Publizierbarer Endbericht

Gilt für Studien aus der Programmlinie Forschung

A) Projektdaten

Allgemeines zum Projekt	
Kurztitel:	LUCRETIA
Langtitel:	The role of Land Use Changes on the development of intra-urban heat islands
Zitiervorschlag:	
Programm inkl. Jahr:	ACRP11
Dauer:	01.09.2019 bis 31.08.2022
KoordinatorIn/ ProjekteinreicherIn:	Dr. DI Maja Zuvela-Aloise
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Projekt- und KooperationspartnerIn (inkl. Bundesland):	-
Schlagwörter:	Stadtklima, Landnutzung, Wärmeinseleffekt, Modellierung
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B) Projektübersicht

1 Kurzfassung

Landnutzung und Landbedeckung (LU/LC) spielen eine wichtige Rolle bei der Bestimmung lokaler Klimaeigenschaften und ihrer räumlichen Variabilität, insbesondere in städtischen Gebieten, kann zu starken Temperaturschwankungen des Mikroklimas führen. Diese Datensätze werden als Eingangsinformationen für Stadtklimamodelle verwendet, welche unter anderem die aktuellen und möglichen zukünftigen Klimaentwicklungen simulieren können, und dienen als solche als wichtige wissenschaftliche Grundlage in der Stadtplanung. Insbesondere sind sie relevant bei der Entwicklung von Strategien zur nachhaltigen Stadtentwicklung und Anpassung im Kontext des Klimawandels. Unterschiedliche Qualität, Detailierungsgrad und methodischer Einsatz von LU/LC-Datensätzen in Stadtklimamodellen führen jedoch zu Unsicherheiten in den Modellergebnissen.

Ziel des LUCRETIA Projektes war die Analyse der innerstädtischen Temperaturvariabilität auf Basis unterschiedlicher Stadtklimamodelle, so wie Crowdsourcing-Beobachtungsdaten. Ergänzend dazu wurden verschiedene bestehende LU/LC-Datenquellen analysiert und in Stadtklimamodellen integriert, um deren Auswirkungen und Einfluss auf Temperaturmuster in städtischen Gebieten zu bewerten und dadurch Unsicherheiten ermitteln zu können. Zusätzlich wurden historische LU/LC-Datensätze verwendet, um die Veränderungen in der Stadtstruktur zu analysieren und die langfristigen klimatischen Auswirkungen, die durch LU/LC-Modifikationen entstehen, mittels eines Stadtklimamodelles zu bewerten.

Um die Auswirkungen von LU/LC-Änderungen auf das Mikroklima zu quantifizieren, wurde die innerstädtische Temperaturvariabilität am Beispiel der Stadt Wien untersucht. Dazu wurden verschiedene LU/LC-Daten unterschiedlicher Qualität und räumlicher Details, wie z. B. Urban Atlas und CORINE Daten des Copernicus Land Monitoring Service der EU, die Daten und das Klassifizierungssystem der lokalen Klimazonen (LCZ) sowie lokale und nationale Daten zu LU/LC, die von Stadtverwaltungen oder nationalen Behörden bereitgestellt werden, herangezogen. Die Ergebnisse zeigen, dass, obwohl das räumliche Muster auf Stadtebene mit höheren Temperaturen in dichtem Stadtgebiet und niedrigeren Temperaturen in der umgebenden natürlichen Umgebung in den Modellergebnissen unabhängig von der Wahl des LU/LC-Datensatzes gut repräsentiert ist, die Unterschiede auf Bezirksebene groß sein können. Sie weisen lokal höhere oder niedrigere Werte für die Hitzebelastung auf, die mangels ausreichender Klimabeobachtungsdaten nicht verifiziert werden können. Eine Verfeinerung der LU/LC-Daten mit mehr räumlichen Details und die Integration zusätzlicher Informationen zu städtischen Strukturen, z. Gebäude- und Vegetationsdichte und -höhe, Versiegelungsgrad, führen zu konsistenteren räumlichen Mustern, unabhängig vom verwendeten LU/LC-Grunddatensatz oder Klassifizierungsschema.

Die Auswertung der Modellergebnisse zur innerstädtischen Variabilität der stündlichen Lufttemperaturen wurde für einen ausgewählten 3-Tages-Zeitraum während einer Hitzewelle im Jahr 2018 durchgeführt. Zwei Modellierungsansätze, das Stadtklimamodell MUKLIMO_3 (Sievers 2016) und das neu entwickelte PALM-4U-Modell (Maronga et al. 2020), wurden verglichen. Die Simulationen wurden auf Stadt- und Bezirksebene mit einer räumlichen Auflösung zwischen 10 m und 100 m durchgeführt. Die zur Auswertung der Modelle verwendeten Beobachtungsdaten umfassten Messungen von offiziellen

Wetterstationen sowie qualitätsgeprüfte Daten eines Netzwerks privater Wetterstationen der Firma NETATMO. Die Ergebnisse zeigten im Allgemeinen eine ähnliche Modellleistung, was bestätigt, dass beide Modelle für stadtklimatologische Anwendungen gut geeignet sind. Das hochauflösende PALM-4U-Modell ermöglichte jedoch eine detailliertere Analyse der innerstädtischen Temperaturschwankungen und eine bessere Identifizierung heißer/kühler Zonen in der Stadt. Eine bessere Übereinstimmung mit den Beobachtungsdaten aufgrund der höheren Modellauflösung konnte jedoch nicht bestätigt werden.

Die Analyse der LU/LC-Veränderungen anhand historischer Daten für Wien (1981–2005) und Graz (1952–2004) zeigte in beiden Städten eine fortschreitende Urbanisierung, insbesondere die Umwandlung von landwirtschaftlichen Flächen in Bau- und Verkehrsflächen. Die landwirtschaftlich genutzten Flächen gingen in den jeweiligen Zeiträumen in Wien um 5,3 % und in Graz um 18,9 % zurück. Die meisten Veränderungen betrafen Siedlungs- und Verkehrsflächen, die für Wien um rund 1,6 % bzw. 4,1 % und für Graz um 12,8 % bzw. 2,0 % zunahmen. Zudem verzeichneten beide Städte eine Zunahme der Waldflächen (+0,7 % in Wien und +2,9 % in Graz). Die Modellsimulationen mit historischen LU/LC-Daten bestätigen, dass sich die LU/LC-Veränderungen positiv oder negativ auf die Hitzebelastung auswirken können. Die Änderungen der Wärmebelastung sind lokal am stärksten, Erwärmungs- oder Abkühlungseffekte - mit geringerer Intensität und begrenzter räumlicher Ausdehnung - sind jedoch auch in der Umgebung zu finden.

Die Ergebnisse der Projekte verbesserten das aktuelle Verständnis von LU/LC-Veränderungen und deren Auswirkungen auf das Stadtklima in Wien und Graz. Diese Studie kann auch auf andere österreichische Städte ausgeweitet werden. Die aktuelle LU/LC-Daten, insbesondere historische LU/LC-Datensätze, reichen jedoch meistens nicht aus, um Modellsimulationen in ähnlicher Form durchzuführen. Es wird empfohlen, dass Stadtverwaltungen oder andere Behörden die LU/LC-Daten so genau wie möglich harmonisiert erheben, aktualisieren und bereitstellen, einschließlich der Archivierung zusätzlicher Parameter über städtische Strukturen, z. Gebäudegrundrisse und -höhe, Versiegelungsgrad, Vegetation, sowohl für städtische Gebiete als auch für deren Umgebung.

Obwohl die Bewertung der verschiedenen Modellierungsansätze und Sensitivitätssimulationen für verschiedene LU/LC-Eingabedaten dazu beigetragen haben, Unsicherheiten in den Modellierungsergebnissen zu reduzieren, wird weitere Modellentwicklung, insbesondere in Hinblick auf das PALM-4U-Modell empfohlen. Viele Merkmale des Modells, wie Nesting, dynamische Kopplung, agentenbasierte Modellierung, könnten weiter untersucht werden. Trotz der hohen Anzahl aktuell verfügbarer Messstationen in Wien (>1000, darunter private Wetterstationen) fehlt es noch an Beobachtungsnachweisen zur Bewertung hochauflösender Modellergebnisse. Dies gilt insbesondere für Quartiers- und Gebäudesimulationen mit räumlichen Auflösungen von 10 m oder höher. Unter den Haupteinschränkungen für die Bereitstellung einer soliden Beobachtungsdatenbank, wenn private Wetterstationen in Betracht gezogen werden, sind die Qualität, Verfügbarkeit und Zuverlässigkeit der Daten. Zusätzliche Messkampagnen können weiterhelfen, die Modellierungsergebnisse zu evaluieren. Die im Projekt gewonnenen Schlussfolgerungen wurden Stadtplaner*innen aus Wien und Graz präsentiert. Die Hauptergebnisse des Projektes wurden in Form eines Empfehlungskatalogs zusammengefasst. Diese Ergebnisse können als Orientierungshilfe für die Klimaanpassung in der zukünftigen Stadtplanung verwendet werden. Weitere Austausch und Zusammenarbeit mit den Städten ist geplant.

2 Executive Summary

Land use (LU) and land cover (LC) play an important role in determining local climate characteristics, and their spatial variability can result in large fluctuations in temperature, especially within urban areas. Among others, these data sets are used as input information for urban climate models, which simulate current and possible future climate conditions. The data from such simulations serve as an important scientific basis in urban planning, particularly to develop suitable strategies for climate adaptation and sustainable urban development in the context of climate change. However, these LU/LC data sets exhibit differences in quality, level of detail and type of integration which lead to varying results when input in urban climate models. The aim of the project was to improve the information available on intra-urban variability of temperature by comparing different LU/LC data sets, their usage in urban climate models and evaluating the results with observations from a dense monitoring network. Furthermore, historical LU/LC data sets were used to track changes in urban structure and in combination with climate models they provided insight into long-term climatic effects caused by LU/LC modifications.

In order to quantify the effects of LU/LC changes on the microclimate, the inner-city heat load variability was examined on an example of Vienna using various LU/LC data of different quality and spatial details, such as Urban Atlas and CORINE LC data from the EU Copernicus Land Monitoring Service, the Local Climate Zones (LCZ) data and classification scheme, as well as local and national data on LU/LC provided by city administrations or national agencies. The results show that, regardless of the source of LU/LC data, the city-scale spatial pattern with higher temperatures in dense urban areas and lower temperatures in the surrounding natural environment is well represented by the model. However, the size of the district-scale differences varies depending on the choice of the LU/LC data set. They display locally higher or lower heat load values that cannot be verified due to the lack of long-term climate monitoring data. However, refining the LU/LC data with more spatial detail and integrating additional information on urban structures, e.g. building and vegetation density and height, degree of sealing, leads to more consistent spatial patterns independent of the basic LU/LC data set or classification scheme in use.

The evaluation of model results on intra-urban variability of hourly air temperatures was performed for a selected 3-day period during a heat wave in 2018. Two modeling approaches, urban climate model MUKLIMO_3 (Sievers 2016) and the newly developed PALM-4U model (Maronga et al. 2020), were compared. The simulations were performed on a city and district scale with spatial resolution varying between 10 m and 100 m. The observational data used to evaluate the models included measurements from operational weather stations and quality-checked data from an online available network of private weather stations of the company NETATMO. The results showed generally similar model performance, confirming that both models are well suited for the urban climate applications. However, the higher-resolution PALM-4U model enabled a

more detailed analysis of inner-city temperature fluctuations and allowed a better identification of hot/cool zones in the city. Nevertheless, a better agreement with the observational data due to higher model resolution could not be confirmed.

The analysis of LU/LC changes based on historical data for Vienna (1981–2005) and Graz (1952–2004) showed progressive urbanization in both cities, in particular through the transformation of agricultural land into building and traffic areas. The area used for agriculture decreased by 5.3% in Vienna and 18.9% in Graz, in the respective periods. The majority of changes were related to built-up and traffic areas, which increased by around 1.6% and 4.1% for Vienna and 12.8% and 2.0% for Graz. In addition, both cities had an increase in the forest area (+0.7% in Vienna and +2.9% in Graz). The model simulations with historical LU data confirm that the changes in the LU/LC can have a positive or negative impact on the heat load. The changes in heat load are strongest locally, but warming or cooling effect can be found in the surrounding area, however with less intensity and with limited spatial extent.

The results of the projects improved the current understanding of LU/LC changes and their impact on urban climate in Vienna and Graz and the study could be extended for other Austrian cities as well. However, the current LU/LC database lacks sufficient historical LU/LC data sets to perform such analyses in a similar form. As a result of the project, it is recommended for city administrations or other agencies to compile, harmonize, update in regular intervals (e.g. every 5 years) and provide the LU/LC data as accurately as possible, including archiving of additional parameters about urban structures, e.g. building footprints and height, degree of sealing, vegetation, both for urban areas and their surroundings.

Although the evaluation of different modelling approaches and sensitivity simulations for diverse LU/LC input data helped reduce uncertainties in modelling results, further model development, especially regarding the PALM-4U model, is recommended as future work. Many features of the model, such as nesting, dynamical coupling, agent-based modelling, could be further explored.

Despite the very high number of currently available monitoring stations in Vienna (>1000, including private weather stations), there is still a lack of observational evidence to evaluate high-resolution model results. This is particularly valid for district and building-scale simulations on spatial resolutions of 10 m or higher. The main obstacles for providing a solid observational data base, when citizen weather stations are considered, are the quality, availability and reliability of data. Additional measurement campaigns can further help to evaluate the modelling results.

The conclusions derived in the project were presented to urban planners from Vienna and Graz. Model results were summarized as recommendations for urban planning in the form of a brochure. These results can be used for guidance in climate adaptation in the future urban planning. Further communication, continuing support and cooperation with cities is planned.

