Investigation and comparison of heat mitigation potentials of climate change adaptation measures in urban areas between Cologne/Germany and Pune/India using the urban microclimate simulation model ENVI-met

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Abstract

Many urban areas around the world are characterized by both a growing population and an intensification of the urban heat island effect in the context of climate change. The increasing heat exposition of urban dwellers causes significant health risks, not only expressed by higher mortality rates, but also by economic damages. Climate change adaptation strategies are therefore needed in urban design to reduce heat loads and improve thermal outdoor comfort. Cooling potentials of different heat stress mitigation measures must be evaluated based on sound-scientific analyses to identify and recommend best performing options for urban planners. Heat mitigation potentials of technical- and nature-based solutions vary, also between cities depending on the climatic and hydrological conditions, urban geometry and structure as well as cultural differences.

High-resolution microclimate modelling and scenario analyses are a promising approach to evaluate thermal effects of various adaptation measures in urban areas during heat events. The physically-based 3D-gridded ENVI-met model is used to compare the microclimatic effects of climate change adaptation measures between a humid mid-latitude urban area in Cologne/Germany and a semiarid tropical urban area in Pune/India exposed by pronounced monsoon conditions. The models are parameterized and driven based on field measurements in the study areas and remote sensing data. Model outputs are validated using densely-distributed microclimate sensor networks installed within the study areas for different heat periods also including an extreme 20-year heat event. The quality-controlled, standardized and calibrated citizen science sensor networks with around 60 NETATMO sensors as well as research-grade reference stations within each of the two heterogeneous urban study areas (16 ha) represent a novelty and combine the scientific requirement of high resolution and accuracy with the participation and activation of citizens needed for later implementation of climate change adaptation measures.

A mean Nash-Sutcliffe model efficiency coefficient of 0.9 and up to 0.98 for simulated air temperature indicates a high statistical goodness-of-fit of the model to sensor measurements, proving the model reliability for scenario analyses. 92 different scenarios implementing adaptation measures like facade or roof greenings, wet roofs, cooling building materials, street trees, greened front gardens, grass grid paver unsealings, reflective ground surfaces, sunsail shadings or nozzle water spray systems are developed and simulated. Scenarios also take into account future climate change projections. To our knowledge, such a holistic toolset of scenarios including combinations of different measures and different degrees of implementation was never compared in previous research. Simulated air temperature and physiological equivalent temperature (PET) of the scenarios are compared to the status-quo reference to quantify cooling potentials. Heat mitigation effects are checked for statistical significance and compared between both study areas to investigate which measures perform best under the given climatic conditions.

While significant mean air temperature differences of -1.6 K were observed for Cologne, cooling effects are mainly smaller in Pune with mean air temperature differences of only -1.2 K. For PET, heat mitigation potentials are also smaller in Pune with mean differences of -1.6 K, while mean cooling effects of -2.9 K were found for Cologne. These effects are in a magnitude to compensate expected global warming until the end of the century. While technical solutions such as white surfaces mostly perform better in Pune for air temperature, nature-based solutions mainly have a better heat mitigation potential in Cologne. This can be attributed to higher radiative forcing, limited water availability as well as reduced ventilation in India. PET cooling effects are smaller in Pune than in Cologne for nearly all technical- and nature-based solutions. Overall, higher cooling effects were observed for combinations of different solutions than for single measures. More realistic implementations like 25% greened buildings still have a high potential for heat mitigation in the entire quarter. Reflective surfaces and sunsails do not significantly improve thermal outdoor comfort.

This study implies that careful parameterization of urban microclimate models based on quality-controlled field measurements is essential for a high model accuracy. Densely-distributed sensor networks using a citizen science approach can support scientific applications as well as activate stakeholders to implement adaptation measures. Findings have important implications for strategical decision-making in urban planning and highlight the relevance of local assessment of adaptation pathways taking into account urban characteristics and environmental conditions. The identification of best-performing measures ensures human wellbeing in a changing climate and supports several Sustainable Development Goals of the United Nations.

1. Introduction

The increasing frequency and severity of extreme weather events such as heat, drought or flooding is a major problem in cities and a key challenge for urban planning (YANG et al., 2022). While an average global temperature increase of +1.5 to +2.5 Kelvin is expected by the end of the century according to climate projections (ARMSTRONG MCKAY et al., 2022), an even higher warming is forecasted for urban areas. This is caused by reduced albedo, low evapotranspiration as well as poor ventilation of urban environments (ZHAO et al., 2021; MASSON et al., 2020) which results in a future intensification of the urban heat island effect for many cities around the world (HAMDI et al., 2020; KEAT et al., 2021; LO et al., 2020). The ongoing densification of urban areas worldwide due to population growth will cause more people being prone to urban heat stress in future (DARMANTO et al., 2019; HE et al., 2022). By the end of the century, 85% to 90% of the global population is expected to live in urban areas (United Nations, 2018). An increase in health risks and mortality rate due to heat exposure with significant economic consequences results from both trends (EBI et al., 2021; SANTAMOURIS, 2020; WINKLMAYR, 2023).

Climate change adaptation strategies are therefore especially important for urban planning and design to reduce heat loads and negative health effects (SHARIFI, 2021), in line with several sustainable development goals (SDGs) of the United Nations. SDG 13 (*climate action*), which focusses on strengthening capacity to adapt to climate-related hazards, integration of climate protection into policies, strategies, and planning, as well as mobilizing financing for this, is especially relevant in urban contexts. The sub-goal SDG 13.3 highlights that education and raising awareness about climate change and adaptation as well as participatory approaches are a central pathway. SDG 13 is directly linked to SDG 11 (*sustainable cities and communities*) aiming at reducing environmental impacts and developing resilient, sustainable and environmental-sound cities e.g., by green spaces. It is embedded into the context of challenges of rapid urbanization with a special focus on vulnerable groups and aims to strengthen participatory and integrated urban planning approaches. Both goals in turn are related to the scope of SDG 3 (*good health and wellbeing*) which targets to reduce mortality, preventing and managing health risks and ensuring and promoting measures supporting human well-being (United Nations, 2018). Climate-resilient urban planning and the implementation of climate change adaptation measures require both governance by decision-makers (top-down approaches) as well as citizen participation (bottom-up approaches) (SCHNEIDER et al., 2025).

