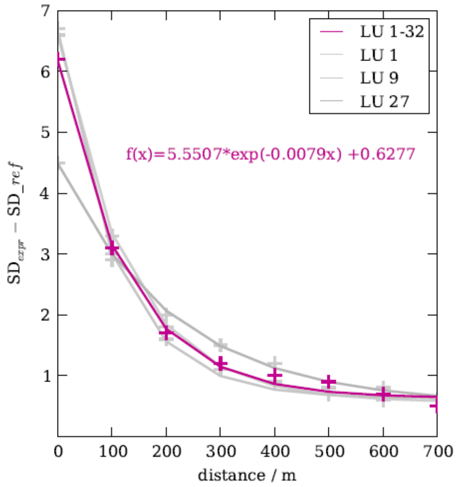


Figure 15 Evaluation of distant heat load signal for the experiment with hypothetic growth of the city in the Southeast rural area (up). Average difference in mean annual number of summer days compared to the reference simulation at the surrounding surfaces is calculated dependent on distance from the urbanized area. Evaluation is given for different land use categories (LU 1-32: all surfaces; LU 1: low density built-up; LU 9: industry; LU 27: agriculture).

However, if the newly urbanized area is positioned on a different location such as the Western region of Vienna (Figure 16), the heat load intensity and remote effects are much larger. In this case, the heat load signal itself is stronger since forest areas have been modified into built-up surfaces (in comparison to modified agricultural fields in Southeast region) and the propagation of the signal is enhanced due to the elevated topography and prevailing Northwest wind direction.

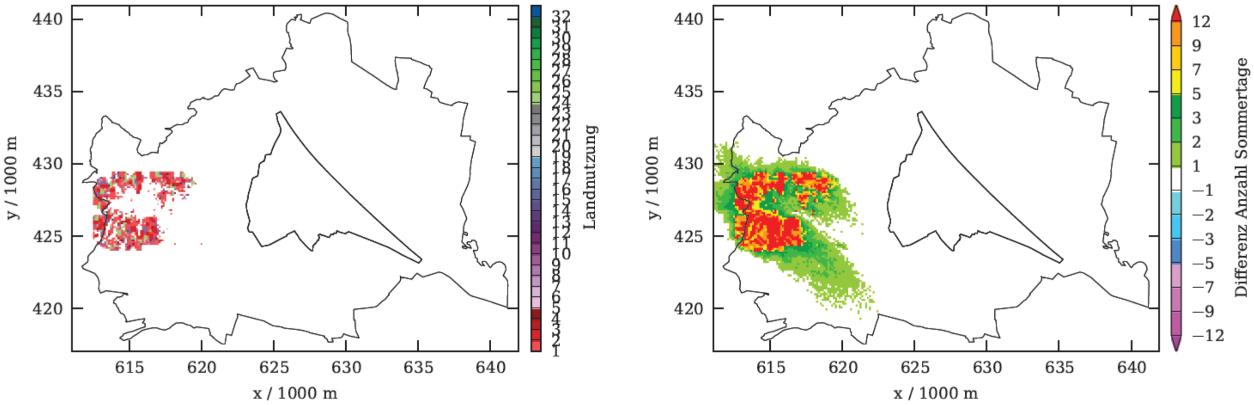


Figure 16 Modified land use (left) and difference in mean annual number of summer days (right) compared to the reference simulation in the experiment with hypothetic growth of the city in the West forest area.

In an example in Figure 17 both urban densification and urban sprawl in the Southeast and Northeast regions are considered. Strong warming effect and moderate impact on the surroundings could be demonstrated.

