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Numerical Simulation of Urban Heat Islands – Evaluation of Simulation Results by Thermal Measurements

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Abstract

Urban development, including urban surfaces, vegetation, and water bodies, influence the urban climate in various ways. In addition to the geometric features of the built environment, material properties such as thermal storage capacity and the radiative behavior of roofs, facades, and transportation infrastructure significantly impact the local climate and the formation of heat islands.

Climate simulations are well established and scientifically recognized for predicting thermal conditions by means of thermal-hygro-energetic room and building simulations and urban and environmental climate simulations. However, numerical simulations regularly raise questions regarding their predictive potential and the accuracy of the results.

This article focuses particularly on the approach of evaluating simulation results using different climatic parameters (air temperature, wind speed, surface temperature). The measurements are taken both in-situ and remotely sensed using drones.

By comparing the simulation results with the measurements, the input parameters of the simulation can be refined. This enables the development of reliable forecasts to assess the effectiveness of additional green infrastructures, such as green roofs and facades, in reducing the urban heat island effect. Based on these insights, suitable adaptation strategies can be planned to make cities more resilient to increasingly intense heat waves.

Introduction

The local climatic effects of urban development are summarized under the term "urban heat islands" (UHI). Climate change is increasing the frequency of overheating and extreme weather events. Buildings influence the urban climate in many different ways. In addition to geometric conditions, material properties such as thermal storage capacity and the radiative behavior of street surfaces, roofs, and facades also impact the local climate. The question remains as to what extent and in what combination these parameters contribute to urban heat islands. Furthermore, it has not been conclusively determined where and to what extent vegetation and water bodies can have the greatest positive influence on the local climate.

In an ongoing research project, climate forecasts are being developed using urban simulation models with the ENVI-met program. These prognosis aim to provide reliable recommendations for integrated and climate-adapted urban planning to prevent the development of an urban heat island or reduce its intensity. The goal is to enhance the quality of life in cities. Accurate input data are essential for reliable simulation results, and these results should be evaluated with real-world data to adjust the simulation parameters if necessary.

Heat islands and remote sensing

Due to the negative effects of heat islands on urban populations, research into urban microclimates has increased in recent years (Graça et al., 2022; Yang et al., 2023). Initial studies examined the relationships between population density and heat island intensity, temperature differences between urban and surrounding areas, and dependencies on local boundary conditions (Hupfer et al., 2005; Kuttler, 2004). Current studies focus on strategies and measures for adapting to and mitigating the effects of climate change on cities (Qi et al., 2020; Carter, 2015).

Remote sensing in construction (Debus & Mellenthin Filardo, 2021) and urban areas has also been gaining importance for years (Ahmad & Eisma, 2023; Brunn & Wilch, 2022; Brunn & Meyer, 2016). Some research projects investigate urban heat islands using both remote sensing and simulation techniques (Bechtel, 2015; Heldens & Heiden, 2012; Heldens et al., 2017; Leichtle et al., 2023). The SmaCiSe project by the Institute for Sustainable Technologies (AEE INTEC, 2021) is notable in this context. These studies analyzed and evaluated data from satellite and airborne images, concluding that urban heat islands can be characterized from low Earth orbit and that reflection spectral data from urban surfaces can be integrated into climate simulations (Heldens & Heiden, 2012). The main challenges in such investigations include data availability and the spatial and temporal resolution of the data (Leichtle et al., 2023).

Methodology

To accurately predict the climatic effects of urban planning decisions aimed at reducing overheating, numerical simulations are conducted in combination with drone-based input data. Geometric and material input data are precisely recorded using photogrammetric and hyperspectral drone images. These data, along with meteorological information and the properties of trees, plants, and other vegetation, are merged into a holistic ENVI-met model.

Furthermore, the simulation results of the existing urban situation (case 1: reference model) are evaluated using real climate measurements. Figure 1 illustrates the methodological approach of integrating drone-based data acquisition with urban climate simulations using ENVI-met.

