Evaluation of High-Resolution Simulation of the Urban Heat Island in Vienna, Austria

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1 ABSTRACT

The recently developed microscale model for urban applications PALM-4U was used to simulate the thermal variability in Vienna on different spatial scales and to evaluate its ability to capture thermal characteristics in real urban environment.

The model simulations cover the entire city of Vienna with a spatial resolution of 20 m. The static data related to geographical information and urban infrastructure are based on GIS data provided by the city administration of Vienna, available as spatial multi-purpose maps (Flächen-Mehrzweckkarte - FMZK), street tree cadastre, Digital Elevation Model and Digital Surface Model, which were combined with the national land cover data (Land Information System Austria - LISA) to account for the unresolved vegetation and Open Street Map to include building properties in the surrounding region (Lower Austria) of the model domain. The simulations were performed for a selected clear-sky hot day in August 2022.

The results for hourly air temperature were evaluated with conventional weather stations of the national weather service and the city of Vienna and with quality-controlled data from citizen weather stations from the company NETATMO. The results show high intra-urban variability during daytime, but distinct spatial patterns at night with higher air temperatures in urban regions. In addition, spatial patterns of surface temperature were compared to remote sensing data from ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and with the modelling results from previous studies, but with coarser grid spacing (e.g. urban climate model MUKLIMO_3 with 100 m spatial resolution).

The results indicate that the microscale model PALM-4U shows general agreement with observations and is able to simulate atmospheric processes in urban regions. However, during the night a strong temperature inversion is present in the model, which can be related to the choice of model configuration and requires further investigations. The spatial patterns in urban-rural temperature gradient are similar as found in coarser scale model simulations and remote-sensing data, but show higher variation in surface temperature amplitude.

Keywords: surface temperature, climate modelling, urban heat island, simulation, palm-4u

2 INTRODUCTION

Due to the modified energy balance in built-up environment, urban areas are generally warmer than their surroundings (e.g. Oke, 2019; Oke et al., 2017), an effect known as the Urban Heat Island (UHI), or Surface Urban Heat Island (SUHI), when surface temperatures are considered. Building materials often have low reflectivity, high heat capacity and thermal conductivity, which enhances the absorption of solar radiation during the day and the excess heat is being slowly released during the night. Especially in densely built areas, with lack of vegetation and appropriate ventilation, the heat is being trapped in street canyons. Large water surfaces and green areas, usually provide regulating function in reducing the temperature extremes, through evaporative cooling and enhanced ventilation, in case of water, and shading, in case of trees. However, diversified relief, land use and land cover of cities, as well as characteristics of built-up structures, make the distribution of urban temperatures spatially inhomogeneous. Mapping of areas with extreme heat or cool zones and understanding the development of UHI became an important issue in urban planning in order to protect the beneficial natural areas, decrease the impact of existing and avoid generation of new hot-spots through further urban development.

As a measure to reduce negative aspects of urban climate, the City of Vienna developed an UHI strategic plan (UHI MA22, 2015) including a number of urban planning measures for buildings and open spaces, particularly measures based on green infrastructure. The strategic plan was based on various data sources and climate studies assessing urban climate of Vienna (e.g. Schwab&Steinicke, 2003; Zuvela-Aloise et al. 2013; Stiles et al., 2014). Additional heat vulnerability map of Vienna was published in 2019 based on the thermal infrared sensor from Landsat 8 with a spatial resolution of 100 m, which was used to derive a weighted average surface temperature for Vienna, covering the years 2015 to 2019 and combined with information on distribution of vulnerable age classes and a vegetation index (Bhattacharjee, 2019). An updated urban climate analysis map was provided in 2020 based on a GIS procedure and illustrates thermal characteristics, but also the cold air flow during the night. All studies of urban climate in Vienna indicate higher heat load in the densely built urban centre and lower temperatures in forested areas westward and along the river Danube. However, detection and exact localization of hot-spots, as well as selection of appropriate measures to reduce the UHI effect remained an issue. Various background data, spatial resolution and different mapping techniques lead to uncertainties in resulting urban heat maps.

One of the main tools for analysing UHI development are the urban climate models that take into account both urban morphology and meteorological data and can be used for climate assessment, as well as for evaluation of urban planning measures and spatial development plans. Newly developed urban microclimate model PALM-4U (Maronga et al. 2020) allows simulation of entire cities with a very high-resolution enabling detection of small-scale temperature variations on a building-scale. However, the model has not been tested yet in various urban environments and an evaluation of model performance is needed to quantify possible uncertainties.