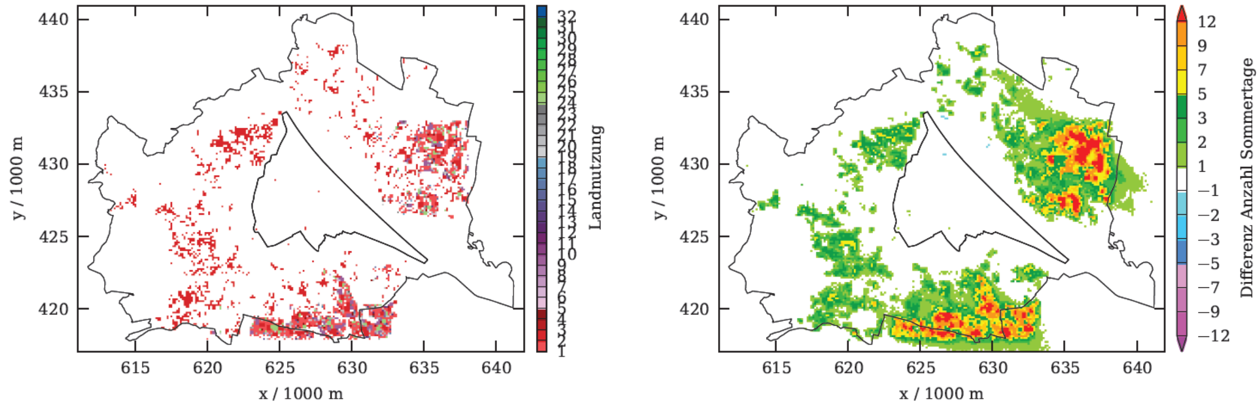


Figure 17 Modified land use (left) and difference in mean annual number of summer days (right) compared to the reference simulation in the experiment with hypothetic growth of the city in South-East and North-East rural areas combined with an increase in building fraction for existing low-density built-up areas.

As opposed to the extensive green infrastructure, we simulated the possibility of extreme urbanization where all agricultural areas have been modified into a virtual city (Figure 18). The modelling results show large expansion of the UHI and spreading of the heat load on surrounding areas.

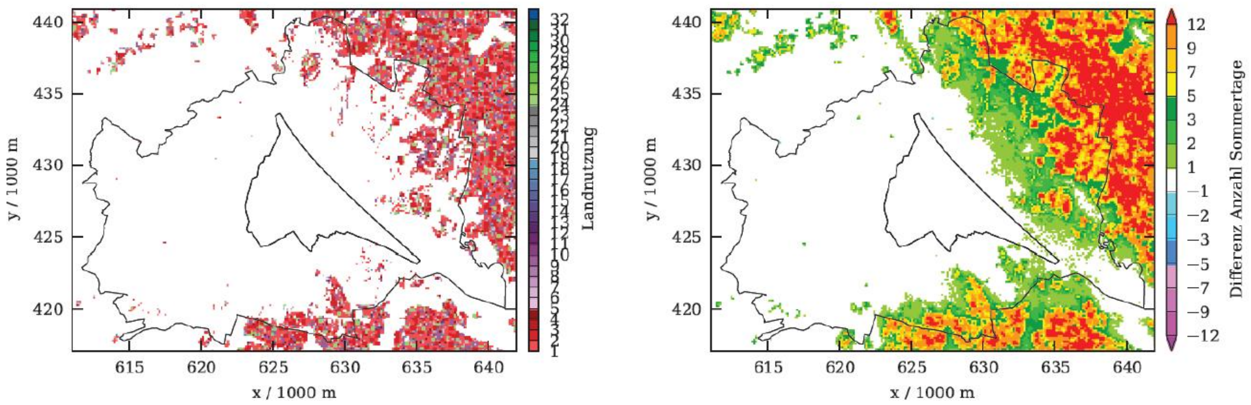


Figure 18 Modified land use (left) and difference in mean annual number of summer days (right) compared to the reference simulation in the experiment where agricultural areas have been modified into urban areas.

4 Schlussfolgerungen und Empfehlungen

Conclusions

- Based on the urban climate modelling simulations and on-site measurement campaign, critical areas with excessive heat load in Vienna were mapped. The inner city of Vienna, surrounding densely built districts, streets and industrial and residential areas in the flat terrain have been identified as particularly hot zones during daytime in the summer period.

- The existing meteorological monitoring network and available observational data base in Vienna should be enlarged for appropriate assessment of atmospheric processes on the urban scale. Further investment in urban climate model development is necessary as well. Additional measurement campaigns in urban environment and corresponding development of modelling methods would contribute to a better understanding of processes on urban scale delivering reliable and accurate meteorological fine-scale information.

- Future climate projections for Vienna based on downscaled regional climate scenarios indicate further increase in heat load in the next decades. Minor to moderate increase is expected by the middle of the 21st century (climatic period 2021–2050) and strong increase by the end of the century (climatic period 2071–2100) in comparison with the reference climatic period 1971–2000.