3 Hintergrund und Zielsetzung

LU/LC play an important role determining local climate characteristics and their spatial variability can result in large variations in microclimate, especially in urban areas. This influence is well illustrated by the Urban Heat Island (UHI) effect, where climate conditions in a built environment are notably different from the conditions in the surrounding rural areas, resulting in higher temperatures in urban areas (e.g. Oke, 1995). However, even within urban areas, variations in microclimate can be found due to the inhomogeneous urban fabric, e.g. different building density and height, percentage of soil sealing. Considering the importance of this information for urban planning, in recent years much effort has been spent on the development of accurate LU/LC data sets on local, national and international level. For example for the City of Vienna there are various data sources that can be used to provide LU/LC information (**Figure 1**): Urban Atlas and CORINE land cover data of the EU Copernicus Land Monitoring Service, the Local Climate Zones (LCZ) classification scheme supported by World Urban Database (WUDAPT) initiative (Stewart and Oke, 2012), Urban Standard Typologies (UST) developed by Green4Cities GmbH, as well as local land use mapping provided by the city administration and LC data from national agencies (e.g. LISA data set for Austria).

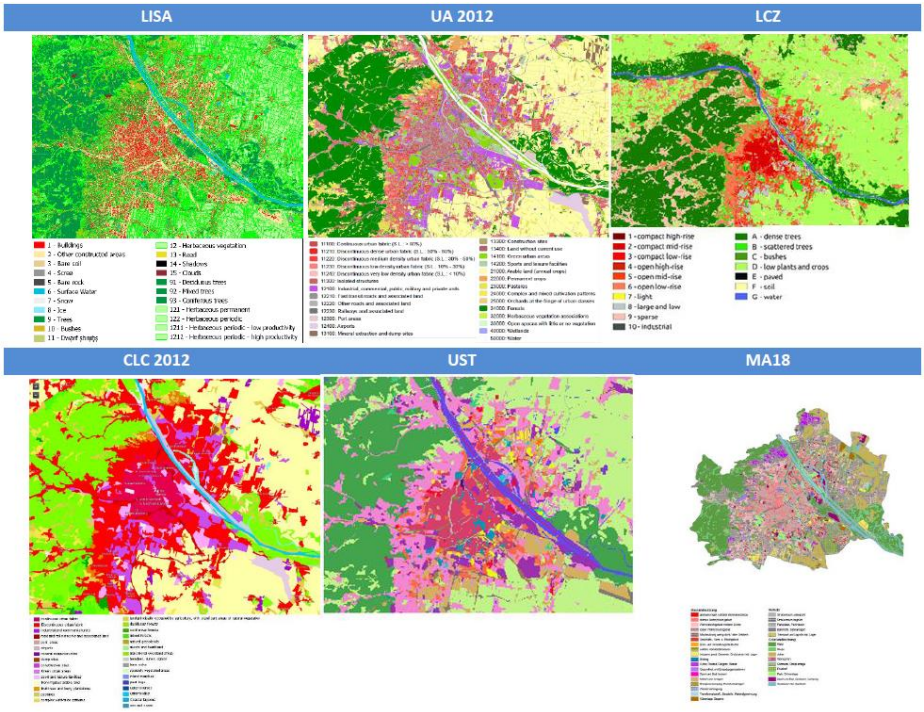


Figure 1: Different land use classifications on the example of Vienna: Very High Resolution (VHR) Land Cover Map of Vienna provided by Land Information System Austria (top left), Urban Atlas (top center), Local Climate Zone classification (top right), CORINE Land cover data set provided by the Copernicus Land Monitoring Service (bottom left), Urban Standard Typologies developed by green4cities GmbH (bottom center), local classification provided by the city administration of Vienna (MA18) (bottom right).

The LU/LC data, as well as information on urban climate derived from these data sets, are used in urban planning in the context of climate change and sustainable development. In order to provide climate information for city planners, such as high-resolution urban heat load maps, different numerical modelling approaches are employed that use LU/LC data as input for model simulations. Several of these data sets have been used in modelling approaches to investigate urban climate of Austrian cities (Žuvela-Aloise et al. 2016; Bokwa et al. 2018; Oswald et al. 2020; Reinwald et al. 2021). However, the uncertainties in resulting spatial patterns in urban heat load have not been investigated in detail. Recent developments in urban climate modelling and observational techniques have allowed for simulations and evaluation of local climate on even finer spatial scales than previously possible, facilitating better quantification of intra-urban variations in microclimate and their uncertainties.

While most of the urban climate research has focused on the current status or future developments, the historical information was often not available or not prioritized. However, the most convincing observational evidence of the impact of LU/LC on microclimate can be found by examining the past changes. This project aimed to provide new insight into historical LU/LC changes and their impact on urban climate. The resulting information can be further used to inform urban planners as well as general public about issues related to LU/LC and climate change and can help to speed-up or prioritize the implementation of developed climate adaptation strategies (e.g. BMNT, 2017; UHI-STRAT, 2015).

The following objectives were defined in the project:

Objective 1: To analyze different existing LU/LC information sources for selected Austrian cities in order to evaluate their impact and influence on air temperature patterns in urban areas and determine uncertainties arising from representations of land use information in different urban climate model applications.

Objective 2: To demonstrate the benefit of using quality-controlled crowd-sourced air temperature observations to capture the variability in microscale climate illustrated for an example of selected Austrian cities.

Objective 3: To analyze the intra-urban heat islands and variations in temperature patterns based on dense crowd-sourced monitoring networks and urban climate modelling tools for selected Austrian cities.

Objective 4: To investigate the effects of urbanization on air temperature patterns in urban areas and the relationship between LU/LC changes and development of intra-urban heat islands based on historical land use information.

Objective 5: To reconstruct the past urban climate for selected Austrian cities using historical LU/LC information and climate data as a new database to support evidence-based climate adaptation and urban planning.

4 Projektinhalt und Ergebnis(se)

The activities performed in the project are described per Work Package (WP) as illustrated in **Figure 2**.

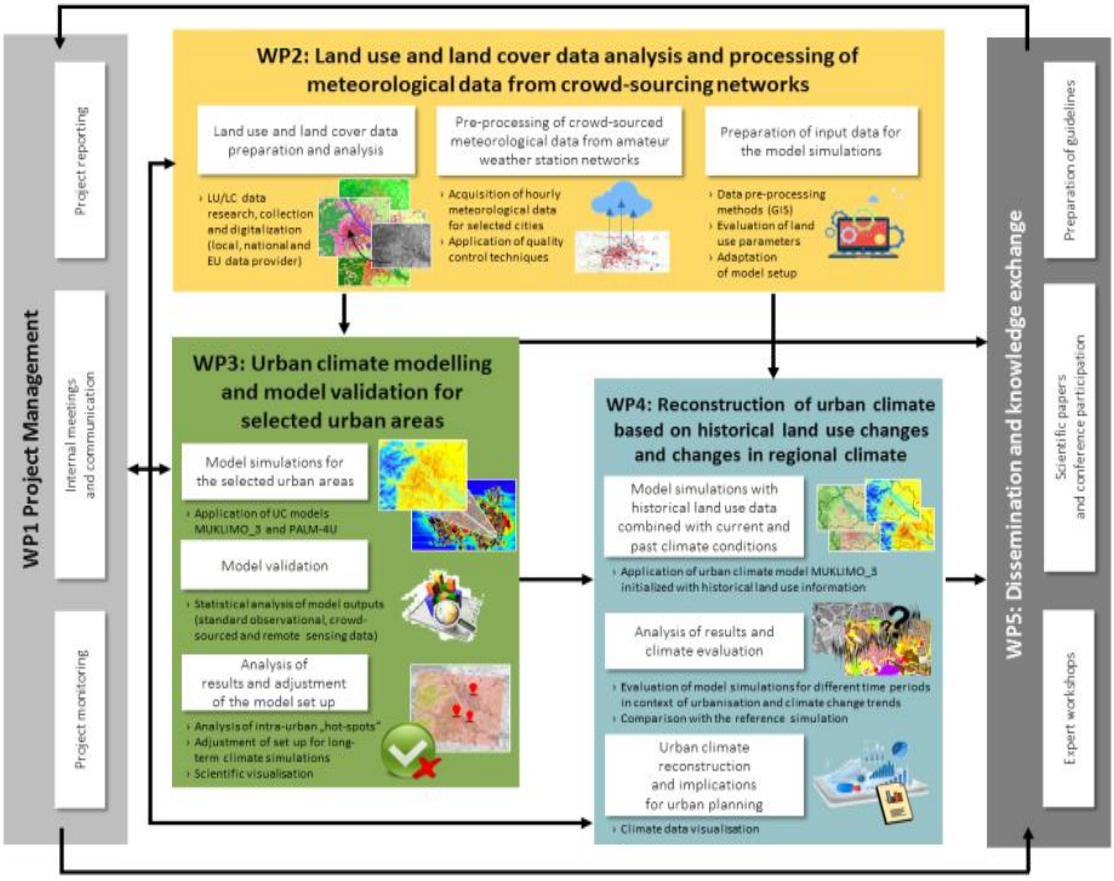


Figure 2: Work package scheme of the LUCRETIA project.

The **WP1 Project Management** handled coordination of project activities and all administrative tasks including organization of meetings and reporting. Therefore, it is not included in the description of project results.

The activities in this **WP5 Dissemination and knowledge exchange** were related to dissemination of project results, presentation at conferences, exchange of information with technical experts, discussions with stakeholders and publications. The activities are described in more detail in the next section C under Point 8.

WP2: Land use and land cover data analysis and processing of meteorological data from crowd-sourcing networks

The availability of current and historical LU/LC data was investigated through an online survey including Web-GIS portals from city administrations, national (e.g. LISA) and EU sources (Urban Atlas, CORINE, products of Copernicus Land Monitoring Service), internal ZAMG archive and outputs from previous projects. In addition, a questionnaire was sent to city administrations of the Austrian federal capitals (Vienna, Salzburg, Innsbruck, Klagenfurt, Graz, Linz, St. Pölten,

Eisenstadt, Bregenz) in which different departments took part. The information was collected not only for LU/LC data, but also for possible supplementary data related to buildings, pavement and vegetation. A short overview of available data is given in **Table 1**.

The compiled information showed that cities have very different approaches in collecting the LU/LC information and the data archives differ. Most of historical data is limited to aerial imagery and is available only for recent years as LU/LC information in digital format. Based on data availability, the cities of Vienna, Graz and Linz were selected for further analysis. However, even these data sets were not complete to cover all model input information and same historical periods. In the case of Linz, the historical data was available as city plan maps and the extraction of LU/LC typologies was not satisfactory. Therefore, it was not further used in the model analysis.

Table 1 Overview of current (2020) and historical LU/LC data available for Austrian federal capitals.

	Contact	**LU mapping**	**Historical orthophotos and air born imagery**
Linz	Amt für Planung Technik und Umwelt, Vermessung und Geoinformation	Vector data from 2008 Pixel data: 1742, 1802, 1863, 1876, 1887, 1910, 1926, 1945, 1962, 1976, 1990, 2003 and since2007 every year	1945, 1988, 1998, 2004, 2007, 2008, 2009, 2011, 2014, 2016, 2017, 2019
Bregenz	Amt für Planung und Bau, Umweltschutz	current	1998, 2001, 2005, 2009, 2012, 2015, 2018 digitalized orthophotos available from the Land Vorarlberg in a much lower resolution
Salzburg	Amt für Stadtplanung und Verkehr	current	1945, 1953, 1973, 1987, 1999, 2002, 2007, 2010, 2012, 2014
Wien	Stadt Wien Stadtvermessung (Magistratsabteilung 41)	Realnutzungskartierung Wien 1981, 1985, 1991, 1994, 1997 - MA 18* 2001, 2003, 2005 - OGD: 2007/2008, 2009, 2012, 1014 - OGD: 2016, 2018 - MA 18, Flächen-Mehrzweckkarte 2008-01, 2009-02, 2010-01, 2011-12, 2012-12, 2014-1, 2015-01, 2016-01, 2017-01, 2018-01 - MA 41	Luftbildplan 1938, 1956, 1970, 1980, 1990, Other years between 1956 and 1996 partially not available for the entire city or not in digital (but in analogue) form - MA 41, SW Orthofotos: 1996, 1999, 2001, 2003, 2005, 2007, 2008, 2009, 2010/2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019
Innsbruck	Raumplanung und Stadtentwicklung	on demand (only in case of an assignment)	Historical maps of Tirol (georeferenced): 1750, 1813, 1820, 1825, 1843, 1857, 1894, 1900, 1940

Klagenfurt	Abteilung Vermessung und Geoinformation	currently in change-over phase	currently in change-over phase
Graz	Stadtvermessungamt Graz	1944/45, 1952, 1968, 1975, 1984, 1990, 1997, 2004, 2007, 2011, 2015, 2019 (work in progress)	Orthophotos (non rectified): 1943*-1945*, 1952*, 1956*, 1957*, 1958*, 1959*, 1968*, 1975*, 1984*, 1989, 1992, 1993, 1996, 1999, 2000/I, 2000/II, 2004, 2007, 2009, 2011, 2014, 2015, 2018, 2019 | *limited right of use Orthophotos: 1952*, 1958*, 1959*, 1968*, 1975*, 1984*, 1996, 1999, 2000/I, 2000/II, 2004, 2007, 2009, 2011, 2015, 2018, 2019 | *limited right of use
St. Pölten	Geoinformation und GIS	DKM-Nutzungsflächen since 2002	1998, 2006, 2007, 2009, 2011, 2014, 2017
Eisenstadt	Landesplanung, Sicherheit, Gemeinden und Wirtschaft	since 28.1.2004 (to date)	

To investigate impact of LU/LC input data on current climate simulations, the LU/LC data for Vienna (**Figure 1**) were prepared in the form of raster layers at 100 m x 100 m. The LU/LC parameters (e.g. building density and height, soil sealing, tree cover) were prepared both in raster format and calculated for each LU/LC type in a table format in order to be used as input data for the MUKLIMO_3 urban climate model with two different methods. For the sensitivity study of different model resolution the input data for MUKLIMO_3 were prepared on a 40 m x 40 m grid for two selected regions: Vienna Inner City (**Figure 3**) and Hernals.