In this study the urban climate model PALM-4U was applied to simulate the UHI in Vienna with grid-resolved building and vegetation canopy on a spatial resolution of 20 m. The simulations are compared to existing modelling simulations with the MUKLIMO_3 model used in previous studies (Hollosi et al. 2021; Zuvela-Aloise et al., 2022) and observational data. The modelled surface temperature was compared with the remote sensing data from ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and the near-ground air temperature was evaluated against monitoring data from citizen weather stations.

3 DATA AND METHODS

3.1 Urban climate simulations

The open-source modelling system PALM (PArallelized Large-Eddy Simulation Model) with recently developed additional modules for urban boundary layer (PALM-4U) is a new modelling tool for high spatial resolution simulations of urban environment based on the large-eddy simulation (LES) technique (Raasch and Schröter, 2001; Maronga et al., 2015; 2020). In this study, the PALM-4U model was applied for the city of Vienna to evaluate the model performance and was compared with the established modelling approach based on urban climate model MUKLIMO_3 (Sievers, 2016). In comparison to PALM-4U, the MUKLIMO_3 model uses RANS-type turbulence parametrization, parametrization of buildings and land use based on a tile approach and has typically a lower spatial resolution (20 - 100 m). The simulations were performed for August, 16-17, 2022, as a representative hot day with clear-sky conditions. The models were initialized at 06:00 UTC with the initial vertical profiles of meteorological variables from the AROME numerical weather forecast model in operation by GeoSphere Austria.

Both models use information on terrain, land use and land cover, building and vegetation properties, however, in different format and spatial detail. In case of the PALM-4U model, the static information was provided from Digital Elevation Model and Digital Surface Model for the City of Vienna and Lower Austria, land cover data from Land Information System Austria (LISA), Open Street Map, street tree cadastre (Baumkataster) and spatial multi-purpose maps (Flächen-Mehrzweckkarte - FMZK) of the City of Vienna. The spatial information was prepared in a raster format with 20 m spatial resolution according to Heldens et al. (2020). In case of the MUKLIMO_3 model raster data with 100 m spatial resolution were provided for terrain height, land use types based on Copernicus Urban Atlas enriched with LISA land cover data, building height, wall area index of buildings, building density, tree cover and proportion of sealed surfaces based on High-Resolution Layers of Copernicus Land Monitoring Services.

3.2 Observational temperature data

The standard meteorological monitoring network in Vienna includes about a dozen of official semi-automatic weather stations, so-called TAWES stations, and additional environmental monitoring stations employed by the city administration departments (MA22). In order to evaluate the modelling results with high spatial resolution, a higher density of monitoring stations is needed. For this purpose, the monitoring data from a network of over 1000 private weather stations available in Vienna provided by the company NETATMO was used. To minimize the uncertainty associated with the non-standardized temperature measurements, a statistical quality control as proposed in Napoly et al. (2018) was applied. As previous studies for Vienna have shown (Hammerberg et al. 2018, Feichtinger et al. 2020), a rigorous quality control which detects outstanding temperature observations, can help to reduce sources of errors and the data can be used to investigate the intra-urban air temperature variations.

The remote sensing data for surface temperature were provided by ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission. The ECOSTRESS Land Surface Temperature and Emissivity Daily L2 Global 70m V001 dataset (Hook & Hulley, 2019), which is part of the ECO2LSTE Version 1 data product providing atmospherically corrected land surface temperature and emissivity (LST&E) values derived from five thermal infrared bands including layers of LST, emissivity for bands 1 through 5, quality control for LST&E, LST error, emissivity error for bands 1 through 5, wideband emissivity and Precipitable Water Vapor were used. The dataset has a spatial resolution of about 70 m. In this study, the LST and corresponding quality control data for LST layers available for August 16, 2022 were considered. A short overview of data used in model validation is shown in Table 1.

	MUKLIMO_3	**PALM-4U**	**ECOSTRESS**	**NETATMO**
Type of data	RANS microscale model output	LES microscale model output	satellite imagery	private weather stations
Spatial resolution	100 m	20 m	70 m	over 1000 stations with quality-controlled data
Time output	hourly	hourly	snapshot	30-min to hourly
Air temperature	reference at 2 m, defined vertical model levels	reference at 2 m, defined vertical model levels	not available	variable
Surface temperature	temperature of soil, streets, building roofs and top of vegetation (trees)	temperature of soil, streets, building roofs and the soil under the vegetation (trees)	temperature of surface visible by satellite (excluding clouds)	not available

Table 1: Overview of meteorological data used in the study.