- Large uncertainties in the future climate signal are found. Previous climate studies for Vienna employing statistical and dynamical downscaling method (Formayer et al., 2008; Zuvela-Aloise et al., 2011) indicated similar temporal development. However, analysis was based on a single global-to-regional model dataset (regional: REMO, COSMO-CLM, global: ECHAM5) and the possible span of warming trends was unknown. New experiments point out a much wider range of possible future climates with large deviations especially in the first half of the 21st century.

- The divergence between the future climates signals mostly originate from the regional climate data used in the analysis. Moreover, the differences in future climate signal between different regional modelling setups (spatial resolution, choice of the global model and different initialization) are often larger than the expected differences between the different emission scenarios. These results point out large temporal variability of the local climate and further progress in reduction of uncertainties in downscaling technique from global to regional scale need to be achieved prior to appropriate quantification of the future climate signal on a local scale.

- Modelling experiments related to urban planning strategies show that adaptation measures should be applied to a large extent in order to reach substantial reduction in urban heat load on a city scale. For example, random increase in green areas of 10% yields to mostly local and limited cooling effects. On the other hand, roof albedo increase from 0.2 to 0.7, if applied to all build-up areas, leads to strong cooling.

- If only particular areas are considered, the adaptation measures could be optimized through targeted and combined implementation. With minor, but joint application of several adaptation measures (decrease in building density and pavement, enlargement in green and water surfaces, albedo increase), it is possible to achieve substantial cooling effect in critical areas, which could partly compensate the expected climate warming.

- Modelling results show that same adaptation measure might have different effects on different locations due to influence of topography, prevailing atmospheric circulation and characteristics of the immediate environment. Neighbouring surfaces could amplify or damp the efficiency in heat reduction and the efficiency of the mitigation strategy could non-linearly depend on the size of the applied area. As an example, fragmentation of modified areas could bring limited local effects, while agglomeration of areas could lead to possible intensification. Therefore, for a designated urban planning project it is recommended to conduct a specialized study in order to appropriately quantify the expected results, rather than using standard values or defining parameters for integration into urban planning policies.

• Analysis of long-term urban development (comparison of land use distribution in Vienna at the end of the 18th century, current land use survey and future urbanization trends) and modelling experiments showing consequent expansion of areas with excessive urban heat load emphasize the importance of implementation of adaptation measures in urban planning and necessity of sustainable urban development in order to ensure life-quality for the city inhabitants in the future.

Recommendations

Application of dynamical urban climate model on climatological scales and urban meteorology in general, is a new and emerging field of research requiring significant development of modelling methods and tools as well as appropriate data acquisition. Due to the important role of cities within the climate change problematic, urban climate is becoming especially relevant and further research investment is justified by multiple benefits and direct applicability of the research findings. During the project execution new aspects of urban climate in Vienna and development requirements were brought to attention and can be recommended for further investigation. The research topics for future development concerning urban climate count:

- necessary model development to provide reliable and robust numerical solutions in order to benefit from a broader scope of applications regarding different temporal scale and meteorological variables (minimum temperature, relative humidity, wind, radiation) in urban environment. The reduction of model uncertainties is achievable through accurate input data, improved model dynamics and consistent validation of results.

- enlargement of the meteorological monitoring network and organization of additional adaptive observing campaigns to provide an observational database for modelling applications. The measurement methodology does not need to be limited to standard observational networks, but novel low-cost measurement systems and potential of mobile technologies for data acquisition should be considered.

- coupling of the urban climate modelling results with other indices related to human comfort for example evaluation of nocturnal cooling and bio-climatological factors and risk assessment related to population distribution.

- definition of temperature thresholds and climate risk assessment relevant for urban infrastructure and operational systems (buildings, traffic, energy, cooling systems).

- comparison of modelling results for different city case studies, analysis of alternative urban climate modelling approaches and the added value of the downscaling technique.

- integration of specific urban designs in modelling setup and further sensitivity studies in cooperation with city administration and urban planners for envisaged urban planning projects

- dissemination of results especially by education of young professionals in fields of climate impact research and urban planning

- rising awareness in problems related to heat hazards, climate change and urban climate among public and institutional stakeholders

The project was intended to provide a climatological base relevant for urban planning. Dissemination of results for city administration of Vienna particularly the department of urban planning and development was included in the project plan and will be considered in future urban planning programs for Vienna. Except the city administration, other organisations and groups of professionals, which are involved in strategic planning of urban infrastructure and climate risk assessment related to heat hazards can use and benefit from the project results. These groups include architects, medicinal and tourist organisations and professionals in energy, mobility and educational sectors.