In case of urban climate simulations with the PALM-4U model, several data sources were combined to provide information on all necessary input parameters. These include Digital Elevation (DEM) and Surface Model (DSM) of the city of Vienna and Lower Austria, multi-purpose spatial maps of the City of Vienna (FMZK- Flächenmehrzweckkarte), LISA data set for Austria, Open Street Map and tree cadaster of the city of Vienna. The data were prepared as raster layers with different spatial resolutions: 20 m covering the city of Vienna and surroundings and 10 m for the selected subdomains Inner City and Hernals.

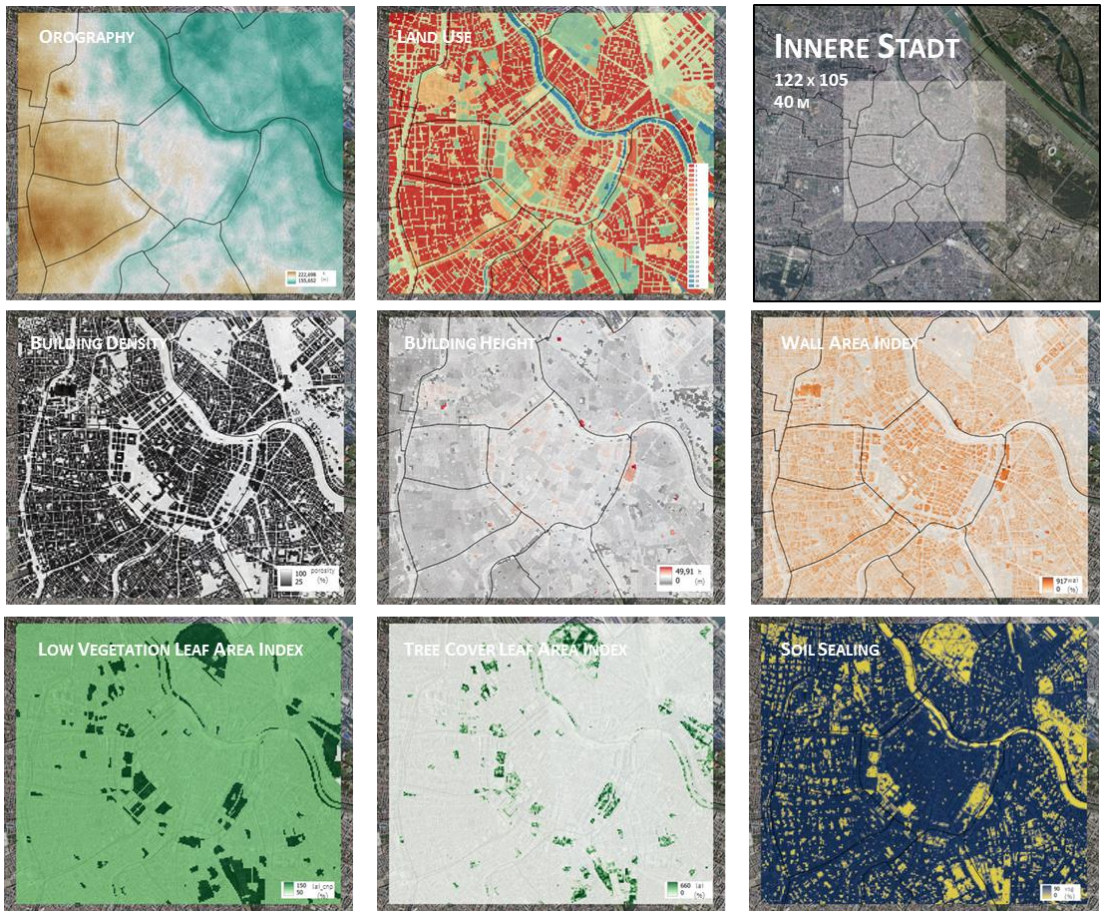


Figure 3: Input data for MUKLIMO_3 model on example of Vienna Inner City with 40 m spatial resolution. Data sources: Vienna GIS.

For the historical simulations, the LU/LC data for Vienna and Graz available in vector format were prepared in the form of raster layers at 100 m x 100 m spatial resolution. The LU/LC parameters (e.g. building density, soil sealing and tree cover) were calculated for each LU/LC type and prepared in a table format in order to be used as input data for the MUKLIMO_3 urban climate model. Since this information was only available for the current climate, the same parameter values were used for the historical simulations and only spatial modifications in LU/LC are therefore detected in model simulations. Historical data on LU/LC distribution were prepared for Graz for the years 1952, 1968, 1975, 1984, 1990, 1997 and 2004 and for Vienna for the years 1981, 1985, 1991, 1994, 1997, 2001, 2003 and 2005. These years were selected based on the availability of the LU/LC data with the identical classification method, which differs between the cities and has been modified throughout the years, which poses additional uncertainties in model results. **Figure 4** shows the land use for Graz in (a) 1952 and (b) 2004 with the outskirts of the city changing as land previously occupied by farms and agriculture (orange color) is converted to residential buildings (pink and red) and industry (purple). Vienna exhibits a similar change to its land use distribution (**Figure 5**).

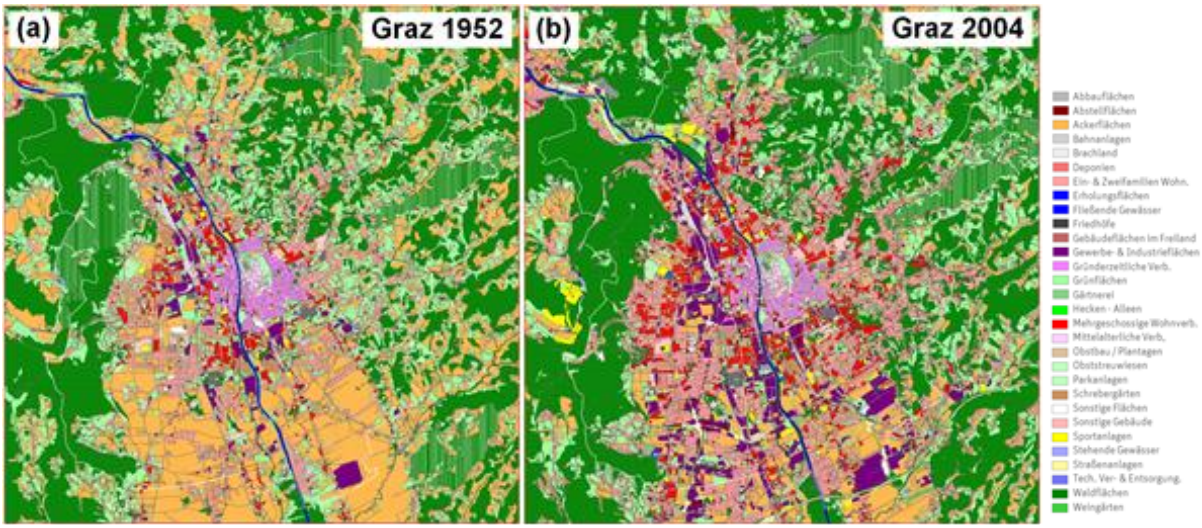


Figure 4: Land use/cover for Graz in (a) 1952 and (b) 2004. Relevant categories include farms and agriculture (orange), residential (pink and red) and industry (dark purple).

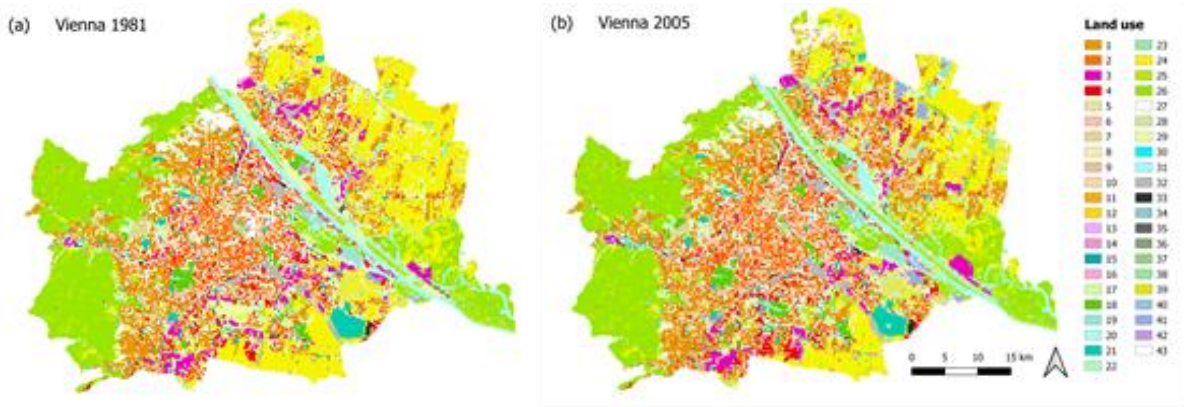


Figure 5: Land use/cover for Vienna in (a) 1981 and (b) 2005. Relevant categories include agricultural areas (yellow), residential areas (orange and red) and industry (pink).

Meteorological data from private weather stations

The large number of NETATMO stations in Vienna, as illustrated in **Figure 6**, provided a solid database for studying urban temperature patterns and evaluating climate model results. Quality control of the data was performed, as documented in Feichtinger et al. (2020). Additional remote sensing data sets, such as land surface temperature in appropriate spatial resolution, were not available for the selected heat wave period.

WP3: Urban climate modelling and model validation for selected urban areas

Depending on model application and spatial resolution, different model domains and configurations (**Table 2**) were selected for the simulations. **Figure 6** illustrates orography and selected model domains for both models.

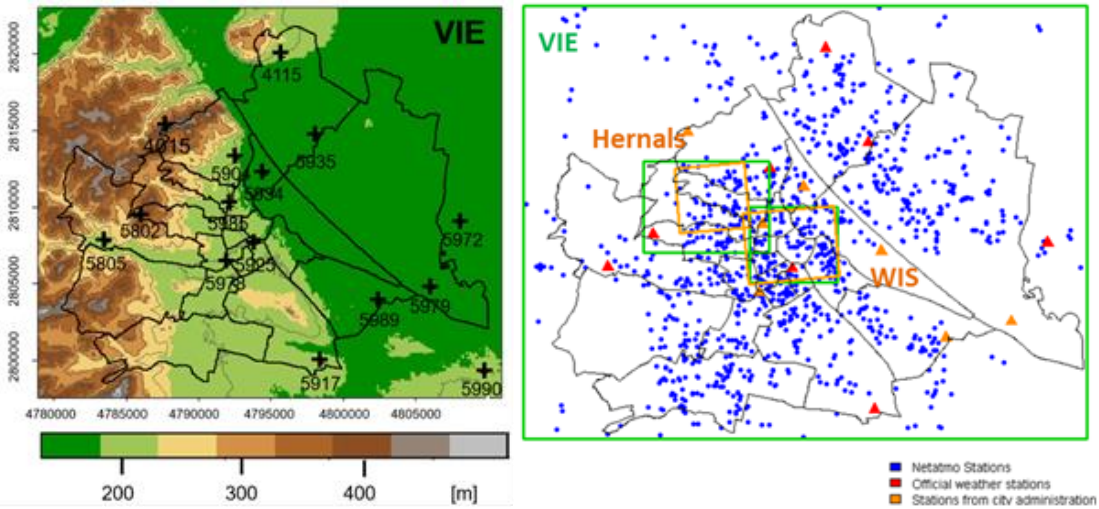


Figure 6: Orography (left) and location of conventional weather stations and NETATMO weather stations in Vienna, that were available for the 3-day validation period in August 2018 (16.–18.08.2018), including model domains used in the study for MUKLIMO_3 (green) and PALM-4U (orange) model.

Table 2: Overview of modelling domains.

	Domain	Modell grid size (x/y/z)	Spatial resolution	Model	Scientific question
Vienna	WIEN100	314/239/39	100 m	MUKLIMO_3	Large scale UHI analysis
	WIEN20	1536/1536/144	20 m	PALM-4U	
Vienna Inner City	WIS40	122/105/39	40 m	MUKLIMO_3	Effects of buildings, urban parks, water and pavement
	WIS10	510/390/182	10 m	PALM-4U	
Vienna Hernals	HERNALS40	175/125/39	40 m	MUKLIMO_3	Effects of orography, forest, cooling and temperature inversion during the night
	HERNALS10	390/360/182	10 m	PALM-4U	
Vienna Hohe Warte	ZAMG10	96/96/98	10 m	PALM-4U	Micro-scale analysis and effects of resolved urban structures and vegetation
	ZAMG1	250/250/152	1 m	PALM-4U	

MUKLIMO_3 simulations using the LU/LC parameters in tabular form as well as the GUAMO method with different LU/LC classifications were performed for the city of Vienna. Climate indices for the time period 1981–2010 were calculated using the statistical approach called the cuboid method (Früh al al. 2011).