To mitigate urban heat stress, various nature-based solutions and technical solutions are suggested as climate change adaptation measures (LIU et al., 2021; ALBERS et al., 2015). Urban green spaces or green infrastructures are recommended as a central heat mitigation strategy due to its transpiration cooling effect (WONG et al., 2021b; MARANDO et al., 2022; GRAÇA et al., 2022). Especially in urban high-density areas with space limitations for parks and areal green infrastructures, facade or roof greenings can serve increasing latent heat flux for cooling down indoor as well as outdoor conditions (MAYHOUB et al., 2021; JAMEI et al., 2021). Green roofs can also be combined with photovoltaics which supports the shading of vegetation and generates energy for air conditioning when the cooling performance of the green roof is insufficient (SHAFIQUE et al., 2020). As technical adaptation measures, the implementation of materials with reduced heat storage capacity or high albedo surfaces can mitigate heat loads (LOPEZ-CABEZA et al., 2022). However, adverse effects of reflective surfaces on pedestrian comfort within street corridors were found due to increased radiation loads (SCHRIJVERS et al., 2016; LIU et al., 2024). Combinations of reflective surfaces with other measures like street trees can counteract this effect (SMITH et al., 2023). An improvement of thermal outdoor comfort can be reached by technical shading measures such as sunsails (LAM et al., 2023). However, technical and natural shading measures like street trees can also increase temperature if ventilation is limited due to higher roughness. Strategic placement, canopy structure and tree coverage ratio are therefore important factors to optimize cooling effects (WANG et al., 2023). Significant cooling effects can also be enabled by surface unsealing like permeable pavers or grass grid pavers (BATTISTA et al., 2023). They can decrease the absorption of incoming radiation by a higher albedo and shift the partitioning of the surface energy balance towards latent heat flux, reducing the sensible and ground heat flux (DEL SERRONE et al., 2022; HERATH et al., 2018). As an alternative for green infrastructure, blue infrastructure or blue-green infrastructure is often recommended. Microclimatic effects of urban water bodies are proven by XU et al., 2022. But warming effects of water bodies on air temperature can be observed during the nights due to the high heat storage capacity. Another option is given by the implementation of water-cooling systems like blue roofs that can help to cool building materials but have limited effects on pedestrian thermal comfort (TEEN et al., 2022). During extreme heat events, water spray systems in street corridors can therefore be a suitable climate change adaptation measure to regulate urban microclimates during peak hours (ZHAO et al., 2024). Blue or irrigated green infrastructure can also be implemented in combination with water storage capacities for extreme precipitation to serve both flood risk mitigation and heat mitigation in urban areas. To implement such climate change adaptation measures in cities, participation by all parts of society is needed (CORTES et al., 2022). Thus, it is important to involve stakeholders throughout the process, starting from evidence-based diagnosis of microclimatic effects all the way to the implementation and maintenance of climate change adaptation measures.

While microclimatic effects of climate change adaptation measures already implemented in urban environments can be measured on site, the assessment of heat mitigation potentials of further measures or combinations as well as analyses of the cooling performance under future climate conditions can only be performed using model experiments (KWOK et al., 2021; YANG et al., 2019). High-resolving microclimate modelling approaches are a useful tool to investigate heat mitigation potentials of adaptation pathways (WONG et al., 2021a). Scenario analyses can support evaluating thermal effects of measures in comparison to the status-quo of urban environments (OUYANG et al., 2022; FARAGALLAH & RAGHEB, 2022). The physically-based 3D-gridded ENVI-met model is an established software to simulate energy fluxes and mass transfer in urban areas using a high spatial and temporal resolution of up to 1m³ and 0.5 seconds (FOROUZANDEH, 2021; BRUSE et al., 2022). The model uses Reynolds-averaged Navier-Stokes (RANS) equations in contrast to state-of-the-art large-eddy-simulation models (LES) which need more computing power (RUI et al., 2019; BERARDI et al., 2020). As microclimatic effects of small-scale climate factors like urban surfaces or obstacles are very heterogenous and highly spatially deviant, an extensive model parameterization, calibration and validation is important to represent the microclimate of real urban environments with a high accuracy and reproduce all the relevant physical processes (DETOMMASO et al., 2021; YILMAZ et al., 2018; SHINZATO et al., 2019).

The performance of ENVI-met was successfully evaluated using field measurements in previous research (ZANGO et al., 2018; JAMEI et al., 2019; ACERO & ARRIZABALAGA, 2018), indicating the suitability of ENVI-met for urban microclimate simulations. ENVI-met model validations in previous studies were often based only on single temperature measurements (BANDE et al., 2019; KOLETSIS et al., 2019) or mobile pseudo-synoptic measurement campaigns for individual points in time (MILOŠEVIĆ et al., 2022). Studies are often limited to only very few in-situ measurement sensors, small building block-scale model domains, idealized or homogenous study areas (AYYAD & SHARPLES, 2019), or to very short validation time periods (ELRAOUF et al., 2022). Previous research mostly analyses simulation results only for single grid cells or on average for the entire model domain (WANG et al., 2023; THOMAS et al., 2023). However, it is crucial to use more than single measurements to representatively validate microscale models as microclimatic conditions are highly variable in heterogeneous urban environments with different building structures, density, geometry, greenery and ventilation (LIU et al., 2021). Dense 3D sensor networks located not only at average locations but also at extreme locations close to different microclimate factors enable to check if the model can precisely represent physical processes, energy fluxes and complex interactions between the air and different surfaces, materials, structures and vegetation to reproduce lateral and vertical microclimatic pattern including minima and maxima. Microclimate model validation approaches for an ENVI-met model, which was parameterized using local field measurements, based on a quality-controlled, densely-distributed 3D sensor network in a heterogeneous quarter-scale study area and for different weather conditions have never been performed in previous research to our knowledge. Utilizing citizen measurements in urban climate studies can support in this. The potential of crowed-sourced data has been reported by

CHAPMAN et al., 2017; WANG et al., 2019; and MITCHELL et al., 2015. These studies leverage the strengths of combining numerical urban climate modelling techniques and in-situ measurement data collected and provided by citizens to develop local and socially-engaged strategies for heat mitigation under climate change. The increasing abundance of low-cost weather stations worldwide indicates the public interest in this topic. However, citizen measurements are often prone to errors and uncertainties if not implemented following scientific protocols. To our knowledge, establishing quality-controlled, standardized citizen science sensor networks for urban microclimate measurements and linking this with a scientific modelling study for holistic model validation, process analyses and scenario design was not performed so far.

Using scenario analyses, previous research mainly investigated the heat mitigation effects of single climate change adaptation measures like only facade greenings or only shadings, mixed different climate change adaptation measures in one model simulation like trees at the beginning of a street and white surfaces at the end of a street, implemented measures in very small or idealized model domains, or used non-validated ENVI-met model setups (IARIA & SUSCA, 2022; THOMAS et al., 2023; WANG et al., 2023). To our knowledge, no holistic modelling analyses of a full toolset of possible climate change adaptation measures in urban areas were performed in previous research to assess and compare cooling effects of single measures individually as well as combinations of them using a sensor-validated ENVI-met model for a quarter-scale study area.

Challenges and achievements of heat mitigation measures were investigated for different cities worldwide in previous research (ALBERS et al., 2015; LIU et al., 2021). The heat mitigation potentials of various climate change adaptation pathways largely vary between different urban areas around the world depending on the overall climatic and hydrological conditions, urban geometry and density, materials and structure as well as cultural differences. Comparisons of cooling effects of heat mitigation measures in different regions or climatic zones are rare. JAMEI et al., 2021 found the greatest cooling potential for dry climates, while smallest or even no cooling effects were concluded for hot-humid climates. It was found that cooling effects of different adaptation options and strategies are highly variable between cities and therefore need to be compared and assessed locally to identify the best performing measures in different regions and climate zones. Comparative studies were mostly based on remotely-sensed land surface temperature (ZHOU et al., 2017; SMITH et al., 2023; MARANDO et al., 2022). While previous research mainly focusses on 2D analyses on medium-resolution or used indicators, 3D high-resolution modelling studies simulating and comparing microscale cooling potentials of exactly the same climate change adaptation measures and solutions between cities in different climate zones represent a research gap. Our literature search did not yield a paper which has compared the heat mitigation effects of a full toolset of different technical- and nature-based solutions between urban areas in different climate zones using a sensor-validated ENVI-met microclimate model parameterized based on field measurements for a whole urban neighborhood. Especially for Asian regions such as India which are characterized by pronounced monsoon conditions, an overall scarcity of heat mitigation analyses and modelling studies was found (HERATH et al., 2018; SCHEUER et al., 2024; ZHAO & FONG, 2017). Cities in western India such as Pune are facing a significant positive trend in the number and duration of heat events during pre-monsoon season in recent decades (SINGH et al., 2021; JHA et al., 2022; BANERJEE & MAHARAJ, 2020).