C) Projektdetails

5 Methodik

Input data

Land use and elevation

Topography data for Austria are provided by BEV (Bundesamt für Eich- und Vermessungswesen) digital elevation model (DGM) with 50 m resolution. Land use data from two sources with different quality have been combined. The low resolution, satellite-based ARCSYS land use data set for Austria is provided by the Austrian Institute of Technology (AIT) (Steinnocher, 1996). This dataset is used as background information on which a higher resolution data provided by the city administration of Vienna for urban development and planning (MA18) have been superimposed. The input data differentiate between 32 types of land use divided into three main categories: built-up areas, traffic and vegetation including water (Figure 19).

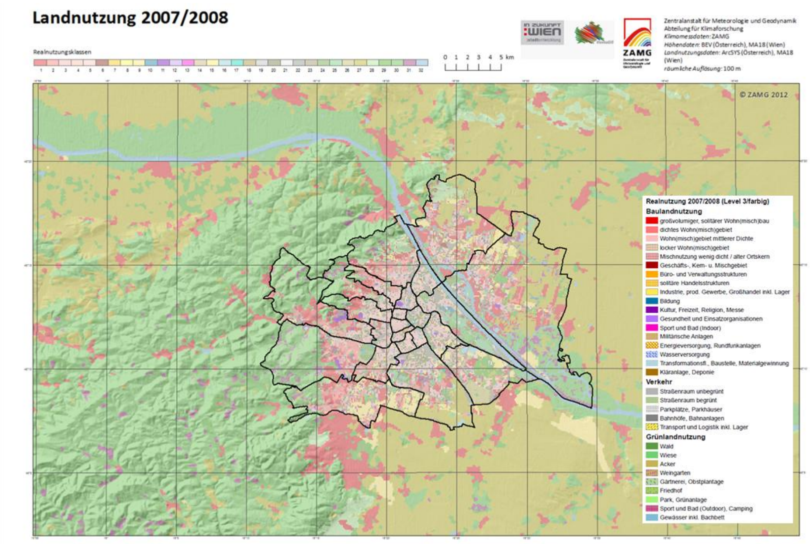
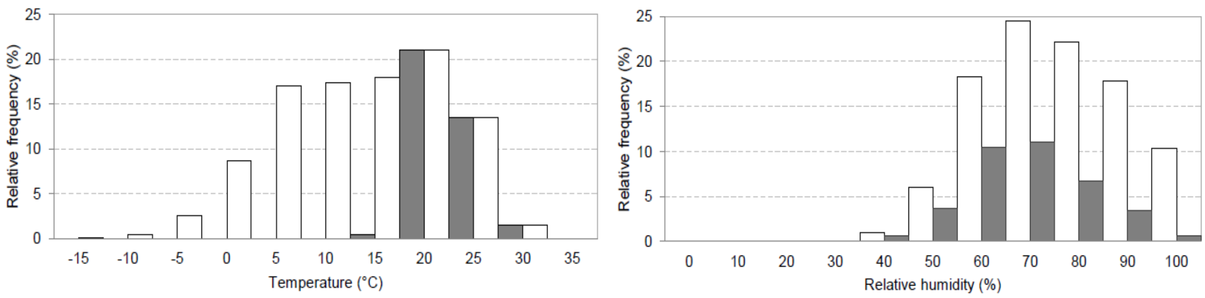


Figure 19 Land use map of Vienna and its surroundings provided by the city administration of Vienna (MA18) and combined with satellite based data from Austrian Institute of Technology (Steinnocher, 1996).

Climate data

Observational climatological data are used as input to derive the reference model simulation. Time series of mean daily temperature, relative humidity and wind speed, including hourly wind direction from the reference monitoring station for the time period 1961–2010 are used as meteorological data to calculate climatic indices (Figure 20). The monitoring station Groß Enzersdorf located in rural environment eastward of Vienna was chosen as representative for the background climate.