Simulations of a 3-day period during a heat wave (16–18 August, 2018) were conducted with MUKLIMO_3 using the GUAMO method, and PALM-4U (**Figure 7**). Both models were initialized with the same vertical profiles of temperature, wind and relative humidity from the numerical weather prediction model of the ZAMG (ALARO/AROME) at 08:00 CEST. The simulations were performed for a daily cycle (24 hours) for each of the three days. The idealized simulations performed with PALM-4U were extended to include variable boundary conditions reflecting the weather situation of the selected hot days. Due to the large computational requirements, the modelling domain of Wien Northwest was reduced in size and used for further testing of the model performance.

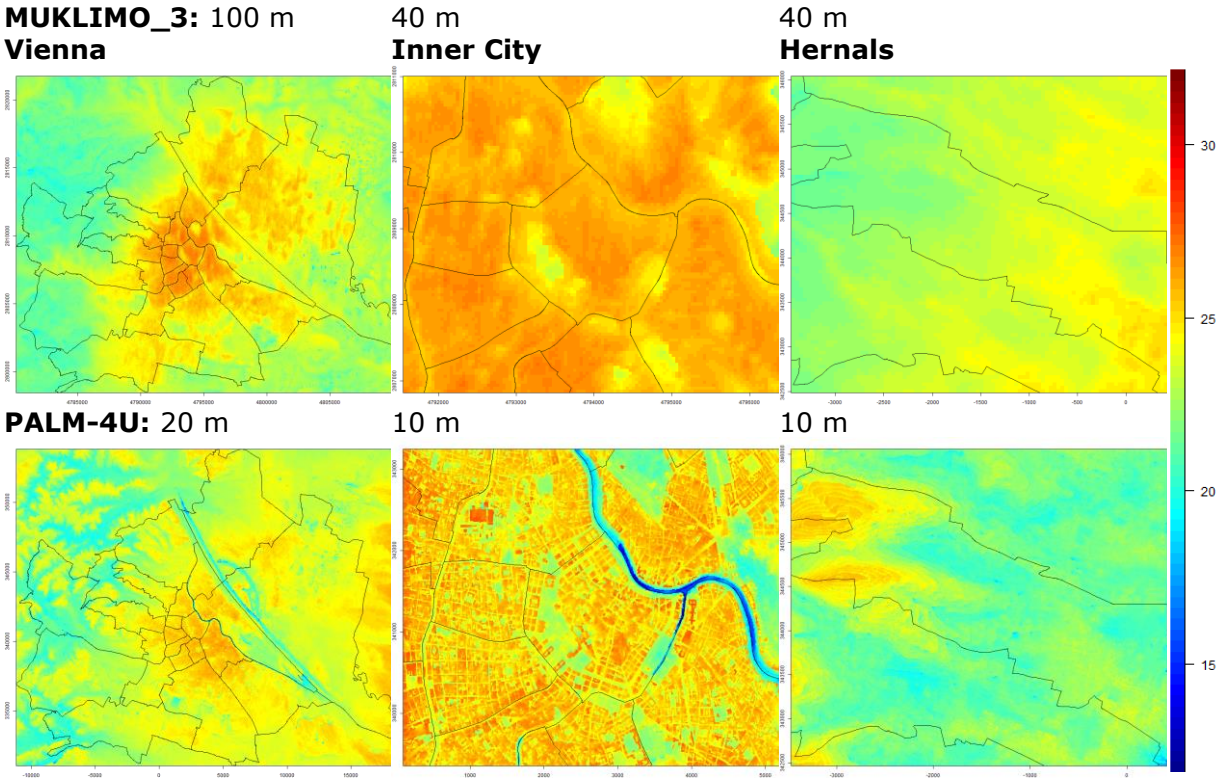


Figure 7: Simulations of air temperature for the city of Vienna and selected areas Inner City and Hernals on August 16, 2018 at 21:00 CEST by MUKLIMO_3 (top) and PALM-4U (bottom) model.

Model evaluation

The evaluation of the model results was performed using conventional and crowd-sourced data indicated in **Figure 6**, first comparing the model results on a city-scale and then for each subdomain. The comparison of the MUKLIMO_3 (100 m) model results with conventional stations resulted in a distinct pattern for most of the stations: air temperature was overestimated at night and slightly

underestimated in the afternoon (**Figure 8**). Similar results were found for the PALM-4U (20 m) model simulations (**Figure 9**). The large underestimation of temperature at station 4015 might be attributed to measurement errors at that station.

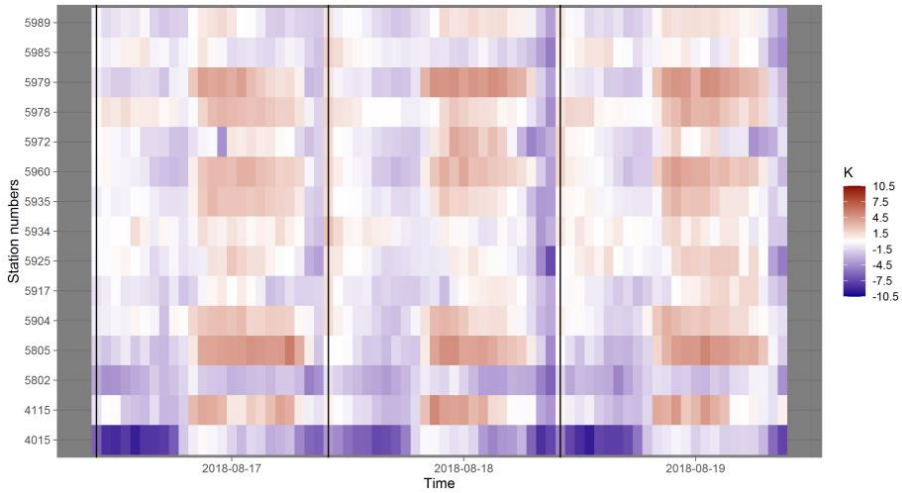


Figure 8: Comparison of MUKLIMO_3 model results (100 m resolution) with temperature data from official weather stations and from stations from the city administration (MA22): T[Simulation] – T[Observation]. Vertical lines mark the starting time for model validation, one hour after the 3D model initialization (10:00 CEST), and the dates at the x-axis are placed at midnight [time in CEST].

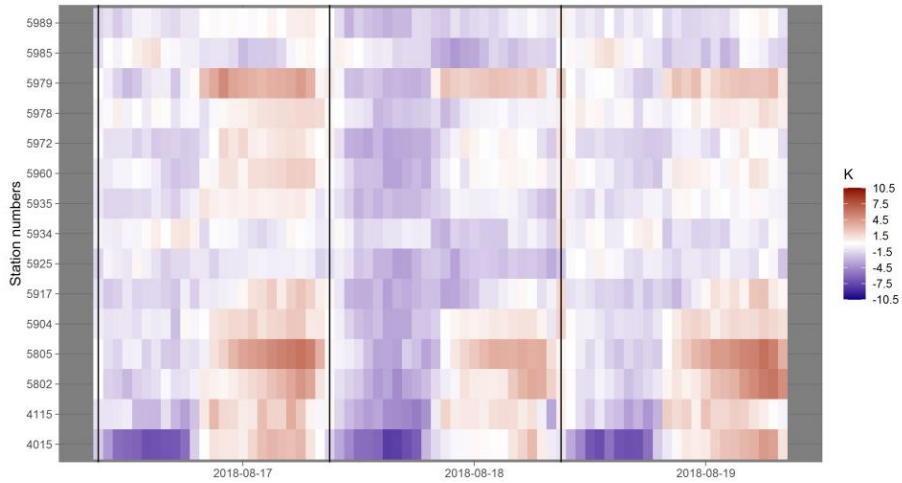


Figure 9: Same as Figure 8, but for PALM-4U model (20 m resolution).

Comparing the model results with the quality controlled temperature data from NETATMO stations also resulted in reasonable results for both models when looking at the mean absolute error (**Figure 10**). An examination of the bias of all stations in relation to the amount of soil sealing in the vicinity of the stations showed that the model performance is better for stations located in areas with a large amount of soil sealing (**Figure 11**). In case of the PALM-4U model (**Figure 12**) the model performance is also related to the terrain height, which could be associated with overestimation of the temperature inversion at night.

VIE – MUKLIMO_3 (100 m)

Performance Measures	Mean	Min *	Max
MAE	1.55	0.07 / 0.7	4.08
RMSE	1.89	0.07 / 0.87	4.32
rPearson	0.93	0.40 / 0.68	0.99
MeanBias	-0.22	-4.07	3.22
Bias	-0.13	-9.33	6.80

VIE – PALM-4U (20 m)

Performance Measures	Mean	Min*	Max
MAE	1.88	0.06 / 0.69	5.32
RMSE	2.20	0.06/ 0.9	5.32
rPearson	0.93	0.27/ 0.54	0.99
MeanBias	-0.99	-5.32	2.52
Bias	-0.83	-9.38	8.08

Hernals – MUKLIMO_3 (40 m)

Performance Measures	Mean	Min	Max
MAE	1.55	0.08	3.23
RMSE	1.95	0.08	3.40
rPearson	0.92	0.67	0.99
MeanBias	-0.27	-2.39	2.32
Bias	-0.33	-7.59	5.82

Hernals – PALM-4U (10 m)

Performance Measures	Mean	Min	Max
MAE	1.72	0.11	3.88
RMSE	2.04	0.11	4.27
rPearson	0.91	0.51	0.98
MeanBias	-0.55	-3.88	2.13
Bias	-0.55	-7.31	7.45

WIS – MUKLIMO_3 (40 m)

Performance Measures	Mean	Min	Max
MAE	1.29	0.07	2.91
RMSE	1.56	0.07	3.16
rPearson	0.94	0.83	0.99
MeanBias	0.17	-2.91	2.90
Bias	0.30	-5.35	5.86

WIS – PALM-4U (10 m)

Performance Measures	Mean	Min	Max
MAE	1.45	0.66	3.56
RMSE	1.75	0.88	3.96
rPearson	0.91	0.58	0.98
MeanBias	-0.03	-3.56	2.48
Bias	0.07	-8.00	7.59

Figure 10: Evaluation of model performance for different modelling setups.

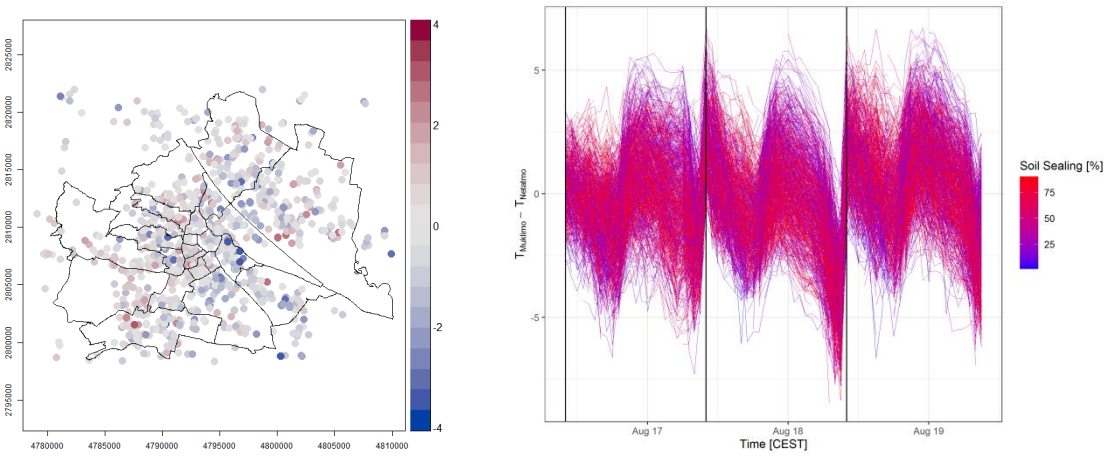


Figure 11: Mean absolute error of MUKLIMO_3 model at each NETATMO station for the evaluation period (left) and temporal variation of the bias (T[MUKLIMO_3] – T[NETATMO]) in relation to the soil sealing at the station location (right). Vertical lines mark the time of model initialization (10:00 CEST) and the dates at the x-axis are placed at midnight [time in CEST].

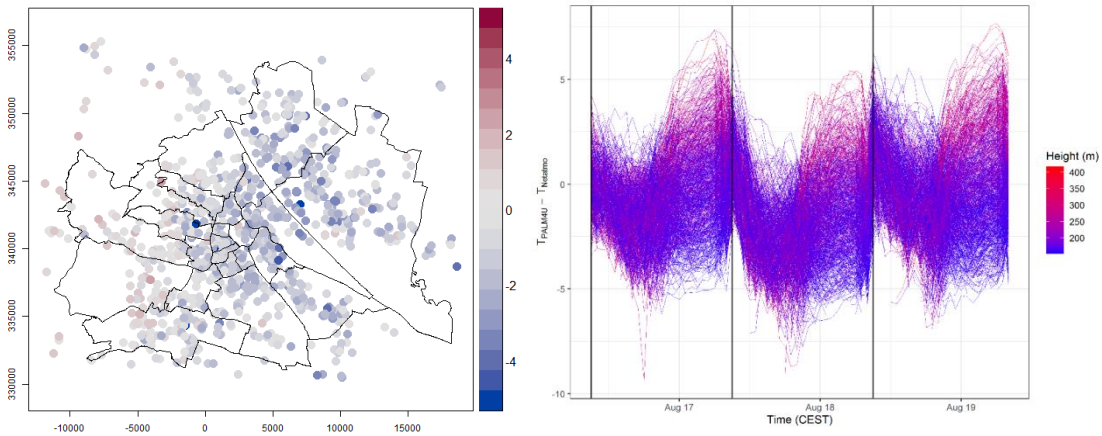


Figure 12: Mean absolute error of PALM-4U model at each NETATMO station for the evaluation period (left) and temporal variation of the bias (T[PALM] – T[NETATMO]) in relation to the terrain height at the station location (right). Vertical lines mark the time of model initialization (10: 00 CEST) and the dates at the x-axis are placed at midnight [time in CEST].