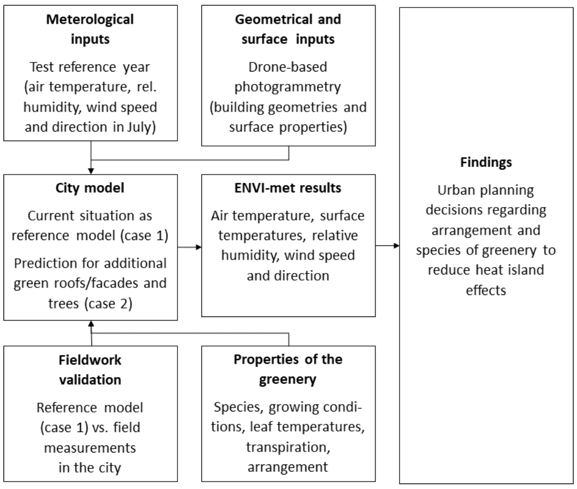

Figure 1: Methodological approach of combining drone-based data acquisition and evaluation with urban climate simulations using ENVI-met.

Measurements conducted during a heatwave in the summer of 2023 and their comparison with thermal simulation results in the cities of Meiningen (Thuringia) and Würzburg (Bavaria) are presented below. These cities exhibit similarities in architectural features and urban characteristics, including structural design, share of impervious surfaces, parks, and water bodies. This targeted selection of cities provides a robust and validated basis for the input parameters in the ENVI-met simulation program. For example, Figure 2 shows the market square in Meiningen's city center.

Figure 2: View of the market square in Meiningen (Thuringia, Germany). Stone surfaces dominate both on the ground and in the surrounding buildings.

In addition to ground-based measurements, thermal data were recorded and evaluated using a drone equipped with a thermographic camera. Subsequently, the geometric data recorded by the drone (Figure 3) were transferred to the ENVI-met numerical simulation program and processed within a microclimatic 3D model to predict the behavior of urban heat islands. The model-process integrates point cloud interpretation, image classification through deep-learning algorithms and spectral analyses, mapping the urban space in three dimensions and capturing the material properties of surfaces (facade, roof, road, and path surfaces).

Figure 3: Drone-based 3D image of the geometric (left) and thermal data (right) of the market square in Meiningen (Thuringia, Germany).

The climate forecast generated from the simulation can then be evaluated against real measurement data from the drone-based thermographic recordings. With the evaluated simulation model, it is possible to more accurately predict the development of the urban climate, allowing for optimized urban space through greening and other measures.

Measurements

The evaluation of simulation results should involve comparing measured and simulated values of air temperature within the city section, as well as the surface temperature of the examined facade. Figure 4 depicts the ground-based measurement points within the city. Data loggers from testo and Ahlborn were employed to collect the data. These measured values can then be juxtaposed with the simulated values extracted from the model's grid cells.