Against this background and scientific context, this dissertation thesis aims at answering the following four main research questions for two selected urban study areas in Cologne/Germany and Pune/India to compare climate change adaptation potentials between humid mid-latitude and semiarid tropical climate conditions:

a) Are the setup citizen science sensor networks suitable to identify microclimatic differences and spatial variations within the two urban study areas?
b) Can the parameterized ENVI-met microclimate models of the two urban study areas represent and reproduce the microclimatic characteristics based on a validation with measurements from the densely-distributed sensor networks?

c) How do cooling effects of simulated climate change adaptation scenarios including various technical- and nature-based solutions differ, and which measures and combinations are best-performing for heat mitigation?
d) Does the cooling potential of the simulated climate change adaptation measures differ between the mid-latitude climate conditions of Cologne and the tropical monsoon conditions of Pune, and what is causing these differences?

To address these main research questions, four methodological approaches are used: i) field measurements based on a citizen science approach, ii) microclimate model parameterization and model validation, iii) scenario design, and iv) spatio-temporal statistical analyses and significance tests to compare model outputs and cooling effects.

After the description of the measurement concept of the sensor network installed within the study area in Cologne, an assessment of the suitability of the measurements to monitor microclimatic differences, identify cause-and-effect relationships, and to support microclimatological modelling with ENVI-met is presented (see chapter 2.1). Building up on the experience from the prototype network in Cologne, the setup, characteristics and quality-control procedures of a similar citizen science sensor network installed in the study area in Pune/India are documented. The suitability of the system for scientific purposes in terms of identifying microclimatic variations including technical stability and accuracy as well as indicators of citizen participation, activation and community building are assessed and compared to the network in Cologne (see chapter 2.2). Based upon the meteorological measurements, sensitivity analyses are performed for an ENVI-met microclimate model setup for the study area in Cologne to evaluate the sensitivity of model outputs to meteorological forcing data, and to identify suitable/ optimal lateral boundary conditions to drive model simulations with an accurate representation of the wind flow field (see chapter 2.3). To precisely parameterize the microclimate model for the study area in Cologne, field measurement methods for the static and dynamical model input data including e.g., albedo of surfaces and walls and vegetation and soil characteristics are presented, as well as the development of the model domain based on field mappings and remote sensing data and the model initialization for different heat periods also including a 20-year heat event. Furthermore, the validation procedure of the model outputs based on the sensor network measurements using statistical goodness-of-fit indicators is explained. Simulation results are investigated for spatial differences and patterns within the study area by applying geostatistical methods (see chapter 2.4). Using this validated ENVI-met model setup for Cologne, scenario analyses can be performed to investigate cooling potentials of climate change adaptation measures implemented in the model domain. Exemplarily, a new model parametrization for grass grid pavers based upon in-situ measurements is developed and tested as such permeable surfaces have never been parameterized for urban microclimate models before (see chapter 2.5). Going beyond, a holistic toolset of 92 different climate change adaptation scenario designs using a variety of technical- and nature-based solutions implemented in private and public spaces in the model domain of Cologne is described. Their thermal effects on air temperature and physiological equivalent temperature (PET) in comparison to the reference status-quo are presented. Cooling effects are investigated in a spatio-temporal context and checked for statistical significance to identify best performing heat mitigation strategies and combinations of measures being able to adapt to projected future climatic conditions (see chapter 2.6). Finally, cooling potentials of these climate change adaptation scenarios are compared between humid, mid-latitude Cologne and semiarid, tropical Pune. Therefore, a similar ENVI-met model is parameterized for the study area in Pune using field measurement and remote sensing data based on the same methods conducted for Cologne. The model is validated using the measurements of the densely-distributed microclimate sensor network in Pune. The same scenario analyses are conducted as for Cologne, and cooling effects are compared between both cities to identify which measures and combinations perform better under the given climatic and hydrological conditions. Differences in heat stress mitigation potentials of adaptation pathways between both study areas are tested for statistical significance as a basis for decision-marking in region-specific urban planning aiming to improve thermal outdoor comfort under global warming (see chapter 2.7).

Chapters 2.1 to 2.7 contain the seven research papers (first authorship) of this thesis focusing on the methodological approaches i) to iv) to address the corresponding four research questions a) to d):

- Chapter 2.1: Microclimatic field measurements for an urban high-density residential study area in Cologne/Germany (a)
- Chapter 2.2: Setup of a densely-distributed and quality-controlled citizen science sensor network in Pune/India (a)
- Chapter 2.3: Investigation of the ENVI-met model sensitivity to different wind direction forcing data (b)
- Chapter 2.4: Parameterization and validation of a high-resolution urban microclimate model for Cologne/Germany (b)
- Chapter 2.5: Simulation of heat mitigation effects of unsealing measures by parameterizing grass grid pavers (c)
- Chapter 2.6: Evaluation of heat mitigation potentials of technical- and nature-based solutions using scenario analyses (c)
- Chapter 2.7: Comparison of climate change adaptation potentials between mid-latitude and tropical conditions (d)

Chapter 3 summarizes the results and discussions of these seven research papers regarding the measurements, model setups and parameterizations, model validations, scenario analyses, identified heat mitigation potentials of different climate change adaptation measures, as well as differences in cooling potentials of heat mitigation strategies between Cologne/Germany and Pune/India. Chapter 4 concludes the thesis with an outlook and perspective for further research approaches.

2. Methods and results

2.1 Microclimatic field measurements for an urban high-density residential study area in Cologne/Germany

Journal Article (published):

Eingrüber, N., Korres, W., & Schneider, K. (2022). Microclimatic field measurements to support microclimatological modelling with ENVI-met for an urban study area in Cologne. Advances in Science and Research, 19, 81-90. https://doi.org/10.5194/asr-19-81-2022

2.2 Setup of a densely-distributed and quality-controlled citizen science sensor network in Pune/India

Journal Article (published):

Eingrüber, N., Korres, W., Löhnert, U., & Schneider, K. (2025). Setup of a densely distributed and quality-controlled meteorological sensor network in Pune, India, for urban microclimate research and citizen participation in the context of climate change adaptation. Journal of Sensors and Sensor Systems, 14(1), 13-26. https://doi.org/10.5194/jsss-14-13-2025

2.3 Investigation of the ENVI-met model sensitivity to different wind direction forcing data

Journal Article (published):

Eingrüber, N., Korres, W., Löhnert, U., & Schneider, K. (2023). Investigation of the ENVI-met model sensitivity to different wind direction forcing data in a heterogeneous urban environment. Advances in Science and Research, 20, 65-71. https://doi.org/10.5194/asr-20-65-2023

Errata: Page 67, Column 2, Line 2: "from 0.82 to 0.88 °C" is incorrect and should read "from 0.082 to 0.088 °C".