Regarding the temporal variation (**Figure 13**), many stations show a similar pattern as the conventional stations: both MUKLIMO_3 and PALM-4U model frequently overestimate temperature at night and underestimate temperature in the afternoon. Often temperature measurements decline faster in the evening then in the model simulations. However, there are also stations where the models consistently underestimate or overestimate temperature. The variation of the bias during the day is larger than for conventional stations.

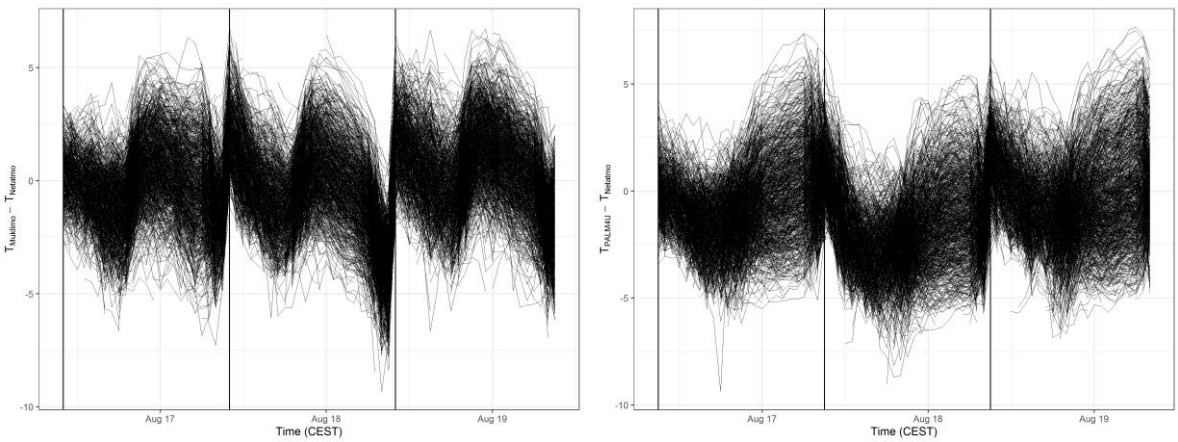


Figure 13: Comparison of MUKLIMO_3 model results (100 m resolution) (left) and PALM-4U (20 m resolution) (right) with NETATMO data from private weather stations. Vertical lines mark the starting time for model validation, one hour after the model initialization (10:00 CEST), and the dates at the x-axis are placed at midnight [time in CEST].

In addition to the comparison of the absolute temperature values, we investigated whether the spatial temperature patterns simulated by models are similar to the spatial patterns retrieved from NETATMO measurements.

Therefore, we have classified for each single time step the measurements, and simulation results respectively, into four groups:

	Stations with highest temperature values (above 75th percentile)
	Stations with temperature values between 50th and 75th percentile
	Stations with temperature values between 25th and 50th percentile
	Stations with lowest temperature values (below 25th percentile)

During the day, the spatial patterns are not similar (**Figure 14**). The reason for this is the strong small-scale variation in temperature during the day, which is caused by shade from buildings, exposure to direct sunlight, exposition etc. The comparison of NETATMO measurements with a higher resolution model PALM-4U, where buildings are resolved, showed a minor improvement of the results.

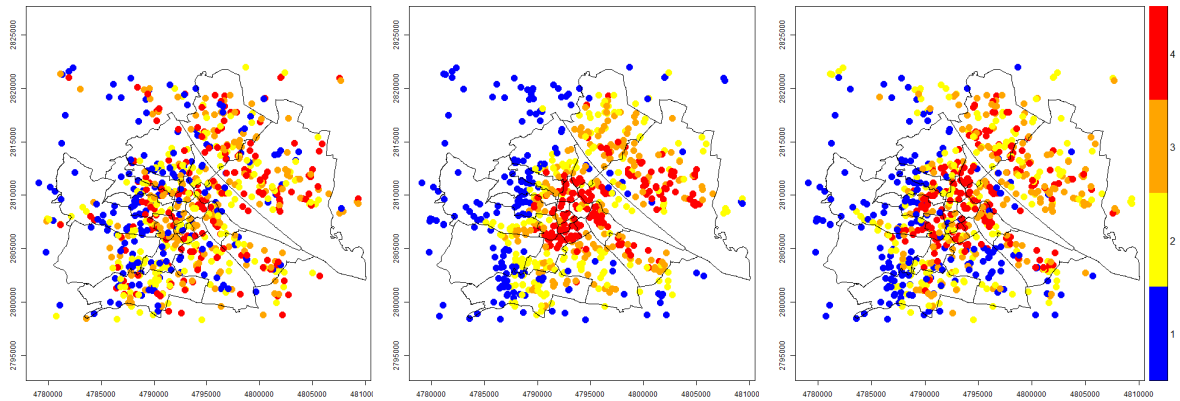


Figure 14: Spatial temperature pattern as measured by NETATMO weather stations (left), predicted by MUKLIMO_3 (middle) and PALM-4U model (left) at the 18th of August at 16:00 CEST. In red (group 4) are the locations with the highest temperature values. Blue (group 1) are the locations with lowest temperature values.

At night, the spatial patterns are similar (**Figure 15**). It indicates that the strong small-scale variation diminishes and the NETATMO temperature measurements become more representative for a larger area. It also shows that the prediction of the spatial temperature pattern by MUKLIMO_3 and PALM-4U are good, despite the often-observed overestimation of temperature at night. In addition, the classification allowed us to quantify the agreement of the class allocation, by calculating the confusion matrix for all time steps and the overall accuracy (**Figure 16**). It is clearly visible that the agreement during the night is higher than during the day in both models. However, in case of PALM-4U simulations the agreement decreases rapidly, possibly due to the overestimation of air temperature inversion, which requires further investigation.

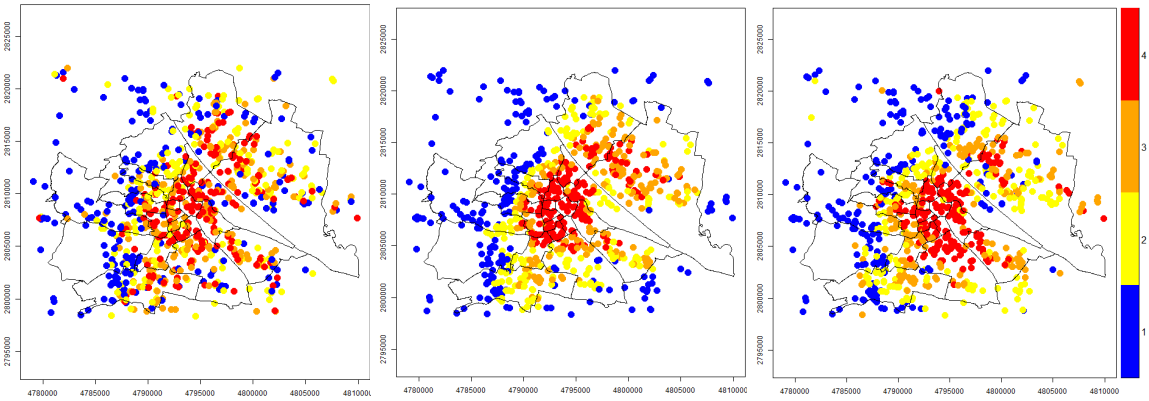


Figure 15: Spatial temperature pattern as measured by NETATMO weather stations (left), predicted by MUKLIMO_3 (middle) and PALM-4U model (left) at the 18th of August at 21:00 CEST. In red (group 4) are the locations with the highest temperature values. Blue (group 1) are the locations with lowest temperature values.

The analysis shows that despite the challenges when working with crowd-sourced data (data quality, uneven distribution of stations, variations of data availability with time), the measurements are useful to investigate the spatial temperature patterns (at least during night time) and show good agreement with the urban model results.

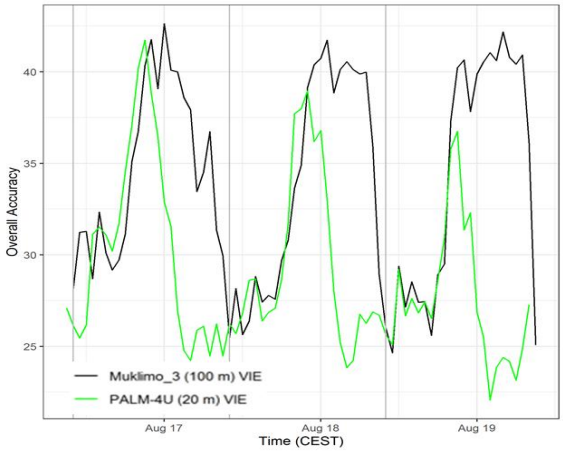


Figure 16: Change of overall accuracy in percent over time, based on confusion matrices, which identify how many stations are allocated to the same group. Vertical lines mark the time one hour after the model initialization (10:00 CEST) and the dates at the x-axis are placed at midnight [time in CEST].

Sensitivity of model results to LU/LC characteristics

City-scale simulations to evaluate the sensitivity of model results on LU/LC characteristics were performed at 100 m spatial resolution with the MUKLIMO_3 model and the spatial patterns in urban heat load were compared. **Figure 17** shows the results for the annual mean number of summer ($T_{max} \geq 25$ °C) days based on the LU/LC information and classification scheme from different sources using defined LU/LC parameters (e.g. average value of building density) for each class.

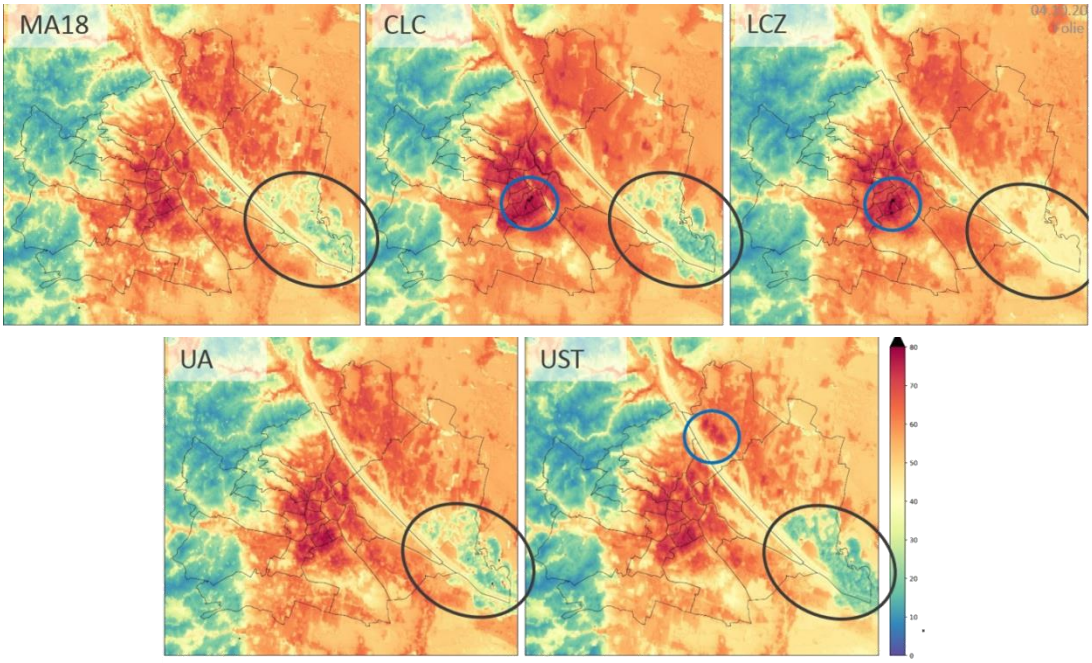


Figure 17: Simulated mean annual number of summer days (T_{max} ≥ 25 °C) for the time period 1981–2010 in Vienna, based on different LU/LC sources and classifications.

In case of the GUAMO method, the model uses the raster data of LU/LC parameters for individual grid cells instead of the predefined LU classes. This means that each cell has its own parameters (e.g., the building height) and non-averaged values representative of a class (**Figure 18**).

While the results of the MUKLIMO_3 model using LU classification scheme depend on the selection of LU/LC data sets, when using the so-called GUAMO or raster method, the MUKLIMO_3 results show a consistent spatial pattern. The results also show different intensity of heat load, which can be assigned to LU/LC parametrization, but the differences are smaller compared to the LU classification scheme.

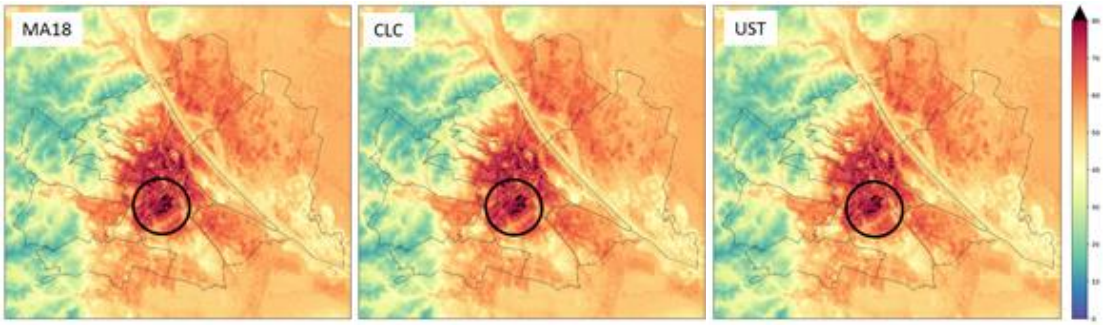


Figure 18: Simulated mean annual number of summer days (T_{max} ≥ 25 °C) for the time period 1981–2010 in Vienna, based on different LU/LC classifications, but based on direct usage of Copernicus raster layers.