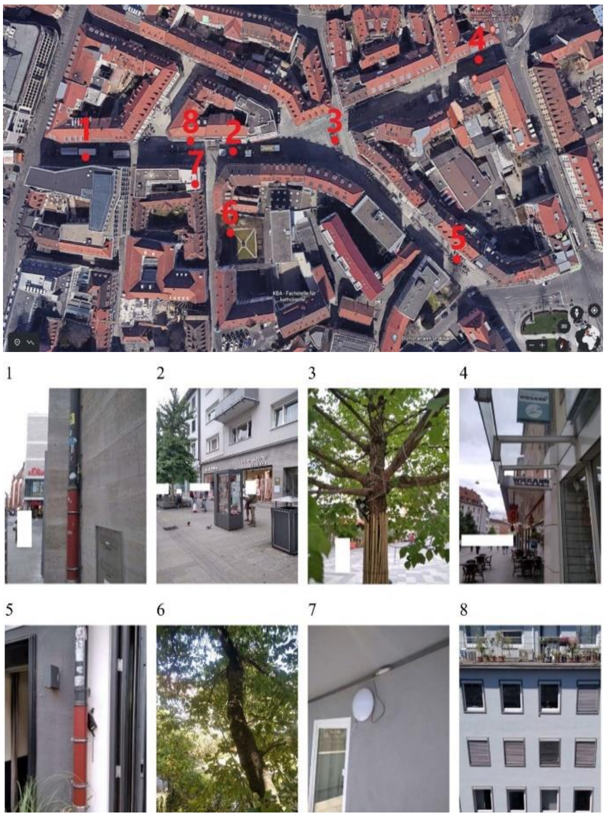

Figure 4: Ground-based measurements of air temperature, relative humidity and wind speed at selected measuring points in the city center

Figure 5 presents an aerial image of the facades on the market square in Meiningen. A DJI Matrice 300 RTK drone, equipped with an optical camera and a DJI Zenmuse H20T thermographic sensor, was utilized for this purpose.

Figure 6 illustrates the nocturnal cooling of the facade surface between 8:30 p.m. and 4:00 a.m. (measuring point 8 in Figure 4). Ground-based measurements, taken from the roof terrace of the opposing building, indicate a cooling of approximately 9 K for the reference point.

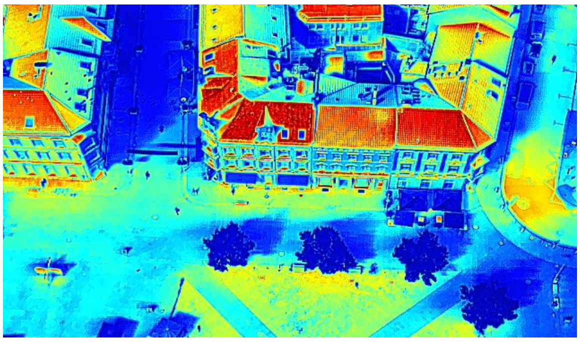

Figure 5: Airborne thermographic measurement of the market square in Meiningen. The image is oriented north-south, clearly recognizable by the high surface temperatures of the south-facing sloping roof surfaces.

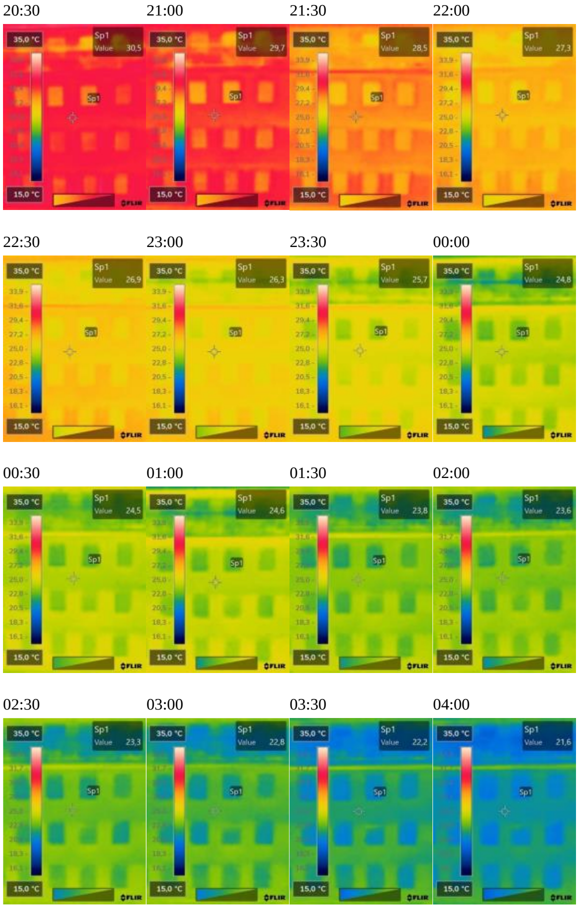

Figure 6: Thermographic images of a house facade taken every 30 minutes from 8:30 pm to 4:00 am. Overnight, there is a decrease in surface temperature of approximately 9 K at the reference point.