4 RESULTS

The observational data for air temperature based on quality-controlled measurements from NETATMO private weather stations show distinct pattern of the UHI island in Vienna during the night. Higher temperatures are found in the city centre and lower temperatures in the surroundings (Fig. 1). The model results show similar large-scale pattern, however, small-scale variation in temperature and temperature inversion with height are more pronounced in the PALM-4U model compared to the model with lower spatial resolution (MUKLIMO_3).

The spatial patterns in surface temperatures based on remote sensing (Fig. 2), show an urban-rural temperature gradient as well, with higher temperatures found in built-up areas and lower temperatures in forested areas and near water. However, agricultural areas in south and east show high surface temperatures during the day as well. This effect is most likely caused by high exposure of low vegetation and free soil to solar radiation and low soil moisture during the heat wave and is well captured by the models. The PALM-4U model overestimates the surface temperatures in urban areas, which can be partially explained by variations in temperatures due to the higher model resolution, but requires further investigation.

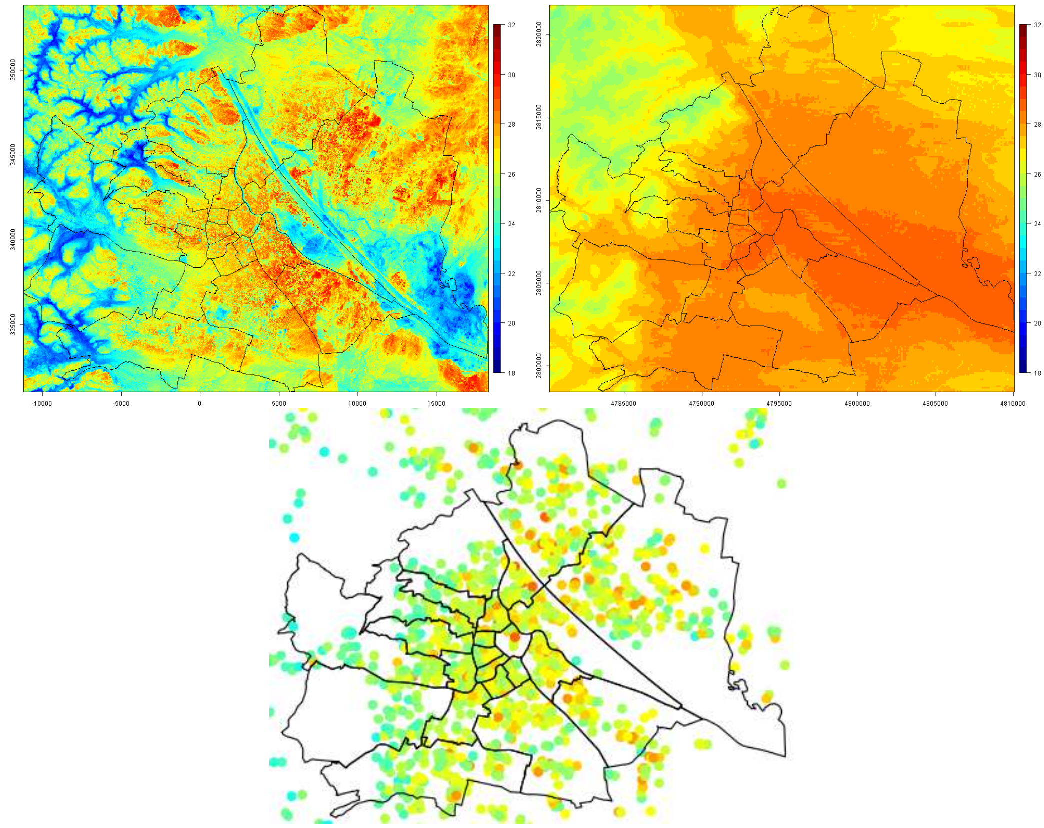

Fig. 1: Air temperature (°C) in Vienna on 16. August 2022 at 19:00 UTC calculated by PALM-4U model (top left), MUKLIMO_3 model (top right) and derived from quality-controlled monitoring dataset of NETATMO private weather stations (bottom).