2.4 Parameterization and validation of a high-resolution urban microclimate model for Cologne/Germany

Journal Article (published):

Eingrüber, N., Berg, P., Korres, W., Löhnert, U., & Schneider, K. (2026). Parameterization and citizen science based validation of a high-resolution microclimate model to identify temperature patterns in a climate change adapted urban high-density area. City and Environment Interactions, 29C, 100302. https://doi.org/10.1016/j.cacint.2026.100302

2.5 Simulation of heat mitigation effects of unsealing measures by parameterizing grass grid pavers for ENVI-met

Journal Article (published):

Eingrüber, N., Domm, A., Korres, W., & Schneider, K. (2025). Simulation of the heat mitigation potential of unsealing measures in cities by parameterizing grass grid pavers for urban microclimate modelling with ENVI-met (V5). Geoscientific Model Development, 18(1), 141-160. https://doi.org/10.5194/gmd-18-141-2025

2.6 Evaluation of heat stress mitigation potentials of technical- and nature-based solutions using scenario analyses

Journal Article (in review):

Eingrüber, N., Zimmermann, D., Korres, W., Löhnert, U., & Schneider, K. (2025). Evaluation of heat stress mitigation potentials of climate change adaptation measures in cities: Scenario analyses for technical- and nature-based solutions using 3D microclimate modelling. Preprint available at SSRN, 6027374. https://doi.org/10.2139/ssrn.6027374

2.7 Comparison of climate change adaptation potentials between mid-latitude and tropical conditions

Journal Article (published):

Eingrüber, N., Zimmermann, D., Löhnert, U., Korres, W., Kumar, S., & Schneider, K. (2026). Comparison of cooling effects of climate change adaptation pathways for urban areas in different climatic zones based on microclimate modelling: Scenario analyses for mid-latitude and tropical conditions. Environmental Challenges, 23, 101456, https://doi.org/10.1016/j.envc.2026.101456

3. Summary and discussion

In this thesis, heat mitigation potentials of climate change adaptation measures in urban areas were investigated by using field measurements based on a citizen science approach, parameterization and validation of physically-based urban microclimate models, design and simulation of 92 different climate change adaptation scenarios, as well as spatio-temporal statistical analyses and significance tests of modelled cooling effects. The heat mitigation performance was compared between the two selected study areas in Cologne/Germany and Pune/India to identify which measures are best suited under the given local climatic and hydrological conditions, and can be recommended for strategical decision-making in urban planning. Thus, this thesis improves knowledge about pathways to increase thermal outdoor comfort in urban environments, and can be used as a scientific basis to derive recommendations for action to increase climate-resilience, health and wellbeing under global warming according to the SDGs 3, 11 and 13 of the United Nations. The following four paragraphs summarize the main findings and discussions of the seven research papers of this thesis according to the four research questions.

1. *Research question: Are the setup citizen science sensor networks suitable to identify microclimatic differences and spatial variations within the two urban study areas?*

The field measurements of the densely-distributed, standardized and quality-controlled citizen science sensor networks established in the two study areas in Cologne and Pune proofed the suitability of the measurement approach to identify microclimatic patterns and differences in heterogenous urban environments based on continuous data collection with a high spatial and temporal resolution. The quality check of the low-cost sensors under laboratory conditions using a 3-point calibration procedure and subsequent validation with high-precision reference devices showed a good accuracy on research-grade level expressed by a mean RMSE of 0.08 K. Long-term stability of the data quality and consistency between the sensors was proven and ensured by regular recalibration procedures and sensor rotations every six months. At the same time, these low-cost sensors have a high potential to facilitate citizen participation in science-based identification of cooling effects of climate change adaptation measures (PHILLIPS et al., 2019; SCHNEIDER et al., 2025). Based on descriptive statistical analyses and tests as well as pairwise comparisons, significant microclimatic differences were observed between the contrasting measurement sites selected according to scientific criteria. Differences can be explained by and attributed to small-scale climatological process drivers. It was found that sensors located close to vegetation, away from obstacles, at greater height levels, or in well-ventilated areas show a significantly lower mean air temperature. Thus, the measurement concept and the dense weather station networks with around 60 sensors in each study area allow to monitor spatial and temporal microclimatic variability, identify cause-and-effect relationships, and differentiate pseudo-homogeneous zones with specific microclimatic characteristics. In comparison between both study areas, a lower data transmission rate was found for Pune than for Cologne due to frequent power shortages in India as well as radio signal transmission issues during monsoon season. However, data quality after recalibration is nearly the same for both study areas so that microclimatic effects and differences can be identified with the setup measurement network in Pune in the same way as in Cologne. These findings show the suitability of the installed, metadata-documented sensor networks for scientific applications such as to support physically-based urban microclimate modelling with ENVI-met for the two study areas (CHAPMAN et al., 2017). Thus, these quality-controlled measurements can be used to evaluate and validate model outputs (DANG & PITTS, 2020).

The engaged stakeholders are highly interested and active in using the corresponding app to monitor the local measurement data and inform themselves about microclimatic effects in their living environment. This reveals the high potential of citizen science and participation in climate change adaptation. The measurement concept allows them to identify environmental issues and heat mitigation potentials in their neighborhoods, and strengthens community building (CALLAGHAN et al., 2019). The developed quality-controlled sensor networks and protocols also enable a future expansion under scientific standards. Our findings highlight the transferability of the approach. As successful climate change adaptation requires extensive research as well as citizen activation using knowledge acquisition and hands-on experience by own measurements and observations, this measurement concept can support in both taking action for individuals as well as decision-making for urban planners.

2. *Research question: Can the parameterized ENVI-met microclimate models of the two urban study areas represent and reproduce the microclimatic characteristics based on a validation with measurements from the densely-distributed sensor networks?*

A high-resolved, 3D-gridded, physically-based ENVI-met model was setup and parameterized for the 16-ha urban high-density study areas in Cologne and Pune to simulate and reproduce the microclimatic conditions. The model domains include more than one million grid cells and were development based on cadastral geodata sets, remote sensing data and field mappings, and parameterized using field measurements of relevant parameters such as surface albedo or leaf area density. The lateral boundary conditions for meteorological forcing as well as the initialization conditions were based on observations within the study areas. Sensitivity analyses demonstrated that the ENVI-met model output accuracy highly depends on the wind direction forcing data. Thus, high-quality measurements of wind direction and wind speed are crucial to drive this microclimate model and reach a good model performance. The models were validated using the measurements of the densely-distributed, quality-controlled in-situ sensors networks to check if the models can represent the microclimatic conditions and small-scale physical processes within these urban environments. The comprehensive validation procedure represents a novelty as, to our knowledge, no holistic validation approaches on quarter-scale for a parameterized ENVI-met model have been conducted before for different meteorological conditions, also including a 20-year extreme heat event in Cologne in July 2022.

Absolute and relative statistical goodness-of-fit indicators showed that the model outputs have a high and significant agreement to the microclimatic measurements, e.g., with an average NSE of 0.89 and up to 0.97 for simulated air temperature in Cologne (mean NSE of 0.85 and up to 0.98 for Pune). The models have a high validity for different altitudes above ground level, in all different spatial units of the study areas from parks or inner courtyards to narrow street corridors, and for all different urban surfaces and ground materials from natural to completely sealed asphalt. The model performance is independent from the distance of sensor sites to obstacles like buildings or trees, and can also represent thermal effects at sensor sites close to facade or roof greenings. The model fit is much higher than calculated in other studies which mostly have not parameterized the model based on field measurements and also have not used a dense network with such a high number of sensors at heterogenous sites for continuous measurements. Thus, the models are a good representation of the real urban environments, and are reliable to reproduce the microclimatic characteristics for different locations with various small-scale climate factors such as different ventilation conditions. This also verifies that the setup models are able to simulate microclimatic conditions and processes such as evapotranspiration with a high statistical fit even at locations with complex site characteristics or very close to energetic transformation surfaces. The models therefore have a high validity in predicting local microclimatic differences, contrasts and variability within the two study areas including extrema. E.g., at sensor sites very close to ground, to (south-oriented) facades, to vegetation, poorly-ventilated or totally shaded, good NSE values of still more than 0.7 were determined. Thus, spatial variations and diurnal cycles are precisely simulated by the models.