WP4 Reconstruction of urban climate based on historical land use changes and changes in regional climate

The long-term simulations were performed with the MUKLIMO_3 model and the cuboid method. The best model performance was found when using the GUAMO method. However, the availability of historical LU/LC information poses a limit for application of the GUAMO method, since not all input parameters are available as raster data sets. Therefore, for the historical climate simulations the mean values of LU/LC parameters was used and for the LU/LC classification scheme, the data from the city administration were used as a base.

MUKLIMO_3 was used to model the climate generated by the LU/LC distributions for Graz in the years 1952, 1968, 1975, 1984, 1990, 1997 and 2004 and for Vienna in the years 1981, 1985, 1991, 1994, 1997, 2001, 2003 and 2005. The climate indicators of the annual average number of summer days, hot days and tropical nights as measures of heat load calculated from MUKLIMO_3 were compared with the derived climate indices from the ZAMG measurement stations based on daily data and showed that the model produced realistic results.

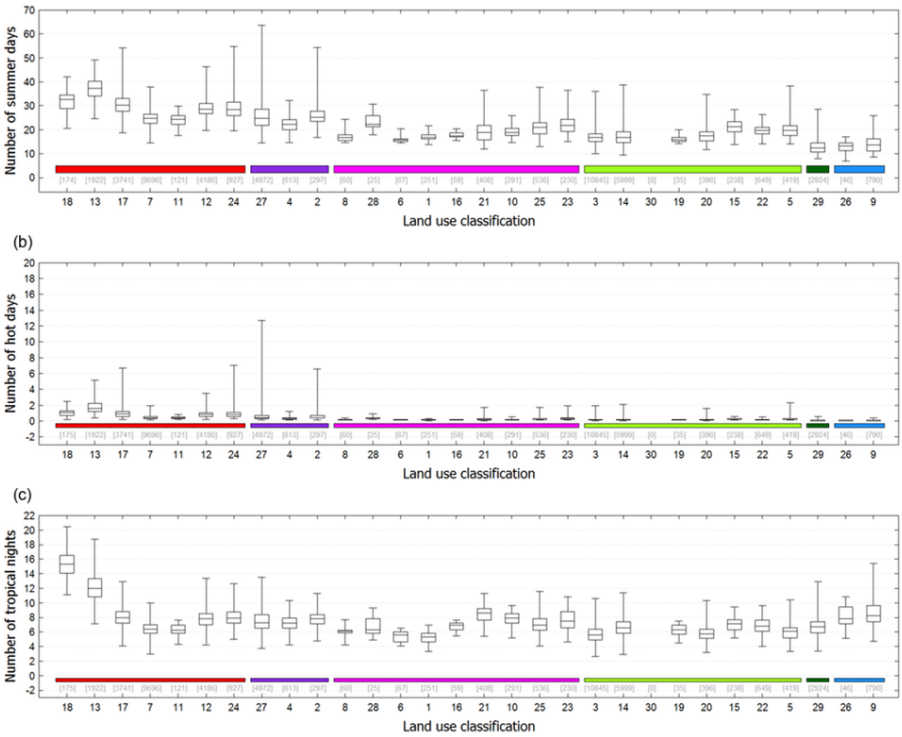


Figure 19: Box and whiskers plots showing Distribution of annual average number of summer days (top), hot days (middle) and tropical nights (bottom) for each LU class in Graz. The lower and upper limits of the box show the lower and upper quartiles, respectively, with the median represented by the line within. The ends of the whiskers represent the maximum and minimum values. The coloured strips above the x−axis represent the different LU/LC categories joined in following groups: built-up (red), transport (violet), industry and other sealed areas (pink), agricultural and green areas (light green), forest (dark green) and water (blue). The numbers in square brackets above the x−axis show the number of pixels of the corresponding LU/LC class.

Each land use category is parameterised within MUKLIMO_3 using a set of 24 parameters, which characterise a number of features such as buildings in terms of their area, height and wall area index, vegetation such as tree heights, coverage and leaf type, amount of surface sealing, albedo and heat capacity. Accordingly, each land use type generates its own heat load as shown in **Figure 19** for Graz in 1952 and **Figure 20** for Vienna in 1981.

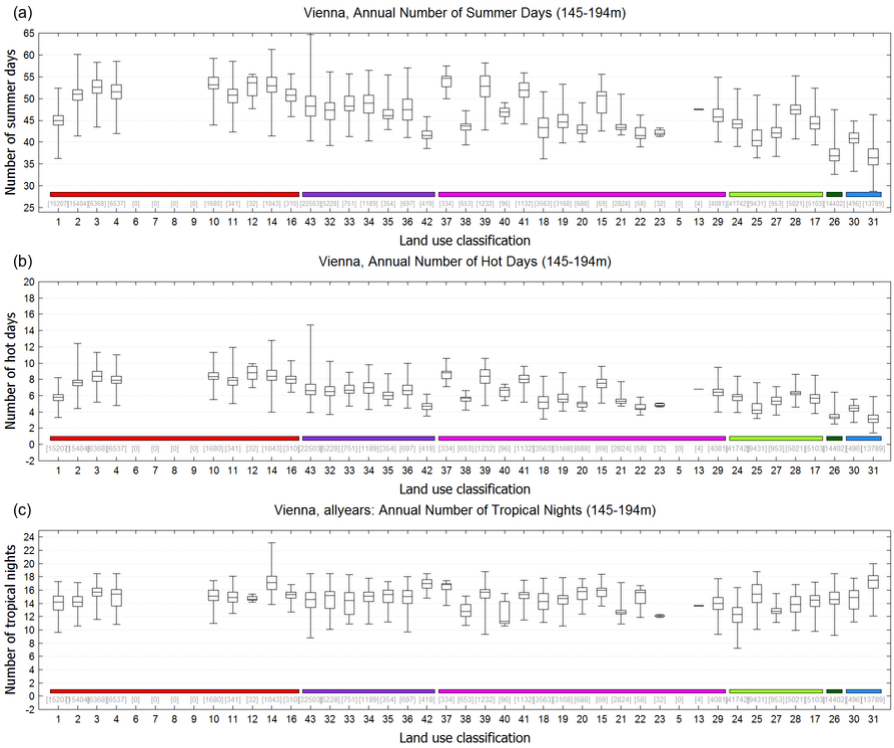


Figure 20: Same as **Figure 19** for Vienna.

In this way, it is possible to estimate which heat load changes can be found when one land use class is replaced by another, e.g. replacing an area of arable land (class 3 in **Figure 21**) with industrial land (class 12 in **Figure 21**) leads to an increase of approximately 12 summer days per year. Same analysis was performed for Vienna based on LU/LC changes from 1981 until 2005 (**Figure 22**).

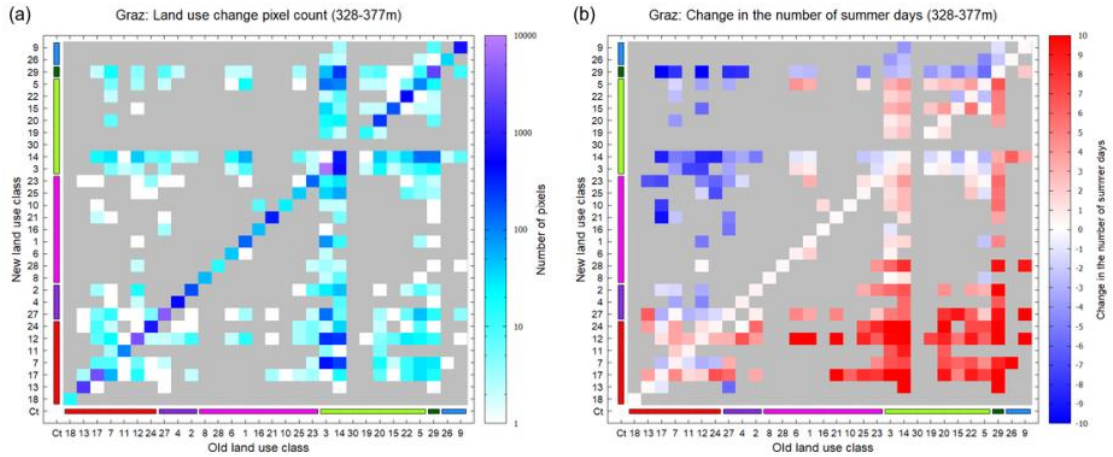


Figure 21: A cluster heat map representation of the LU/LC change for Graz from 1952 to 1968 for the lowest elevation band 328-377 m. (a) Count of the number of pixels on a logarithmic scale and (b) Average changes in summer days on a linear scale. Grey pixels have no data. The LU/LC categories (Ct) are classified numerically in the first row and column.

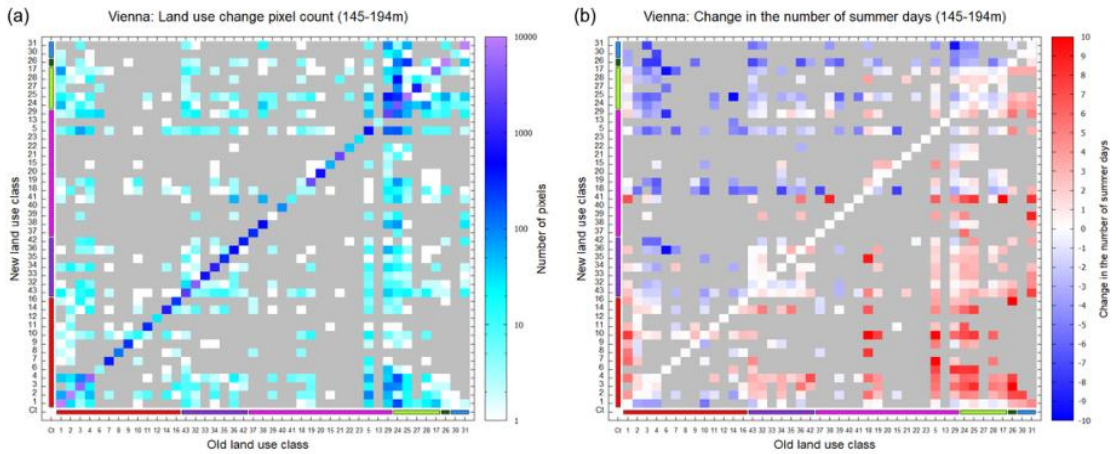


Figure 22: As in **Figure 21** but for Vienna from 1981 to 1985 for the lowest elevation band 145-194 m.

Figure 23 shows the annual average number of summer days, hot days and tropical nights in Graz generated by the LU/LC data of 1952 and the change in heat indices when compared to the year 2004. The evolution of urban heat load shows similar pattern to LU/LC changes with prevailing urbanization of agricultural areas, which lead to increase in the heat load extended into the outskirts of the city.

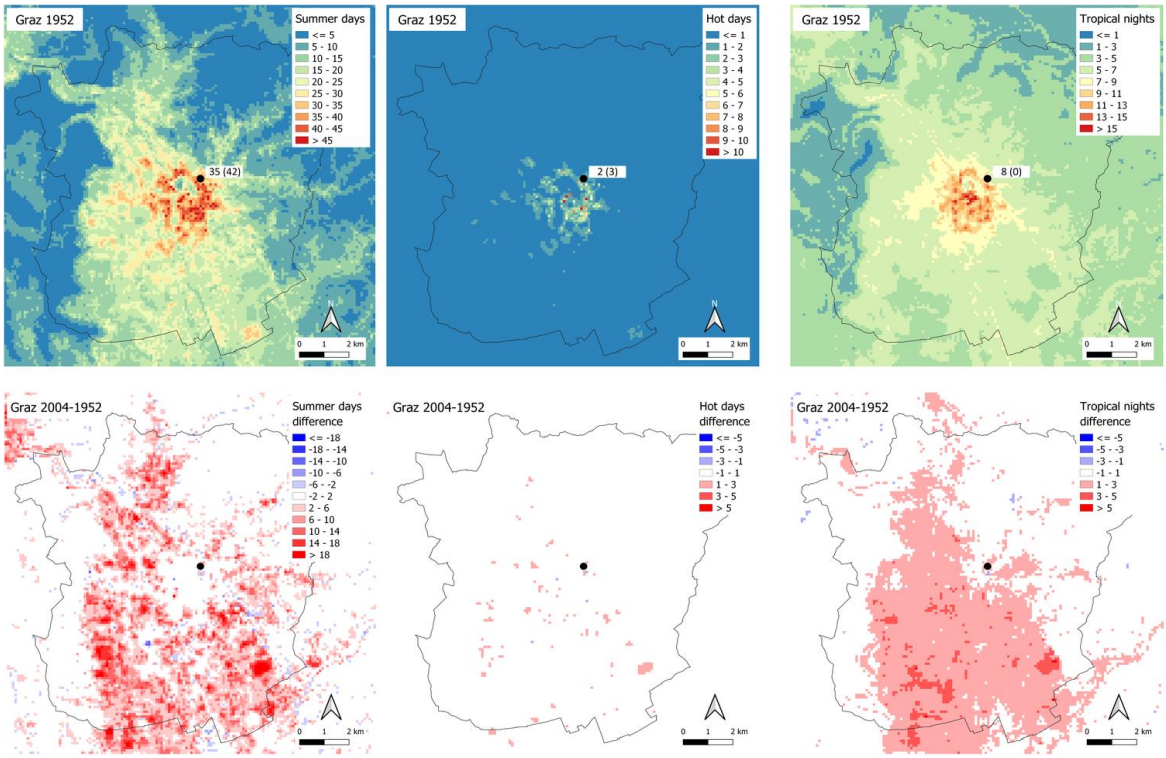


Figure 23: Annual average number of summer days (left), hot days (middle) and tropical nights (right) for Graz based on the land use distribution for 1952 (top) and change in the number of days compared to 2004 (bottom).