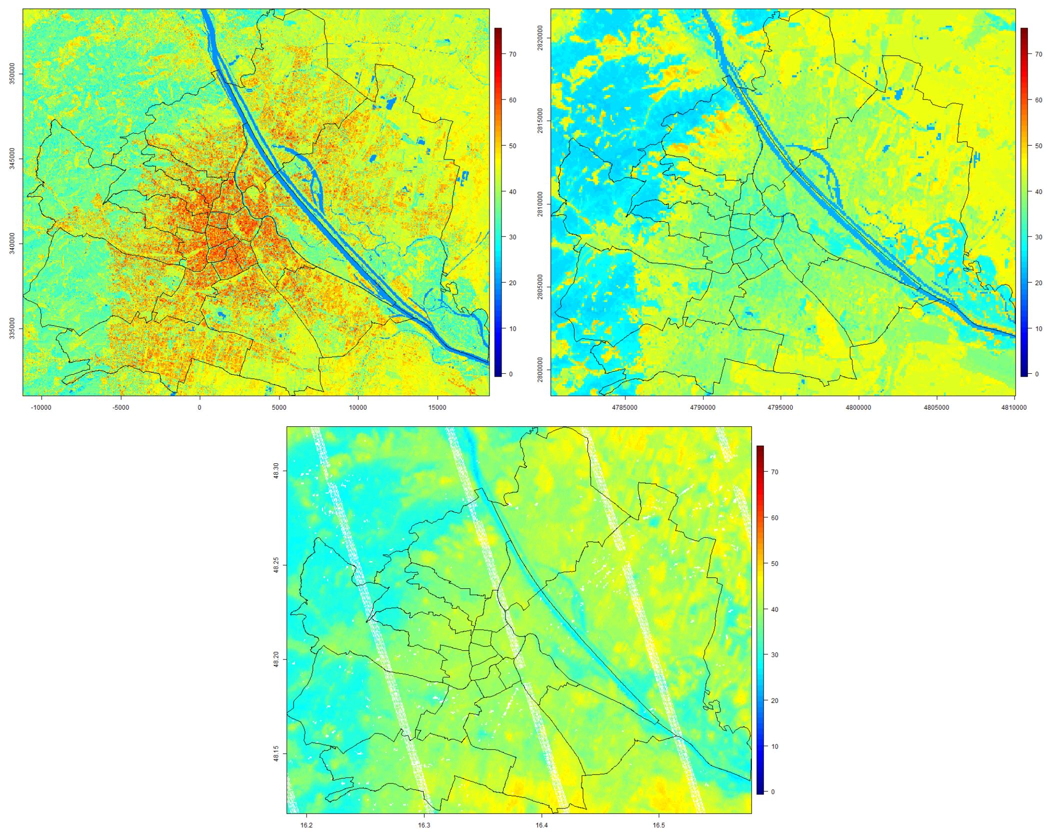

Fig. 2: Surface temperature (°C) in Vienna on 16. August 2022 at 12:00 UTC derived by PALM-4U model (top left), MUKLIMO_3 model (top right) and provided by ECOSTRESS (ECO2LSTE.001, day: 228; time: 11:38:39 UTC) remote sensing dataset (bottom).

5 CONCLUSION

This study investigated the perfomance of the PALM-4U model to simulate the development of the UHI in Vienna during summer conditions. By using models with higher resolution, small-scale processes such as turbulence, shading by buildings and vegetation, interaction between the atmosphere and urban surfaces and building materials are better represented. Increasing the model resolution enables more detailed analysis of inner-city temperature variations and allows detection of additional heat or cool zones in the city. The modelled spatial distribution of near surface air temperature and surface temperature was compared with observational data and lower resolution model results from existing studies.

The results of the PALM-4U model show typical spatial variations of urban heat with higher temperatures in built-up areas and lower temperatures in surroundings, particularly forest and water areas, which is found in previous studies and can be confirmed by observational data. The spatial distribution is different during the day and night-time. The UHI effect is more pronounced during the night, while during the day high local variations in temperatures are found.

When comparing the modelled air temperatures with measurements from NETATMO citizen weather stations, the PALM-4U model shows higher spatial variations than the MUKLIMO_3 model. Large temperature variations are also found in the observational dataset during the day. However, the correlation between the PALM-4U model and observations is not necessarily higher than the MUKLIMO_3 model. The reason is that the temperature variations in the NETATMO dataset during the day are probably related to the specific positioning of stations and influence of local factor such as shading, exposure to radiation and viscinity of buildings which could not be filtered out during the quality control completely.

At night, the spatial patterns between the models and NETATMO temperature measurements are more similar. It indicates that the strong small-scale variation diminishes and the NETATMO temperature measurements become more representative for a larger area. However, a strong temperature inversion during the night is found in the PALM-4U model, which can be related to the choice of model configuration and needs further investigation.

Comparison of ECOSTRESS LST remote sensing data with PALM-4U model simulations shows higher variability in modelled surface temperature than observed, which is partially related to higher spatial resolution of the model. The forest areas are warmer than observed. However, the results can not be directly compared since the model output reflects the surface soil level under the trees, rather than tree tops as observed by the remote sensing. While agricultural areas are well represented by the model, the built-up areas, i.e. building roofs, show very high temperature values (> 60°C) that require further analysis.

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