As the model performance was evaluated for several summer periods with various meteorological conditions like different dominating wind directions, wind speeds or temperatures, and no significant differences in the model performance were found, it can be concluded that the models are suitable to reproduce the microclimatic conditions and its temporal and spatial variations for these heterogeneous urban areas not only for typical summer days, but also for extreme heat events with more than 40 °C. Based on the validated model outputs, spatial patterns of microclimatic conditions within the model domains were identified. In agreement to the measurements, model results showed mean air temperature differences up to 4.8 Kelvin between spatial units like the urban park, inner courtyards, the greened avenue or narrow street corridors.

However, it was found that the model performance is limited especially during very calm conditions without any turbulent exchange when there is nearly no wind speed and no obvious circulation, but highly fluctuating wind direction in the input data. For very low wind speeds and short-term changes in wind direction, the wind flow field might become unrealistic (LOPEZ-CABEZA et al., 2022). Especially in small and closed courtyards of building blocks with limited ventilation and high roughness (also caused by the model assumptions and simplifications of gridded stair-shaped structures of oblique walls), the model can

become unable to accurately represent exchange processes which was also found in LIU et al., 2024. This can result in overestimation of air temperature and underestimation of relative humidity. Furthermore, it was also found that border effects of the model can limit the performance at the edge of the model domain (OUYANG et al., 2022).
Findings highlight the importance of high-accuracy input data as well as model parameterization and initialization to setup precise microclimate models. The validation results show the potential of the two models to analyze microclimatic differences and cause-and-effect relationships with a high spatial and temporal resolution which cannot be identified by measurements only. Without such a detailed and comprehensive parameterization and validation of the models for the status-quo reference case, scenario analyses cannot be performed in a well-founded way. Using these successfully validated model setups, microclimatic effects of different climate change adaptation measures can be investigated. Heat mitigation potentials of scenarios can be quantified and compared to assess adaptation potentials to future climatic conditions.

3. *Research question: How do cooling effects of simulated climate change adaptation scenarios including various technical- and nature-based solutions differ, and which measures and combinations are best-performing for heat mitigation?*

To assess and compare the heat mitigation performance of a wide range of different adaptation measures on quarter-scale, 92 scenarios with various technical- and nature-based solutions were designed to investigate their cooling potentials for Cologne. Therefore, adaptation measures were individually parameterized based on field measurements and implemented in private and public spaces to simulate and evaluate their effects on air temperature and physiological equivalent temperature (PET) during the selected extreme 20-year heat event in comparison to the reference status-quo. In this way, strategies and combinations which are most suitable to reduce urban heat loads for pedestrians and adapt to future climate conditions according to climate projections until 2099 can be identified. Scenarios include measures at buildings like ground-based and non-ground-based facade greenings or intensive and extensive roof greenings, wet roofs and cooling building materials, and measures in street corridors such as street trees, green front gardens, high-reflective ground surfaces, grass grid paver unsealings (GGPs), sunsail shadings, or water spray nozzles, as well as various combinations of those.
Statistically significant air temperature differences of -3.0 K and up to -6.3 K and PET differences of -4.3 K and up to -11.1 K on spatial average in a pedestrian height level were identified for climate change adaptation scenarios with maximum additional greenery in private and public spaces. Many strategies like water spray nozzles can cool down the entire air volume of the study area and not only at locations where they were implemented. Shading measures show a significantly better cooling performance in open areas compared to narrow street corridors. High-albedo building surfaces prove to be ineffective for outdoor heat reduction. They significantly increase mean air temperature by up to +4.32 K and PET by up to +12.49 K. While measures such as facade greenings result in cooler air temperatures nearly all over the day, sunsails would cause a slight heating during nighttime hours but a significant cooling during daytime hours. A slight nighttime warming was also observed under the canopy of street trees, both due to reduced ventilation and sky view factor (limited long wave radiation emission). For blue infrastructure such as urban water bodies, a warming effect was also found during nighttime hours due the increased heat storage capacity of water (XU et al., 2022; JACOBS et al., 2020). The unsealing of asphalt surfaces by using the newly-developed GGP parameterization for ENVI-met causes a significant mean air temperature cooling effect of up to -2.69 K (and -5.43 K for PET).
Even higher cooling effects were observed for combinations of different technical- and nature-based solutions which have a greater magnitude than the sum of the cooling effects of its single measure implementations (CORTES et al., 2022). This clearly demonstrates that there is not the perfect adaptation strategy. A mixture of different solutions would lead to the best cooling performance in urban areas. Especially the combination of street trees with GGPs (-3.3 K) and the combination of green buildings with reflective streets are highly effective in mitigating urban heat loads and would result in a significantly stronger air temperature cooling performance. Those pathways are suitable to adapt to future climate change consequences by

counteracting the mixed effects caused by low albedo and low evapotranspiration in urban areas and thus reducing sensible and ground heat fluxes (ZHAO et al., 2021). For PET, combinations of different climate change adaptation strategies would also lead to a better heat stress mitigation performance than implementations of single measures. In contrast to air temperature, any combinations with reflective surfaces would cause an obvious thermal discomfort due to increased radiation loads reaching the skin of pedestrians (SCHRIJVERS et al., 2016). Thus, the combination of green buildings with white streets showing a high air temperature cooling efficiency is designated as non-effective for heat stress mitigation according to PET. Thermal outdoor comfort could be most improved for combinations of greenery at buildings with street trees as well as for combination of street trees with GGPs (both up to -9.2 K). These combinations can therefore be concluded as the most powerful climate change adaptation pathways for increasing thermal outdoor comfort from all designed scenarios. Thus, combining facade greenings, street trees and GGPs is highly-effective in reducing urban heat stress and the pathway that can be recommend the most for urban planning. Findings clearly show that changes in albedo of buildings or surfaces are not a useful tool for reducing heat stress in urban environments and therefore not worth investing when aiming to improve outdoor comfort conditions.

If maximum greenery would be implemented under future climatic conditions of 2099 based on RCP8.5 projections, the mean temperature increase of +3.1 K could be reduced to +1.7 K and minimum +0.5 K. Correspondingly, an intensive design of green infrastructure as nature-based solution in urban areas would not allow to fully adapt to expected climate change effects, but can reduce the mean warming by -47 % and up to -86 %. Mean PET warming could be reduced to nearly 0 K and up to a cooling effect of -6.5 K. In contrast to air temperature, an intensive design of green infrastructure would allow to compensate and fully adapt to climate change effects. This means that with this scenario design, the climate change adaptation measures can maintain the current status-quo of thermal comfort during heat events even in 2099 if water is not limiting. Thus, future heat stress for pedestrians could remain nearly on the same level as today. With moderate climate change pathways like RCP4.5 instead of RCP8.5, the designed scenarios could even result in a cooling until 2099, or scenarios with a smaller degree of implementation of measures (like 25 %) would then allow to fully adapt to climate change effects. Several measures such as GGP unsealings and blue-green infrastructure cannot only mitigate heat, but also have further co-benefits in mitigating flood risks and droughts as part of the sponge-city concept. When combined with water storage systems like cisterns to buffer extreme precipitation, this enables water spray or irrigation of greenings by pumping mechanisms during heat and drought periods (BEAN et al., 2007; DEL SERRONE et al., 2022; BATTISTA et al., 2023).