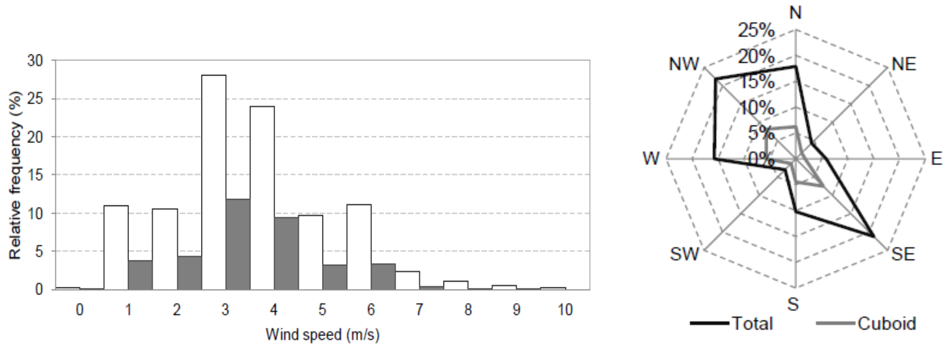


Figure 20 Frequency distribution of daily mean temperature, relative humidity, wind speed and wind direction at 14 CET for the period 1981–2010 at the reference station Groß Enzersdorf. Values in grey indicate range used in the “cuboid method” (T≥15°C).

A set of regional climate model simulations has been selected for the analysis of the future climate signal in Vienna and its surroundings. An overview of regional climate models used in the study is given in Table 4.

Table 4 Overview of regional climate simulations covering Austria.

Projekt	Modell (Institut-RCM-GCM)	Auflösung	ERA 40	C20	A1B	B1	A2
ENSEMBLES	C4I-RCA4-HadCM3 Q16	25 km	x	x	x		
	DMI-HIRHAM5-ECHAM5 r3		x	x	x		
	DMI-HIRHAM5-Arpege			x	x		
	ETHZ-CLM3.21-HadCM3 Q0		x	x	x		
	HC-HadRM3 Q0-HadCM3 Q0		x	x	x		
	HC-HadRM3 Q3-HadCM3 Q3		x	x	x		
	HC-HadRM3 Q16-HadCM3 Q16		x	x	x		
	KNMI-RACMO2-ECHAM5 r3		x	x	x		
	MPI-M-REMO-HadCM3 Q0		x	x	x		
	SMHI-RCA3-HadCM3 Q3			x	x		
	SMHI-RCA3-MPI-MET			x	x		
	SMHI-RCA3-BCM			x	x		
CONSORTIUM RUNS	CCLM-Com-CCLM-ECHAM5 r1	18 km		x	x	x	
	CCLM-Com-CCLM-ECHAM5 r2			x	x	x	
	CCLM-Com-CCLM-ECHAM5 r3			x			
UBA-BFG	MPI-MET-REMO_ECHAM5	10 km		x	x	x	x
RECLIP	ZAMG-WEGC-CCLM-ECHAM5 r2	10 km	x	x	x	x	

Definition of model parameters

Additionally to land use and topography data, available laser-scan and GIS data from Vienna city administration and AIT have been used to estimate realistic values for the land use parameters. For each grid point the fraction and/or mean height of pavement, buildings, trees (≥ 3.5 m) and low vegetation (0.1 – 3.5 m) has been calculated. An example for fraction of pavement is given in Figure 21.

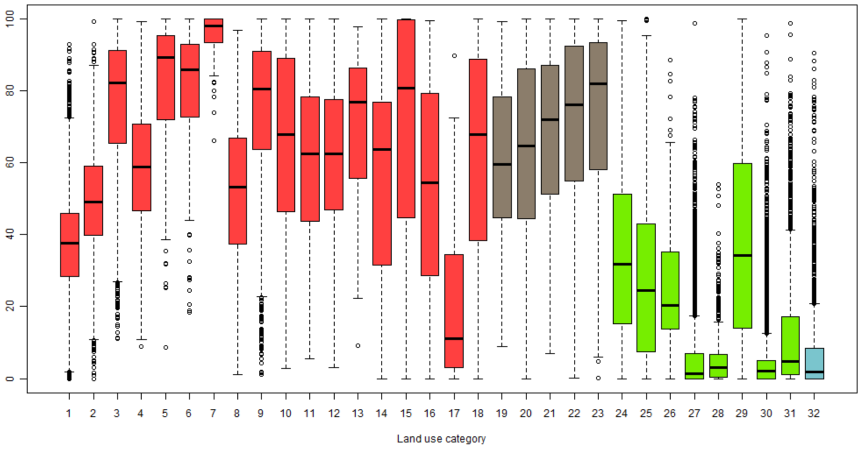


Figure 21 Fraction of pavement calculated on 100 m resolution model grid and evaluated for each land use category (data source: AIT).