Simulation

The microclimatic simulation of sections of the city centers of Würzburg and Meiningen was conducted using the ENVI-met program (version 5.1.1). This software facilitates the prediction, analysis, and visualization of urban microclimatic conditions, incorporating parameters such as air and surface temperature, humidity, wind, and radiation. The microclimatic model is founded on fundamental principles of fluid mechanics, thermodynamics, and atmospheric physics, comprehensively considering interactions between facades, street surfaces, vegetation, emission sources and the air.

Geometric city models were derived from drone-based photogrammetry data, while general climate data were sourced from measurements by weather stations in Würzburg and Meiningen. To enhance computational efficiency, a horizontal resolution of 3 m × 3 m was adopted for the simulated model area, corresponding to 58 × 63 grid cells horizontally (i.e., a city section of approximately 174 m x 189 m). The vertical extent of the model was constrained to 15 cells, each 3 m high. Given the significance of surface temperatures in the lowest three meters, the resolution of the lower layer of grid cells was increased, with reduced vertical resolution above the buildings to optimize computation time. The resulting three-dimensional model comprises nearly 60,000 cells, evaluated hourly over the entire 48-hour simulation period.

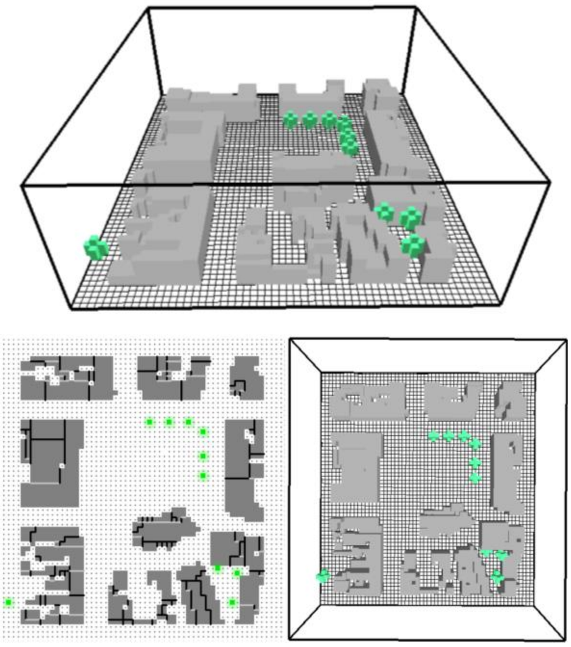

Figure 7: 3D model of the market square in Meiningen (oriented north-south). The horizontal resolution of 58 x 63 grid cells with the dimensions 3 m x 3 m and a vertical resolution of 15 cells and 3 m per cell results in a model with 60,000 cells.

In both cities, Würzburg and Meiningen, the majority of buildings in the inner city area date from the 19th and 20th centuries, leading to assumptions of uninsulated building fabric made of solid materials, likely various mineral bricks. Brick walls were presumed for modeling, with facades treated as completely closed and existing windows excluded from climatic analysis. Emissions from morning delivery traffic in the city center were disregarded. Physical parameters used in the simulation, including albedo, emissivity and surface roughness, are listed in Table 1.

Table 1: Summary of surface information.

Type	**Albedo [-]**	**Emissivity [-]**	**Roughness Lenght [m]**
Soil	0,20	0,95	0,015
Asphalt Road	0,20	0,90	0,010
Gravel	0,20	0,90	0,010
Concrete Pavement	0,35	0,90	0,010
Facade	0,50	0,90	0,020
Roof Tile (sloped)	0,20	0,90	0,020
Roof Surface (flat)	0,20	0,90	0,020
Green Roof	0,20	0,70	0,020

The models did not account for the topography of the urban areas studied, as the terrain slope in both cities consistently remains less than 1%, exerting a negligible influence on the microclimate. Vegetation in the urban areas under investigation is limited to a few trees and small green areas. Existing trees displayed insignificant variations and were in the simulation represented by a fictitious tree model corresponding to a young maple, with characteristics including its deciduous nature, seasonal foliage, a height of 6.50 meters and a crown diameter of 5 meters.