It is important to discuss that heat mitigation effects of climate change adaptation measures are highly variable in space and time. Depending on specific local conditions and urban structures, cooling performances can largely vary between day and night, are direction-dependent, and are influenced by the predominant wind speed and the given wind direction in the study area. The variety of surfaces and shapes in urban areas exhibit a high diversity of features influencing the environment. The interplay of different processes contributes to the complexity of the urban microclimate and individually affects cooling potentials of measures. Heat mitigation effects can therefore not be generalized and must be considered locally. Furthermore, the identification and quantification of cooling effects in urban areas is a complex procedure and depends on the selection of thermal metrics which cannot be generalized (MIDDEL et al., 2021). Although metrics like mean radiant temperature or thermal comfort indicators such as PET and Universal Thermal Climate Index (UTCI) are better suited for describing heat perception and stress levels of human individuals than air temperature as they also take into account relevant parameters such as relative humidity, solar irradiation, clothing, metabolism and personal characteristics like body mass index, those indices are limited with regard to transferability and generalizability for people of different size, weight, age and gender. They are therefore based on assumed standardizations for comparability reasons (ANDERS et al., 2023). Quantification of cooling effects should therefore always use various metrics instead of single ones to describe direct physical causalities as well as integrative effects and consequences for human heat perception.

It must be noted that the results observed from Cologne have limitations regarding generalizability for other regions. Findings might be partially representative for some cities in western and central Europe with similar climatic conditions and urban geometry, arrangement, structure, density and topography, but cannot directly be transferred to urban areas in other climate zones around the world. Nonetheless, for very stable low-exchange and clear-sky weather conditions with hardly any turbulent exchange, like during the simulated 20-year extreme heat event, the urban microclimate is only affected by highly-local energy conversion which is independent from spatial city arrangement and geometry. For those specific situations, results might be partially generalizable for other cities globally. Additionally, scenario analyses were only performed for a single event representing extreme summer heat conditions which are most relevant for thermal discomfort, heat stress and health effects of urban dwellers in central Europe. Thus, the results and analyzed heat mitigation magnitudes might not be representative for other meteorological conditions and seasons. Findings can be used as a general guideline for evaluating different options and combinations of climate change adaptation measures. However, specific investigations for diverse local applications in other study areas are recommended.

It was shown that not only the selection of climate change adaptation measures itself is crucial to improve heat mitigation potentials, but also the strategical positioning of measures like trees (MORAKINYO et al., 2020). Challenges for heat mitigation performance are also given due to overall water availability for evapotranspiration of nature-based solutions. Therefore, cooling effects need to be compared between urban areas with different climatic and hydrological conditions to investigate generalizability of findings. This is exemplarily performed between humid Cologne and semiarid Pune characterized by a higher variability in water availability due to a pronounced pre-monsoon heat and drought season.

4. *Research question: Does the cooling potential of the simulated climate change adaptation measures differ between the mid-latitude climate conditions of Cologne and the tropical monsoon conditions of Pune, and what is causing these differences?*

Heat mitigation potentials of different technical- and nature-based solutions can vary between cities depending on specific climatic, hydrological and urban-structural conditions etc. (LIU et al., 2021; ALBERS et al., 2015). As a comparison of cooling performance of a wide toolset of climate change adaptation measures between different climate zones was identified as a research gap, potentials of heat mitigation measures were compared between the humid, mid-latitude urban study area in Cologne and the semiarid, tropical study area in Pune based on microclimatological modelling. 54 scenarios applying different climate change adaptation measures such as roof and facade greenings, street trees, unsealing, sunsails, water spray systems, or high-reflective materials were designed exactly in the same way for both study areas to compare their cooling effects on air temperature and PET.

Analyses showed significant mean air temperature differences of -1.6 K for Cologne, while mean cooling effects are smaller in Pune with only -1.2 K. For PET, heat mitigation potentials are also smaller in Pune with mean differences of -1.6 K, while mean cooling effects of -2.9 K were found for Cologne. Findings highlight that green infrastructure such as facade greenings, street trees, urban forests, greened front or back yards, GGP unsealing, shading by sunsails and combinations of those mainly have a better heat mitigation performance for both air temperature and PET in Cologne than in Pune. Wet roofs, high-reflective building or ground surface materials, extensive roof greenings as well as combinations of those and combinations of white surfaces with other greenery mainly resulted in a better air temperature cooling performance in Pune, but a better PET cooling performance in Cologne. Intensive roof greenings, high-reflective buildings in combination with high-reflective ground surfaces as well as nozzle water spray systems were identified as climate change adaptation strategies which mainly showed a slightly better heat mitigation potential for both air temperature and PET in Pune than in Cologne.

In general, nature-based solutions perform significantly better in the humid climate of Cologne, while technical solutions mainly perform better or equal in Pune. Limited soil water availability for evapotranspiration of vegetation, overall greater solar irradiation, greater building density and lower building heights, longer heat-induced stomata closings, as well as less ventilation than in Cologne were found to be major reasons why some heat mitigation measures perform worse or even counterproductive in Pune (ZIAUL & PAL, 2020; DWIVEDI & MOHAN, 2018). Findings are in agreement with WANG et al., 2023 who also identified reduced cooling potentials in very narrow street corridors with limited ventilation conditions which are significantly more common in Pune than in Cologne. Further minor reasons why some measures perform worse in Pune are already lighter ground and building surfaces than in Cologne and shorter radiation (photosynthesis) hours due to its geographical location. Although an overall better cooling potential of greenings would be expected in Pune due to a greater saturation deficit for evaporative cooling (JAMEI et al., 2021), limited water availability for evapotranspiration was found to be the dominating driver for the better cooling performance of greenings in Cologne. An intensive design of green infrastructures would allow to fully adapt to climate change effects for PET and thus maintain the current status-quo for Cologne, but not for Pune. However, maximum greenery in Pune could reduce the mean PET warming effect by -41% until 2099 under RCP8.5.

Although greenings perform better in Cologne, the implementation of green infrastructure at buildings and in street corridors can be recommended for urban planning in Pune as they still have a significant and powerful cooling potential. Especially in combination with other measures such as sunsail shadings, unsealing or high-reflective surfaces and materials, heat stress can significantly be reduced in Pune (KHORAT et al., 2024). Findings also highlight the relevance of strategical selection of tree and greening species and geometry in India which show a high drought-robustness and no or only partial stomata closings during hot peak hours while maximizing shadow effects and minimizing roughness and limitation of ventilation and sky-view factor (ALI & PATNAIK, 2019). Even if water spray systems proofed a good heat mitigation performance in Pune, their realistic feasibility and operationality is critical and highly limited by overall water scarcity in that region during pre-monsoon hot-dry season. Therefore, when aiming to optimize water usage in Pune, water spray systems can only be recommended during daytime peak hours when they showed the most-efficiently cooling. Heat mitigation performance of shading measures in Pune such as sunsails could also be optimized e.g., by automatically rolling them out during peak hours and rolling them up over nighttime when they resulted in warming effects. In this way, sunsails would not further limit ventilation and cooling processes during nighttime in Pune where ventilation is already more reduced by a higher building density. Findings can support decision-makers and urban planners in selecting, designing, optimizing and implementing best-performing heat mitigation measures as well as assessing their cooling potentials. Our results emphasize the need for taking into account urban-structural constraints and requirements as well as climatic and hydrological conditions when aiming to increase future thermal outdoor comfort and human wellbeing under global warming and a higher magnitude and frequency of heat waves. The comparison between Pune and Cologne can support as a guidance for choosing appropriate climate change adaptation pathways in different climatic contexts, but individual analyses of heat mitigation performance in other regions or seasons are still necessary.