For each land use category, a set of model parameters is defined relevant to describe urban structures. The parameters include fraction of built area, building height, wall area index, fraction of pavement, roughness length, fraction of tree cover, fraction of canopy layer vegetation cover, height and leaf area density of canopy layer as well as mean height and leaf area index of tree trunk and tree crown area. Model parameters were estimated from mean values for each land use class. An example of selected parameters is given in Table 5.

Table 5 Characteristic parameters for selected land use classes: fraction of built area (vg), mean building height (h), fraction of pavement (vsx), fraction of tree cover (sbm) and height of canopy layer (hca).

Land use class		vg (%)	h (m)	vsx (%)	sbm (%)	hca (m)
1	low-density built areas	0.16	5	0.21	0.00	0.5
2	medium dense built areas	0.22	8	0.27	0.00	0.5
3	high-density built areas	0.30	15	0.38	0.00	0.4
6	solitary buildings	0.34	9	0.46	0.00	0.4
9	industry	0.15	8	0.44	0.00	0.4
20	streets	0.00	0	0.63	0.22	0.5
22	railways	0.14	7	0.57	0.00	0.5
24	park	0.00	0	0.25	0.28	0.4
30	forest	0.00	0	0.00	0.90	1.0
32	water	0.00	0	0.08	0.13	0.6

Modelling approach

The study employed the method developed at the German Weather Service (DWD) which combines dynamical modelling of the atmospheric conditions in the urban environment with the urban climate model MUKLIMO_3 (3D Mikroskaliges Urbanes KLImaMOdell; Sievers et al, 1983; Sievers and Zdunkowski, 1986; Sievers, 1995) and the so-called "cuboid method" (Früh et al., 2010).

The model domain covered an area of 31 km x 24 km with a horizontal resolution of 100 m. The vertical grid consisted of 39 unequally spaced levels from the surface to the model top at 1 km. The vertical resolution varied from 10 to 100 m with denser grid spacing near the surface. The initial and boundary conditions were given by a time-varying 1D profile of atmospheric conditions representative for a station outside of the city. The model simulates the daily cycle of temperature, wind, relative humidity and energy fluxes in urban area for potential situations where a summer day (Tmax≥25°C) in the city centre could occur.

Results for maximum temperature from eight idealized simulations for two prevailing wind directions (Northwest and Southeast) are used as a base for the standard temperature distribution in the urban area. Calculation of mean annual number of summer days for 30-year climatic periods is performed using the “cuboid method”: a tri-linear interpolation between the 8 single-day simulations of temperature maximum given the atmospheric conditions from the reference station. The “cuboid” axes ranged: 15°C to 25°C for temperature, 40% to 80% for relative humidity and 0.7 m/s to 4 m/s for wind speed (Figure 22).

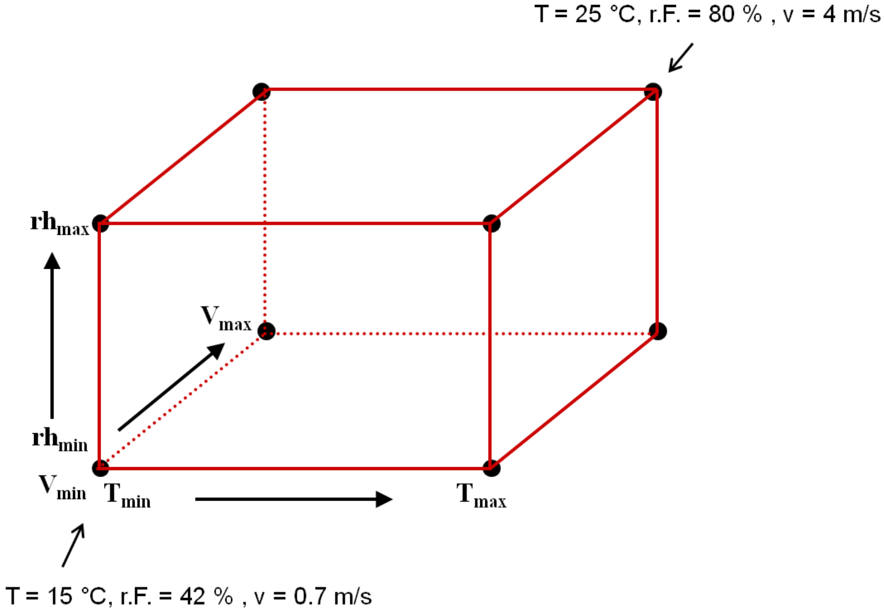


Figure 22 Illustration of the “cuboid method” (Früh et al., 2010). The cuboid corners represent 8 modelling simulations and define the range for mean daily temperature, relative humidity and wind speed at the reference station in situations where a summer day in the city centre can occur.