Under the described boundary conditions, temperatures for the surfaces of facades surrounding the market square were predicted, as illustrated in Figure 8.

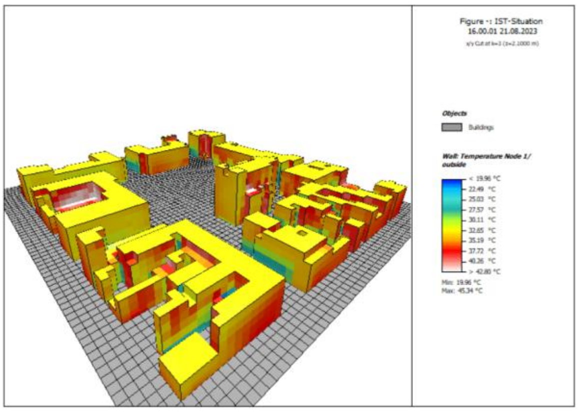

Figure 8: Representation of the surface temperatures of the facades in the downtown area in the simulation model.

Results of the comparison between measurement and simulation

The comparison between measured values on-site and simulation results revealed good agreement, particularly concerning temperatures. This alignment was notable, especially in the comparison of overnight decrease in facade surface temperature (Fig. 9). Similarly, air temperatures exhibited good agreement. Conversely, the concordance for relative humidity and air velocity was poor.

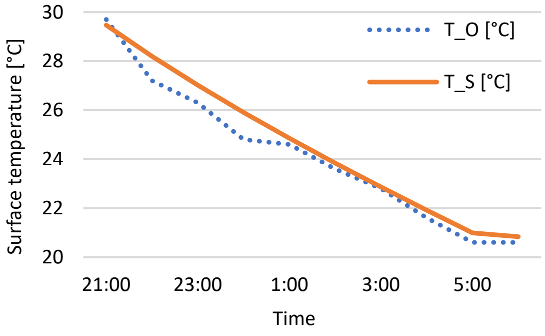

Figure 9: Cooling of the façade overnight. Comparison of the measured T_O (blue) and simulated T_S (orange) façade surface temperatures between 21:00 in the evening and 5:00 in the morning

The accuracy of simulation results compared to real measurements at the listed measuring points (as depicted in Figure 4 below) was evaluated through statistical analysis of the model. Table 2 presents statistical metrics, including the coefficient of determination (R^2), the Willmott index of agreement (d), the root mean square error (RMSE), and the mean absolute error (MAE) for air temperature across various measurement points. It is worth noting that deviations observed at measuring point 2 (as shown in Figure 4) stemmed from placing the data logger on a very hot metal surface which was not considered in the simulation due to its small size.

Table 3: Statistical validation of the simulation results with real climate measurements with (i) as the in-situ measuring points as depicted in Figure 4.

i	R^2 [-]	d [-]	RMSE [°C]	MAE [°C]
1	0.922	0.935	2.004	1.743
2	0.844	0.812	4.361	3.093
3	0.937	0.948	1.864	1.580
4	0.927	0.954	1.895	1.679
5	0.950	0.947	1.791	1.331
6	0.922	0.888	2.894	2.387
7	0.917	0.914	2.468	1.969

Summary and outlook

In conclusion, the integration of drone-based data acquisition into the ENVI-met simulation program yields a high level of agreement in predicting urban climate conditions. Initial findings from the ongoing research project indicate the program's capability to accurately predict climate conditions in cities. Evaluation of results from reference models against real climate measurements demonstrates a strong agreement, particularly regarding predicted surface temperatures.

In addition to geometric data, valuable supplementary parameters such as surface temperatures and material properties can be captured using drone flights. The integration of a hyperspectral sensor in the research project's future phases aims to enhance this capability. Moreover, numerical investigations into heat mitigation measures are planned. These measures will form the basis for forecasts regarding the efficacy of certain greening interventions, such as additional trees, green roofs and facades, utilizing the evaluated simulation models of existing scenarios.

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