4. Outlook and conclusions

The findings of this thesis highlight the relevance of local assessment of cooling effects of climate change adaptation measures under specific urban as well as environmental circumstances. Analyses also show the challenges associated with the implementation of the selected measures in the given urban contexts. In future research, the potentials of heat mitigation measures should be evaluated for and compared to cities in other climate zones and hydrological conditions such as hot-humid climates or cities with different urban structures and geometry to further assess generalizability of the findings and improve regional recommendations for most-suitable and effective climate change adaptation strategies. Further analyses should also investigate the microclimatic effects of the simulated adaptation measures under different meteorological conditions besides extreme heat events such as more turbulent conditions. Further disadvantages or co-benefits of the heat mitigation measures during other seasons such as warming and isolation effects during winter season should also be taken into account. As findings from this thesis are based on thermal outdoor comfort and heat mitigation performance for pedestrians, and can therefore not be generalized for cooling potentials in the interior of buildings, effects of the simulated climate change adaptation strategies on thermal indoor comfort should also be compared between climate zones in future research.

While thermal comfort analyses in this thesis focused on heat perception expressed by physiological equivalent temperature of a standardized human, it would be useful to expand analyses to body characteristics of vulnerable groups such as elderly people or young children in further research. In this way, modelling results could directly be used and transferred to evaluate heat mitigation potentials in the environment of people which are most prone to heat stress and health risks, and recommend suitable measures, e.g., for nursing facilities, retirement homes, kindergartens, schools or playgrounds.

Results from this thesis can also have large implications in supporting cost-benefit analyses for the identification of best cost-effective solutions with the largest cooling effects and smallest installation investment and maintenance costs or smallest water demand at the same time, e.g., in relation to technical air conditioning systems or photovoltaic. Further research progress should also be made for optimizing the performance and efficiency of measures, e.g., under the limitations of water scarcity in semi-/arid regions. For controlled technical systems such as water spray nozzles, optimization could be implemented by adjusting the usage times. For nature-based solutions, the strategical selection of drought-robust species is crucial. For unsealing, substrate characteristics should be optimized to enhance infiltration rates, also in the context of flood risk mitigation and stormwater management. For example, silt-based substrates amended with biochar and organic matter have demonstrated to significantly enhance soil moisture retention in urban soils during heat waves. Thus, further modelling studies are needed to investigate heat mitigation effects of optimized measures, as well as more realistic scenario implementations taking into account real willingness to act and pay for measures of dwellers in urban neighborhoods. Therefore, in ongoing research, agent-based microclimate modelling scenarios will be developed for the study areas including intention and willingness to implement climate adaptation measures by using questionnaire surveys. It is important to select and recommend heat mitigation measures not only based on their cooling performance but also according to their social acceptance in the cityscape.

Although scenarios in this thesis were based on criteria such as space availability, monument protection, statics or traffic loads, other critical components like urban mobility in the context of expansion of bicycle lanes, accessibility for disabled people, evacuation routes, subsurface infrastructure, as well as usage conflicts of different interest groups are difficult to take into account. Additional factors such as technical feasibility, financial viability, and legal frameworks including legislation and land use regulations should also be investigated in further research. While the assessment of this modelling study exclusively focuses on microclimatological benefits, associated co-benefits of further related ecosystem services of urban blue and green infrastructure such as ecological traits and functions, carbon sequestration, air quality enhancement and contribution to biodiversity conservation and expansion, as well as aesthetic and recreational services must also be considered in further interdiciplinary analyses to develop a holistic assessment framework for decision-making. Those services and their monetary values should similarly be included when judging adaptation measures. At the same time, it must be ensured that risks of maladaptation and potentially negative impacts and ecosystem disservices like the production of allergenic pollen or an increase in pest populations are avoided.

For non-experts who might not have resources for performing such a high-accuracy modelling procedure but are interested in analyzing climate change adaptation potentials in urban areas, the presented approach can serve as a guideline highlighting the most relevant parameters and configurations. Furthermore, simulation outputs and results of such precisely parameterized models could be used to train artificial intelligence (AI) tools which can support non-experts in reproducing microclimatic conditions for other use cases and study areas without holistic field measurements and model parameterization. Machine learning could also support in scaling analyses and findings from quarter to full city-scale. In this context, AI trained with high-resolution model outputs from different quarters as well as remote sensing data can fill the gaps between district microclimate modelling with ENVI-met (1 m resolution) and state-of-the-art city-wide meteorological reanalyses (100 m resolution). In further research, it is also recommended to compare our findings obtained from the Reynolds-averaged Navier-Stokes (RANS) model ENVI-met with building-resolving large-eddy-simulation models (LES) such as PALM-4U. LES models can be operated at a similar resolution of 1 m and are more accurate in terms of capturing transient, unsteady flow features and explicit turbulence, but are much more demanding concerning computational power.

Sustainable urban development requires climate change adaptation measures as well as the acceptance of the urban population. To realize the simulated heat mitigation potentials of measures of this thesis, active citizen participation is needed. Further efforts should be made for citizen involvement and activation in climate change adaptation as well as communication of research findings highlighting the promising cooling effects of these measures shown in this thesis. Participatory approaches that activate, engage and empower local communities and stakeholders in implementing climate change adaptation measures in their own living environment must be further developed in line with SDG 13.3. Citizen science as a bottom-up approach represents a central chance in developing resilient urban environments and increasing human wellbeing and comfort in a changing climate, especially for regions with limited adaptation potentials. Transformation can be facilitated through citizen science monitoring networks that build community ownership of local climate data, environmental education programs that enhance local climate literacy, and feedback mechanisms that translate modelling results into actionable guidance for residents and decision-makers. The presented approach in this thesis has a high potential for establishing science-based self-help measures for local communities confronted by climate change impacts. Knowledge acquisition and personal hands-on experience by affordable own measurements and observations combined with a networking and community building approach can support in taking action for individuals in a decentralized, self-motivated and self-organized manner. Measurements offer an experience-based understanding of the risks of climate change to urban life and support in developing judgement skills. This can help in identifying and understanding a suitable course of action towards implementing adaptation measures personally influencing the heat exposure and thermal comfort of individuals. Cooling effects of (self-) implemented measures can directly be observed by citizen scientists to prove their suitability, and scientists can accompany and monitor specific adaptation measures or efforts of initiatives like greening or unsealing projects to improve their research.