The future climate scenarios are calculated using input data from an ensemble of regional climate models in place of observational data. The sensitivity experiments were performed by varying land use distribution and model parameters to account for the possible changes in the urban structure.

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6 Arbeits- und Zeitplan

Presentation of the final work and time schedule

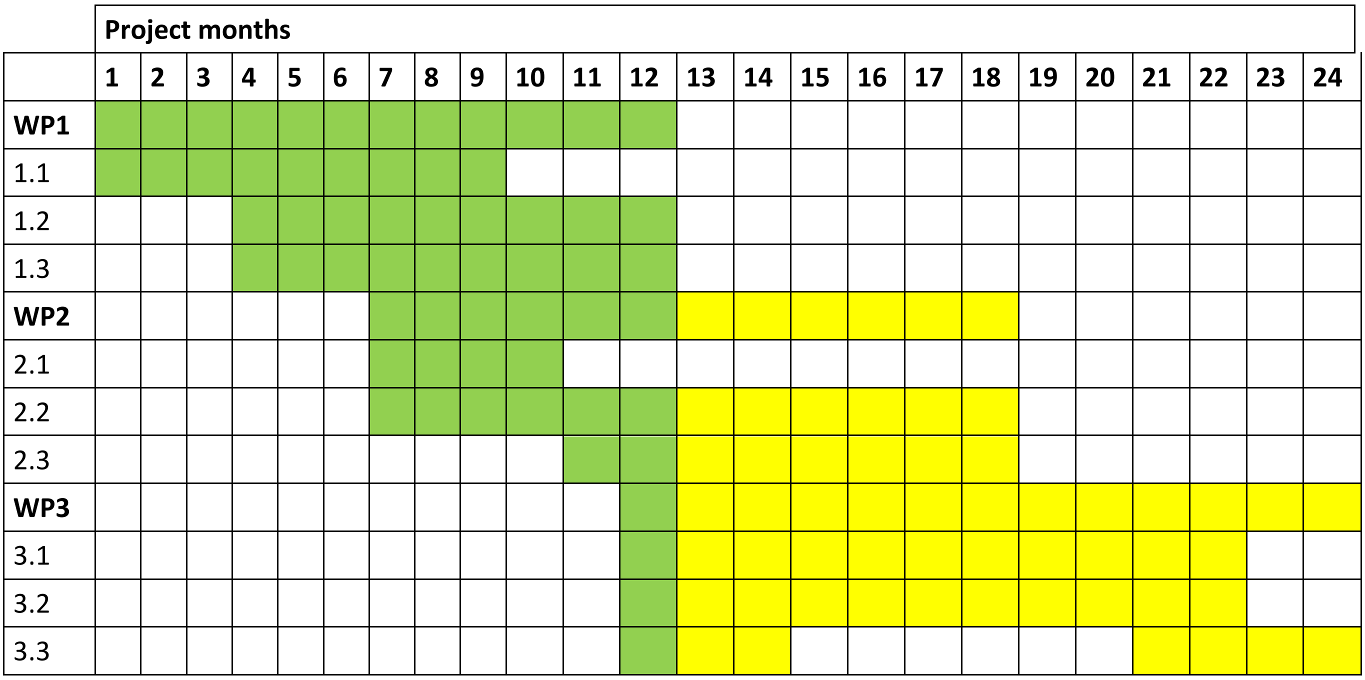

Figure 23 Project work plan. Green boxes indicate tasks completed within the first reporting period.