Similar pattern with increase in heat load in suburban areas can be found in Vienna for the period between 1981 and 2005 (**Figure 24**). However, notable cooling effect is found along the Danube River and the Wienerberg area. The heat load during the day (number of summer and hot days) is reduced along the Danube owing to the creation of the Danube Island park/recreation area, and the Wienerberg recreation park with lake south of the city centre (up to -13 summer days and -5 hot days). However, both of these LU/LC changes result in an increase in the heat load during the night (number of tropical nights), owing to the constantly higher water temperature. The eastern part of Vienna is otherwise dominated by a warming owing to the replacement of agriculture, farmland, and green spaces with residential buildings, streets, and industry (up to +9 summer days and +5 hot days). The south and southeastern parts are also predominantly warmer, e.g. Inzersdorf Industry area south of the Wienerberg recreation park, but to a lesser extent. Otherwise most of the change occurs at small isolated areas scattered across the city.

The heat load of both cities has increased in recent decades due to the combined impact of land use change and regional climate change. However, a comprehensive reconstruction of the urban climate and analysis of future trends is not possible due to the limited historical data dating at different time intervals. The results show that the LU/LC changes in the past decades have high magnitude and lead to increase in local heat load that is comparable with the warming effect induced by the regional climate change.

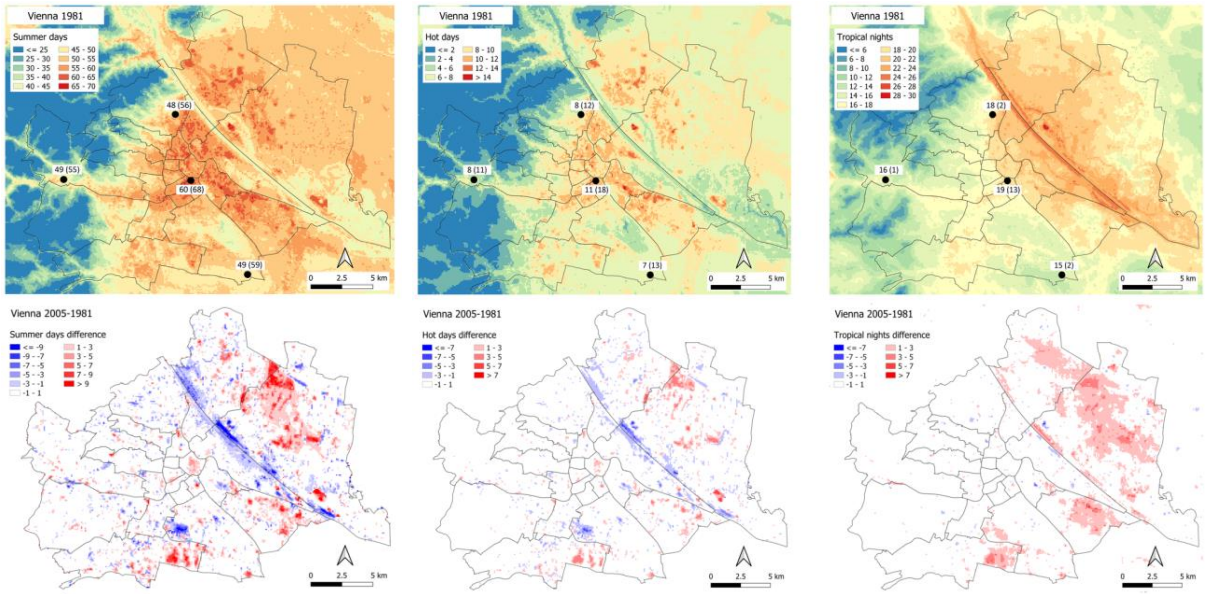


Figure 24: Annual average number of summer days (left), hot days (middle) and tropical nights (right) for Vienna based on the land use distribution for 1981 (top) and change in the number of days compared to 2005 (bottom).

5 Schlussfolgerungen und Empfehlungen

Based on the analysis of the LU/LC data for the two largest Austrian cities (Vienna and Graz), urban climate model simulations and their validation using quality-proved measurement data from operational and private weather stations, the following conclusions and recommendations for urban planning are summarized:

1. The LU/LC data are provided on local, national or international level in different quality and spatial detail. The mapping of LU/LC differs from the method applies and the data availability is not the same for the cities in Austria. Historical data are lacking, in particular, the data related to changes in urban structure, such as the degree of sealing, changes in building height, and vegetation. It is recommended to further compile and harmonize the available LU/LC data for urban areas and their surroundings in order to ensure the quality of the model simulations. In addition, continuous updates, corresponding archiving and availability in suitable formats of data is recommended as well.

2. In order to improve the microclimate simulations, not only high quality LU/LC data re required, but also spatial information on parameters regarding urban structures, e.g. building density and height, degree of sealing, vegetation height is required. Continuous updates, corresponding archiving and availability in suitable formats of these data is recommended as well. The implementation of more detailed information in models provides realistic results in spatial temperature patterns and thus reduces the uncertainties that arise from different LU/LC data and classifications schemes. It is therefore recommended, whenever possible, to include this information in detailed form in model simulations.

3. The heat load of examined cities Vienna and Graz has increased in recent decades due to the combined effect of land use change and regional climate change. However, a comprehensive, spatio-temporal reconstruction of urban climate in these cities is not meaningful due to the limited availability of LU/LC data, which are provided at irregular time intervals and only for certain parameters.

4. The quality-checked data from approximately one thousand private weather stations in Vienna showed that the densely built-up urban areas are warmer than the surroundings, thus confirming the presence of the UHI effect. If the entire urban area is considered, the UHI effect is significantly larger at night than during day-time. Despite the known limitations, such as a potentially unsuitable location for the measurements with high exposure to solar radiation, fewer stations located in green areas or disruptions in data availability, due to the high station density, the data from private weather stations are nevertheless helpful in evaluating model results.

5. The statistical evaluation of model simulations (MUKLIMO_3 and PALM-4U) and comparison with hourly temperature measurements from the operational

measurement network, as well as crowd-sourcing data sources for the selected heat period in 2018 show a similar model performance and agreement between the models and observational data, which confirms that both models are well suited for urban modelling applications.

6. 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. However, with strongly inhomogeneous LU/LC within urban area, the spatial variability of model results also increases and expected better agreement with available observational data due to higher model resolution could not be confirmed. Therefore, for a specific application, the selection of an appropriate modelling approach is more important than solely an increase in spatial resolution.

7. By using models with resolved buildings (e.g. PALM-4U), small-scale processes such as turbulence, shading by buildings and vegetation, interaction between the atmosphere and urban surfaces and building materials are better represented. The higher computational demand for these simulations along with more detailed input data requirements and uncertainties regarding model validation remain a disadvantage for practical use of the model across a wide spectrum of applications. For a specific urban planning application, it is recommended to examine the modelling approach in regard to selection of optimal modelling domain, required spatial resolution and availability of relevant input data.

8. The analysis of land use changes based on historical data for Vienna (1981-2005) and Graz (1952-2004) shows progressive urbanization in both cities, in particular a transformation of agricultural land into built-up and traffic areas. The area used for agriculture decreased by 5.3% in Vienna and 18.9% in Graz, in respective time periods. The major changes were related to built-up and traffic areas, which increased by around 1.6% and 4.1% for Vienna and 12.8% and 2.0% for Graz. In addition, both cities had an increase in forest area (+0.7% in Vienna and +2.9% in Graz).

9. Model simulations with historical land use data confirm that changes in LU/LC can have a positive or negative impact on the heat load. The warmest zones are densely built-up areas and the coolest areas have large amounts of green space and water. The change in urban heat load is strongest at the location where LU/LC was modified, but warming and cooling effects can be found in surrounding areas as well, nevertheless, with less intensity and in limited spatial extent.

10. A quantification of warming effects of LU change shows that transformation of arable land to industrial areas leads to an average increase in the mean annual number of summer days of about +12 days on the exact location where LU change took place and about +3 days in the surrounding area. Evaluation of cooling effects shows that modification of traffic areas into green areas leads to an average reduction in the mean annual number of summer days of approx. -8 days at the same location and of approx. -2 days in the surrounding area.

C) Projektdetails

6 Methodik

LU/LC classification schemes and mapping

Land use classification schemes generally address both LU/LC mapping that is required to measure land characteristics and its impact on the ecosystem. Land cover information describes the observed bio-physical coverage of the Earth's surface; whereas land use is characterized by the activities and input of people to produce or change land cover (Turner et al. 1993). LU classifications distinguish mostly between different natural and built-up areas. However, their degree of detail is largely varying depending on the data source and the field of application. Due to satellite-based LU monitoring methods (e.g. EU Copernicus Land Monitoring Services), standardized and multilevel classifications allow the transferability of information from one city to another and enable comprehensive spatial and temporal comparison of LU inventories.

Within the LUCRETIA project the following LU/LC sources were considered.

CORINE Land Cover (CLC)

As part of the Copernicus Land Monitoring Service and coordinated by the European Environment Agency, the CORINE Land Cover (CLC) provides standardized information on land cover for 39 countries in Europe by combining Earth Observation data with in-situ measurements. The target fields of application cover, among others, ecosystem mapping, climate change impact modelling, agricultural changes, urban sprawl and water management. The CLC scheme consists of 44 different LU/LC classes that on a first level mainly distinguish between artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands and water bodies.

Urban Atlas (UA)

Urban Atlas of the Copernicus Land Monitoring Services uses a similar mapping technique, although with a higher spatial resolution and mainly intended for European cities and its surroundings (population > 50,000). The thematic classes are similar to the CLC nomenclature, but an additional level is used to further refine the sub categories related to artificial surfaces by taking into account the degree of soil sealing, derived from the Very High Resolution (VHR) imperviousness layer. With a total number of 27 classes, the latest version of Urban Atlas (2018) allows for a proper and harmonised monitoring of urban structures across Europe.

Local Climate Zones (LCZ)

The Local Climate Zones classification scheme (Stewart and Oke, 2012) specifically applies to local temperature and climate studies and thus may be used as input for weather and climate models. The LCZ classification scheme comprises 17 classes and its mapping technique mainly incorporates physical

properties like surfaces structure, material and surface cover that affect local climate.

Urban Standard Typologies (USTs)

The Urban Standard Typologies (USTs), provided by Green4Cities GmbH were designed to identify typical morphological urban structures, considering fraction of soil sealing, green areas and open spaces as well as building structures. They are mostly applied to evolve city-specific climatic maps and may further be used to assess the effects of different greening scenarios.

Land Information System Austria (LISA)

LISA aims at providing detailed up-to-date geospatial information about LU/LC in Austria to meet information requirements of various target sectors, including spatial and land use planning sectors, forestry and water management and environmental protection. The LISA land cover mapping technique is mainly based on orthophotos and laser scanning data that have been extended by very high resolution data from Pléides satellites, as part of the CadasterENV project, funded by the European Space Agency. The enriched VHR LC maps, provided for Austrian urban agglomerations, contain up to 20 different LC classes (depending on spatial resolution).

Local land use classification

A specific LU classification generated by the city administration of e.g. Vienna (MA18) provides information about current LU composition, derived from a combination of aerial photos and additional geographical data. It consists of 32 classes that follow a hierarchical structure and are subdivided into the main categories buildings, green areas and traffic. This data set is updated and published about every 2 years on the website of the city administration of Vienna.

Historical LU/LC data

While satellite based LU/LC data are provided only for the recent decades, e.g. Urban Atlas (2006, 2012, 2018), the city administrations generally have a larger archive of local data, such as aerial imagery, orthophotos and city maps, collected over a longer time period, starting from the end of 18th century and onwards. These maps are, however, not suitable for modelling applications in their original form and need to be further processed (see example for urban climate modelling based on historical maps for Vienna in Zuvela-Aloise et al. 2014).

Within the LUCRETIA project, a survey of historical LU/LC data, including additional information on building and vegetation was performed for the Austrian federal capitals: Vienna, Graz, Linz, Klagenfurt, Salzburg, Innsbruck, Bregenz, Sankt Pölten and Eisenstadt. An overview of the available data is given in **Table 1**.

Based on the data analysis from the survey, only historical LU/LC provided in vector format and using the same classification schemes were used for modelling

applications. For this reason, model simulations were conducted only for the cities of Vienna and Graz with the time span of about 25 to 50 years. The LU/LC data for Graz were provided by the City of Graz Transportation and Urban Planning department (Amt für Stadtplanung und Verkehr) for the years 1952, 1968, 1975, 1984, 1990, 1997, and 2004. Historical LU/LC data for Vienna were provided by City of Vienna Urban Development and Planning department (Stadtentwicklung und Stadtplanung MA18) for the years 1981, 1985, 1991, 1994, 1997, 2001, 2003, and 2005. Focus has been on these years as the LU/LC classification scheme for both cities have been consistent, although the classification schemes used for Graz and Vienna are different. In Graz the LU/LC classification consist of 30, and in Vienna of 43 different LU/LC classes. To make the analysis of the two cities comparable, the LU/LC classes of Graz and Vienna were grouped into the broad categories defined by the City of Graz Transportation department of Built-up, Transport Units, Other areas, Agricultural areas, Forests and Water bodies. Some LU/LC classes are identical for both Vienna and Graz, while those that differ are subjectively assigned to the categories in respect to their physical properties.