The increasing abundance of low-cost weather stations worldwide indicates the public interest and highlights the potential of our presented approach of a quality-controlled, standardized and metadata-documented sensor network to be used for citizen activation and urban microclimate research. Our approach enables a future expansion of the two existing measurement networks and the establishment of further similar networks under scientific standards around the world. Initiatives for measurement networks could for example be driven by schools which have a particularly important social multiplier effect regarding their active role in climate change adaptation. To expand this citizen science approach beyond local communities and to initiate further sensor networks in other regions and countries going beyond the direct intervention and resources of scientists, our quality-control protocol with the defined criteria and standards could be provided as a user-friendly and freely-available guidance in several languages. E.g., by directly implementing it in corresponding smart-phone apps of citizen weather stations (like the NETATMO weather app). Smartphone apps offer unique activation elements and opportunities for conducting independent, evidence-based environmental observations. They enable users to measure locally, while simultaneously facilitating networking and cooperation through sharing of collected data and online access to measurements of others. Feedback functions in apps can directly place own observations within a scientific context supporting a learning process to understand cause-and-effect relationships for assessing own options of goal-oriented action. When integrating systematical guidelines like instructions for installation and metadata documentation in apps which is directly linked with data transfer of the measurements and feedback, a standardized global database of quality-controlled microclimate measurements suitable for scientific applications could be established going far beyond crowd-sourcing. This could offer entirely new opportunities for urban climate research and a global to local assessment of climate change adaptation potentials, especially for regions with data scarcity. Such a database of standardized citizen measurements could also be used to be compared to, cross-correlated with, quality-checked, improved and expanded by remote sensing data products like land surface temperature (e.g., from Landsat). Besides validation, statistical downscaling methods could be applied enabling advanced urban microclimate analyses and mapping finer than the grid resolution of satellite data. The database would also allow to observe cooling effects of urban redesign and scientifically monitor transformative processes over longer time periods.

Environmental awareness shows socio-cultural differences within and between populations. Therefore, citizen involvement must address all kinds of social milieus ranging from precarious to high-educated performer milieus, and therefore include stakeholder-specific participation forms. Thus, it is necessary to examine potentials of different forms of activation and as well as access to participation possibilities for various social groups in further research. It is important to also activate and inform groups with limited investment capacity (for measures like air conditioning) and groups which are mostly exposed to heat like homeless people or outdoor workers. Information events, workshops, excursions, citizen dialogues and hands-on experiments in networks like parishes, neighborhood associations or cultural and social facilities can serve as access points. Therefore, integrative co-creation approaches also considering socially disadvantaged milieus should be developed to increase awareness, ability and willingness to implement heat mitigation measures in cities. In ongoing research, we compare two neighborhoods in Cologne that have a different social composition to investigate differences in operational ability to participate and, based on this, assess and compare milieu-related climate change adaptation potentials.

As citizen science proved as a powerful pathway to support numerical urban microclimate modelling, we encourage to further develop and expand such approaches, also in other related scientific applications. Integrating participatory observation and measurement concepts with environmental modelling builds societal trust in modelling results and the effectiveness of climate adaptation measures. It can also support in legitimizing political decisions. Although our specific results from this thesis for Cologne and Pune have limitations in transferability to study areas in other climate conditions, our approach of integrating citizen science into such modelling applications by using measurements from participating local dwellers is generalizable to other regions as citizen science is independent from climate zones. The thesis showed that participatory approaches in urban climate research can significantly contribute to SDG 13 by outlining suitable pathways for action and empowering citizens to implement them. In the context of urban acupuncture, the sum of single measures implemented by individuals finally shows a positive effect on a larger scale to mitigate urban heat island effect.

We also encourage to better integrate research findings on heat mitigation potentials of climate change adaptation measures into decision-making in urban planning and politics as top-down approach. Efforts should focus on reducing constraints, barriers and limitations for implementation by incentives like fiscal policies, reinforcing legislative measures, and promoting support and funding schemes in a non-bureaucratic and attractive way. Reduction of expenditures such as wastewater taxes when implementing green or blue infrastructure is a useful way to increase willingness to pay for climate change adaptation in private households. While most climate change adaptation initiatives currently focus on the implementation of measures in new development areas, strategies for the building stock should be given a special focus as they make up the majority (around 97%) of buildings in urban areas. Solutions addressing the implementation limits in the building stock need to be further developed and established. Additionally, current programs of city departments mainly relate to private house owners who are able to implement climate change adaptation measures, but not to owner communities or renters who are interested and willing to implement measures but do not have capacities or permissions to do so. Renters who are not able or entitled to change something at their homes but willing could be offered to pay an additional tax based on which the city department implements measures in closeby public spaces like street trees in front of the houses. Conflicting interest in urban planning need to be solved based on sound-scientific analyses such as balancing housing and infrastructure needs with benefits of green spaces. Municipalities play a pivotal role and must be equipped with adequate financial and human resources. Collaborations of urban planning authorities from city departments and private urban planning offices as well as investors supporting sustainable urban development (public-private-partnerships) should be stimulated and improved to implement and scale strategies across cities. Health insurance companies could play a central role in financing heat mitigation measures like nature-based solutions as they would directly benefit monetarily from reduced heat loads in urban areas in future due to lower healthcare costs of heat-related illnesses providing a significant return of invest. Companies should also identify potentials of funding and implementing heat mitigation measures in the environment of their employees which increases productivity of labor resulting in monetary benefits.

Research findings of this thesis outline that there is not a knowledge problem in urban climate change adaptation, but an implementation problem. Therefore, our results can act as a catalyst for both policy makers and urban developers to prioritize investment in measures to ensure resilient and livable cities in a changing climate. Our results and recommendations can support decision-makers in identifying best-performing heat mitigation strategies and combinations of solutions to reach the promising simulated cooling potentials in a most effective way, and avoid non-suitable or counteractive measures such as high-reflective surfaces. As proved by our analyses, technical- and nature-based solutions can reduce urban heat loads in a magnitude of expected global warming and thus would allow to fully adapt to climate change if properly implemented. Correspondingly, future thermal outdoor comfort could remain on the same heat stress level as today, directly reducing health risks and mortality rate. Overall, our analyses highlight the relevance and importance of a timely realization of climate change adaptation measures by administrative actors of city departments (top-down) as well as private urban dwellers (bottom-up) equally to contribute to the SDGs 3, 11, and 13 of the United Nations and enable comfortable and healthy future living conditions in cities affected by climate change.

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The following seven partial publications of this thesis are available:

Eingrüber, N., Korres, W., & Schneider, K. (2022a). Microclimatic field measurements to support microclimatological modelling with ENVI-met for an urban study area in Cologne. Advances in Science and Research, 19, 81-90. https://doi.org/10.5194/asr-19-81-2022

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Further publications:

In addition, the following further journal articles and conference contributions were published as part of the doctoral project:

<ins>Journal Articles, Manuscripts and Book Chapters:</ins>

Eingrüber, N., Burdová, N., Dlugoß, V., Domm, A., Bongartz, M., & Nehren, U. (2026c). Hotspots in Urban Areas: A Novel Approach to Assess the Heat Mitigation Potential of Nature-Based Solutions Using Microclimate Modelling. Urban Climate, 65C, 102814. https://doi.org/10.1016/j.uclim.2026.102814

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Eingrüber, N., Schneider, K., Nehren, U., & Dlugoß, V. (2024a). Climate change adaptation through citizen participation: Simulation of the effect of willingness to act on the heat mitigation potential in urban neighborhoods with different social milieu composition. EMS Annual Meeting 2024, Barcelona, Spain, 1–6 Sep 2024, Vol. 21, EMS2024-547. https://doi.org/10.5194/ems2024-547

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