Work Package 1. Establishment of the needed co-operations; preparation of the input data

1.1 Establishing a partnership with the city administration providing land use and elevation data; exchange of know-how regarding urban climate modelling with DWD

1.2 Preparation of observational climate datasets, allocation and retrieval of data from the regional climate models

1.3 Definition and preparation of model input data (cooperation with DWD)

Work Package 2. Setup of the urban climate model, conduction of reference simulation and validation of results

2.1 Definition of model parameters (cooperation with DWD and city administration)

2.2 Urban climate model simulations based on observational background data (cooperation with DWD)

2.3 Validation of model results

Work Package 3. Derivation of future urban climate scenarios, sensitivity experiments and impact assessment

3.1 Conducting the model runs with regional climate input data for future climate projections

3.2 Implementing available urban planning strategies in model setup

3.3 Presentation of model results (cooperation with DWD) to the city administration and to the public institutions

7 Publikationen und Disseminierungsaktivitäten

Publications

Žuvela-Aloise, M. and R. Koch: Evaluating efficiency of climate change adaptation strategies in urban planning using an urban climate model, *Climatic Change*, in progress (Winter 2013/2014)

Žuvela-Aloise, M., Koch R., Neureiter, A. and R. Böhm (2013): Reconstructing urban climate of Vienna based on historical maps dating to the early instrumental period, *Urban Climate*, submitted

Žuvela-Aloise M., Koch R. und B. Chimani (2013): Hitzegefahr: Städte im Klimawandel (Cities in Climate Change). In: *smart city: Wiener Know-How aus Wissenschaft und Forschung*. Schmid Verlag, Wien, 2013, ISBN: 978-3-900607-50-0, 234 – 240.

Žuvela-Aloise M, Nemec J. and B. Früh, 2012. Dynamical modelling of urban climate of Vienna, *Proceedings ICUC8 – 8th International Conference on Urban Climates*, 6th-10th August, 2012, UCD, Dublin Ireland.- extended abstract

Conference contributions:

Zuvela-Aloise M., Früh B, Matulla C, Böhm R, 2011. Urban climate model of Vienna - a sensitivity study. EMS Annual Meeting Abstracts, Vol. 8, EMS2011-366-1, 11th EMS / 10th ECAM, Berlin, Germany

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Koch R., Zuvela-Aloise M.: Modellierung der Wärmebelastung im Stadtgebiet von Wien. In: *9. Deutsche Klimatagung.* Albert-Ludwigs-Universität, Freiburg, 09.10-12.10.2012. (PDF-Datei; 3,9MB)

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Koch R. and Žuvela-Aloise M.: Numerical simulations of urban heat island mitigation strategies in Vienna. In: *EGU General Assembly 2013*. Wien, Österreich, 07.04–12.04.2013. (PDF-Datei; 34 KB)

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Dissemination

Workshops and meetings have been organized to discuss and disseminate the project results. This included urban climate modelling workshops with researchers from the DWD:

- 17–18 August, 2011, ZAMG, Vienna
- 14–15 November, 2012, DWD, Offenbach
- 10–11 June, 2013, ZAMG, Vienna

Presentation of the results to the city administration and representatives from research institutions involved in urban climate and climate change adaptation strategies:

- 29 March, 2011, MA18, Vienna – project presentation
- 27 November, 2012, ZAMG, Vienna
- 5 June, 2013, MA18, Vienna
- 24 September, 2013, MD KLI, Vienna - scheduled

The project description is available online on the ZAMG website:
http://www.zamg.ac.at/cms/de/forschung/klima/stadtklima/focus-i

Several contributions have been intended for broader community:

- Nemec J. und Zuvela-Aloise M.: Temperaturunterschiede in der Stadt – Stadtklima der Zukunft in Wien, 21.02.2012, Vortrags- und Diskussionsveranstaltung der Gruppe "bewusst.nachhaltig" der Agenda 21 plus, Wien Alsergrund
- Böhm R. und Zuvela-Aloise M.: Klimawandel: Ursachen – Tatsachen – Erwartungen mit Schwerpunkt: Stadtklima“, 29.03.2012, Vortrag zu Ringvorlesung Ökologie, TU Wien
- Zuvela-Aloise M. und Nemec J.: Klimawandel: Ursachen – Tatsachen – Erwartungen mit Schwerpunkt: Stadtklima“, 25.04.2013, Vortrag zu Ringvorlesung Ökologie, TU Wien

and public media:

- radio interviews (Ö1, Kronehit)
- APA press release 18.06.2013 Hitzewelle - Viele kleine Parks könnten in Wien große Wirkung haben (cited in: Die Presse, Standard, Kurrier, Österreich, Kronen Zeitung)
- TV (W24)
- internet (orf.science: Wien ist sehr unterschiedlich heiß)