Crowd-sourced air temperature data from private weather stations

For the evaluation of the intra-urban temperature distribution and comparison of model results, an observational monitoring network from a large number of private weather stations was used. The potential of freely available crowd-sourced temperature data in comparison to standard operational monitoring networks was explored. This novel methodology, first used for urban climate studies by Chapman et al. (2017), utilized observations obtained with amateur weather stations to derive high-resolution information of urban temperatures. Traditionally, meteorological observations underlay strict guidelines as defined by the World Meteorological Organisation (WMO) in order for measurements to be as precise and representative as possible. As such, instrumentation is costly, which has resulted in a relatively course measurement network not optimized for detailed urban studies (e.g. Chapman et al. 2017). Although amateur weather stations do not necessarily follow these strict guidelines their use is cost-effective, and their strength lays in the availability of a dense network of measurement points (Chapman et al. 2017, Meier et al. 2017, Napoly et al. 2018).

In the Vienna area, a network of over 1000 amateur weather stations was available for the period of investigation in 2018. In addition, about a dozen official semi-automatic weather stations, called TAWES stations, or other stations employed by the city administration departments (MA22) were present. Combined with a rigorous quality control, the full benefit of these novel and alternative data set for use in urban climate studies can be leveraged (Meier et al. 2017). Promising results using this technique were already showed in studies for Vienna (Hammerberg et al. 2018, Feichtinger et al. 2020).

To minimize the uncertainty associated with the crowd-sourced temperature data, the statistically-based quality control as proposed in Napoly et al. (2018) was applied to identify spurious temperature observations. As previous studies have shown that main error sources mainly arise due to the siting of the amateur weather stations and not as a result of sensor quality (Napoly et al. 2018 and references therein), this methodology aimed at identifying those observations resulting from incorrect placement of the station (e.g. indoor instead of outdoor, or direct exposure to solar radiation). By exploiting the number of observations in the dense network of private weather stations, these implausible measurements were filtered out. Of the 1357 NETATMO weather stations available for Vienna during a hot period in August 2018, 1083 stations have successfully passed the quality control (according to Feichtinger et al. 2020) and were therefore used to investigate the intra-urban air temperature variations and to evaluate the urban climate models.

Urban Climate Modelling

Two modelling approaches were used within the project to evaluate the intra-urban temperature variability and sensitivity of model results on LU/LC characteristics.

MUKLIMO_3 urban climate model:

The urban climate model MUKLIMO 3 (in German: Mikroskaliges Urbanes Klima Modell; Sievers and Zdunkowski 1986; Sievers 1990, 1995, 2016) was developed by the German Meteorological Service (DWD) to investigate atmospheric processes in urban areas. The model simulates daily cycle of meteorological variables, such as air temperature, relative humidity and wind using Reynolds-Averaged Navier-Stokes (RANS) equations, including parameterization of unresolved buildings through a porous media approach for unresolved buildings (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 latest thermo-dynamical version of the model, v200629 (from June 29, 2020) that is an extension of the previous version documented by Sievers (2016), was used in the project.

The new model version allows for two different approaches to represent LU/LC parameters in the model:

1. Tabular form, using mean values of LU/LC parameters per LU/LC class

2. Raster form or so-called GUAMO method, using LU/LC parameters calculated for each grid cell.

The LU/LC parameters defined in the MUKLIMO_3 model include 26 parameters which characterize features such as buildings, surfaces, trees and vegetation within each LU/LC class. These parameters define numerically the quantities such as building fraction, building height and wall area (wall area index), surface and wall albedo, surface sealing and roughness, tree and vegetation coverage, tree

and stem height, and leaf area index and density. The mean values of these parameters have been defined in previous studies for Vienna (e.g. Zuvela-Aloise et al. 2016) and Graz (Zuvela-Aloise et al. 2017).

The raster method was recently developed by the DWD within GUAMO (Utilization of GMES Urban Atlas for urban climate modelling) project initiated by the European Union's Earth Observation Programme, Copernicus and the German Federal Ministry of Transport and Digital Infrastructure (BMVI). The parameters represented in a raster form are building fraction, building height, wall area index, surface sealing fraction and tree coverage. In addition to spatial data on LU/LC, MUKLIMO_3 model uses data on topography.

City-scale simulations with the MUKLIMO_3 model were performed at a 100 m spatial resolution and district-scale model simulations for selected areas in Vienna: Inner City and Hernals, used a 40 m spatial resolution. A vertical grid spacing of 10 m is used near ground level increasing to 50 m near the top of the domain at 0.85 km above the lowest level. The model simulations were initialized with temperature, relative humidity, and wind profiles in the morning hours (08:00 CEST). In the case of the simulations during the heat wave period, the meteorological profiles were extracted from the ZAMG numerical weather prediction model ALARO. For details of the application see Hollosi et al. (2021). In the case where climate indices with the cuboid method were calculated, the simulations are started with idealized vertical profiles.

The cuboid method was developed by Früh et al. (2011) in order to reduce computational efforts of the long-term high-resolution urban climate model simulation. The dynamical-statistical downscaling technique combines 2D model output and climatological timeseries to derive heat indices (number of days per year when a certain threshold value of minimum or maximum air temperature is exceeded). The method uses 16 single-day model simulations for a range of weather situations and a trilinear interpolation of the model results to calculate the temperature distribution for specific day, according to the daily observations of mean temperature, mean relative humidity and wind speed. The cuboid method was used to calculate 30-year averages of climate indices, which were used in evaluation sensitivity of model simulations to choice of LU/LC data sets as well as historical LU/LC modifications.

***PALM-4U modelling system**:*

The newly developed Parallelized Large-Eddy Simulation Model for Urban Applications - PALM-4U (Maronga et al. 2020) has been applied for the city of Vienna to evaluate the model performance and compare it with the established modelling approach (MUKLIMO_3). PALM-4U was developed by the Leibniz University Hannover in Germany in cooperation with other research centres under the MOSAIK project funded by the German Federal Ministry of Education and Research. The model was designed as a highly efficient, high-resolution urban climate model which allows micro-scale simulations with grid-resolved building and vegetation canopy on a spatial scale from 1 m to 100 m resolution

covering urban applications for a single building environment up to entire cities. As an alternative to RANS-type turbulence parametrization in e.g. MUKLIMO_3 model, the PALM-4U model uses the turbulence-resolving LES mode, which is computationally more demanding. Simulations can be carried out for entire cities on powerful parallel computers, where limitations are mainly imposed by available computational resources. Within the LUCRETIA project several model versions were tested. The latest version used for the simulations within the project was released in October 2021.

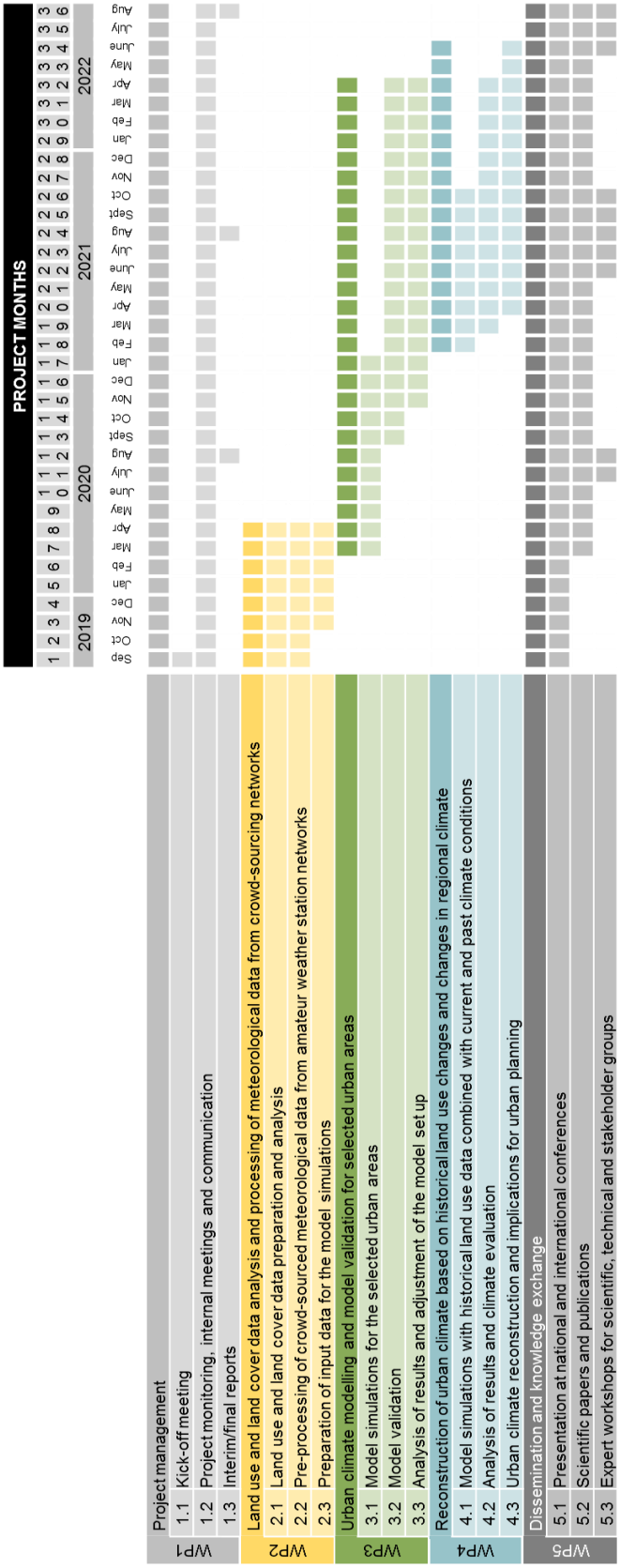
The static data related to geographical information and urban infrastructure are based on 2- and 3-dimensional GIS data from the city of Vienna, available as spatial multi-purpose maps (Flächen-Mehrzweckkarte - FMZK), street tree cadastre, Digital Elevation Model and Digital Surface Model, which were combined with the national land cover data (Land Information System Austria - LISA) to account for the unresolved vegetation. The data were prepared according to Heldens et al. (2020).

The simulations were performed for a 3-day heat wave period in August 2018, starting each daily run at 08:00 CEST with the initial vertical profiles of meteorological variables as used in the MUKLIMO_3 simulations.

In the first phase of the project, the simulations were performed for selected areas in the city: Inner City and Hernals, with 10 m spatial resolution and for ZAMG Hohe Warte with variable spatial resolution (1, 2, 4, 10 m). In the last phase of the project simulations were extended to cover entire city of Vienna with a 20 m spatial resolution.

7 Arbeits- und Zeitplan

Final work and time schedule of the project.



8 Publikationen und Disseminierungsaktivitäten

Following tables contain dissemination activities related to the LUCRETIA project, including conference contributions and scientific publications, es well as public dissemination and external events organized within the project.

Table 3: List of scientific publications and dissemination activities from the LUCRETIA project

Contribution	Title	Link
Virtual conference presentation	Sandro *Oswald et al. - Die Rolle der Landnutzung und ihre Veränderung in Bezug auf die Entwicklung von Intra-Urbanen Hitzeinseln (LUCRETIA), Österreichischer Klimatag 2020 & 2021 ACRP-Qualitätssicherung 2020, September 3-4, 2020*	https://ccca.ac.at/fileadmin/00_DokumenteHauptmenue/05_Veranstaltungen/Klimatag/2020/ACRP_04_09_LUCRETIA.pdf
Virtual conference presentation	*Robert* Goler *et al. - Investigating the effect of land-use change on the heat load within two Austrian cities, European Meteorological Society (EMS) Annual Meeting 2021, September 3-10, 2021*	https://meetingorganizer.copernicus.org/EMS2021/EMS2021-165.html
Virtual conference presentation	Claudia *Hahn et al. - Assessing urban climate model results with crowd-sourced data, European Meteorological Society (EMS) Annual Meeting 2021, September 3-10, 2021*	https://meetingorganizer.copernicus.org/EMS2021/EMS2021-152.html
Conference presentation	Claudia Hahn et al. - *Evaluierung von Stadtklimamodellen_mit_Hilfe_privater Wetterstationen, DACH 2022 Meteorologie Tagung, Leipzig, March 21-25, 2022*	https://meetingorganizer.copernicus.org/DACH2022/DACH2022-195.html
Virtual conference presentation	Zuvela-Aloise et al. *Building-resolved simulations with the urban microscale model PALM-4U for case studies in Vienna, Austria, IAUC 2022 International Association for Urban Climate, August 30 – September 1, 2022*	https://iaucposter2022.com/program/
Scientific Paper	Goler R, Zuvela-Aloise M, Oswald S, Hollosi B, Hahn C, Kainz A: *Investigating the effect of land-use/land-cover changes on the heat load of two Austrian cities, Landscape and Urban Planning, in prep.*	In preparation, to be submitted in 2023
Press release	APA press release on 11.10.2022 *„Änderung der Landnutzung kann Hitzeinseln in Städten verstärken oder mildern"*	https://www.zamg.ac.at/cms/de/klima/news/aenderung-der-landnutzung-kann-hitzeinseln-in-staedten-verstaerken-oder-mildern
Brochure	LUCRETIA Brochure for urban planners: *Die Rolle von Landnutzungsänderungen bei der Entwicklung innerstädtischer Wärmeinseln*	Layout in preparation, to be distributed in 2023

Table 4: List of project meetings and external events related to LUCRETIA project

Dissemination Event	Date	Participants
Expert workshop	February 17, 2021	Urban climate modelling experts from DWD
Expert workshop	July 7, 2021	Urban climate modelling experts from DWD
Stakeholder workshop	July 22, 2021	Representatives from city administration of Vienna
Follow-up stakeholder meeting	September 10, 2021	Representatives from city administration of Vienna
Final stakeholder meeting	August 2, 2022	Representatives from city administration of Vienna and Graz

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