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Combining Social Aspects of Climate Change with Urban Heat Stress Modelling – a Case Study from Bremerhaven, Germany

Markus Groth, Steffen Bender, Ricarda Klafka

(Dr. Markus Groth, Climate Service Center Germany (GERICS) – Helmholtz-Zentrum Hereon, markus.groth@hereon.de)
(Apl.-Prof. Dr. Steffen Bender, Climate Service Center Germany (GERICS) – Helmholtz-Zentrum Hereon)
(Ricarda Klafka, Technische Hochschule Bingen)

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1 ABSTRACT

The impacts of climate change create interconnected ecological, economic, and health challenges that act as multiple drivers shaping local social conditions in urban areas. While municipal adaptation strategies increasingly address physical risks such as heat, flooding, and drought, the social dimensions of climate change often remain underrepresented. Vulnerability to climate impacts, however, is not evenly distributed. Certain population groups – such as older people, children, people experiencing homelessness, and individuals with low income – are particularly at risk. Moreover, low-income neighborhoods are often disproportionately affected by heat waves. This is partly due to the fact that these areas typically have below-average access to open spaces such as parks or water bodies. Furthermore, the distance to public recreational areas often increases as household income decrease.

Against this background, the paper presents a case study on heat stress modeling in Bremerhaven, Germany. The analysis focuses on the Goethestraße district, which faces significant socio-economic challenges and holds the lowest social index of the city. Bremerhaven itself is characterized by the second-highest unemployment rate and the highest rate of over-indebtedness among all German cities. The case study employs a top-down approach using scientific data – including environmental parameters, weather observations, and regional climate projections – as inputs for model simulations conducted with the "Tygron Platform". This was complemented by a bottom-up approach involving key stakeholders from the city administration to integrate expert knowledge, local perspectives, and community-based assessments. Through this transdisciplinary and co-creative process, all major decisions – like the definition of the current and future climate scenarios to be taken into account, the potential adaptation measures to improve the thermal comfort (mainly the integration of green spaces, urban trees, and water areas), the integration of aditional stakeholders from the city admistration, the future communication of the modeling results – were taken collaboratively and on an equal footing.

Beyond conventional urban climate modeling approaches and indices commonly applied in Germany, the study also incorporates planning principles from the Netherlands, notably the 3-30-300 rule. In addition to presenting modeling results, the paper discusses possible practical adaptation options and first next steps to strengthen socially inclusive climate adaptation strategies.

Keywords: climate change adaptation, co-creation, social aspects of climate change, urban heat stress modeling , urban resilience planning

2 INTRODUCTION

The impacts of climate change pose ecological and economic challenges that are also influencing and interacting with the local social conditions in urban areas (IPCC, 2022). While physical risks such as heat, heavy rainfall, or drought are increasingly considered in municipal adaptation strategies, social aspects often remain underrepresented (EEA, 2025; Teebken, 2024; Teebken & Schipperges, 2024; Juhola et al., 2022). Certain population groups – such as older people, children, the homeless, or individuals with low income – are particularly more vulnerable to climate impacts (Etzel et al., 2024; Prina et al., 2024; Proulx et al., 2024; IPCC, 2022; Swanson, 2021). Especially heatwaves disproportionately affect low-income urban neighborhoods. This is for example because compared to more wealthy neighborhoods, socially disadvantaged ones often show higher proportions of sealed and developed land. In combination with an associated lack of shades from trees or cooling effects of green spaces and water bodies, these districts can heat up more easily. Additionally, housing conditions in these areas tend to exacerbate vulnerability, as buildings are often poorly insulated and overcrowding limits opportunities for retreat during extreme heat events. Therefore residents are often unable to find relief from heat at home or within walking distance of their homes (Yin et al., 2023; IPCC, 2022; Rehling et al., 2021).

These circumstances for example contradict one of the goals of the Federal Climate Adaptation Act (KAnG)[1] – the German regulatory binding framework for climate change adaptation – aiming to prevent the increase of social inequalities caused by the negative impacts of climate change. Additionally, the German Strategy for Adaptation to Climate Change[2] aims to strengthen the resilience and resistance of ecological systems, the economy, and society to create equal living conditions. In this context, impact assessments are key for developing climate adaptation concepts. However, the use of the commonly used models to examine spatial vulnerabilities often focuses solely on identifying hot spots related to land use and building structures, only indirectly addressing social issues. However, it is important to also consider social aspects from the outset, as a one-sided focus on physical exposure can lead to maladaptation.

Against this background, the paper presents a case study of heat stress modeling for the district Goethestraße in Bremerhaven, Germany.[3] The Goethestraße is characterized by significant socio-economic challenges. It has the highest population and building density in Bremerhaven and is marked by high proportions of residents with migration backgrounds as well as children and adolescents, of which about one-half live in households receiving basic income support for job seekers. Overall, the district has the lowest social index in Bremerhaven – a city that itself in 2024 had the second-highest unemployment rate (14.5%) and in 2025 was the city with the highest rate of over-indebtedness (18.3%) in Germany (Creditreform, 2025; Statista, 2025).

To assess current and future heat stress and to estimate the effectiveness of potential adaptation measures, heat exposure and the impacts of various scenarios were simulated for the Goethestraße district using an urban climate module of the “Tygron Platform”. The analysis also focused on testing the applicability of this modeling tool, which relies on simplified process assumptions and is commonly employed in the Netherlands to support the implementation of the 3-30-300 rule in urban planning (Konijnendijk, 2024; 2023; 2021). This guideline stipulates that residents within a neighborhood should: i) be able to see at least three trees from their home or workplace, ii) benefit from a minimum tree canopy cover of 30%, and iii) live no more than 300 meters away from a green space or park suitable for recreation. A secondary objective was to explore, through scenario-based simulations, how local heat stress is projected to evolve under future climate conditions and to what extent different adaptation measures can contribute to improve the thermal comfort.

The case study includes a top-down approach based on scientifc data – containing environmental data, weather observations and results from regional climate projections – as input for the model simulations carried out by the Tauw GmbH using the “Tygron Platform”. This setting was combined with a bottom-up approach involving local key stakeholders to incorporate local expert knowledge, stakeholder perspectives, and community-based assessments. Based on this transdisciplinary and co-creative approach, all key decisions – like the definition of the current and future climate scenarios to be taken into account, the potential adaptation measures to improve the thermal comfort (mainly the integration of green spaces, urban trees, and water areas), the integration of aditional stakeholders from the city admistration, the future communication of the modeling results – were taken collaboratively.

The paper is structured as follows. Section 3 briefly highlights main aspects regarding the current discussion on social aspects of climate change. Section 4 introduces the destrict Goethestraße as the model region as well as the specific heat stress modeling approach. Section 5 presents and discusses the main results for all four scenarios taken into account. Section 6 concludes by summarizing main results, reflecting on the specific indicators used and highlighting possibel next steps.

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[1] https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Gesetze/kang_en_bf.pdf.

[2] https://www.bundesumweltministerium.de/DL1322-1.

[3] The specific content of the conducted modeling approach is based on the TAUW final report ‘Hitzemodellierung Bremerhaven – Ortsteile Goethequartier und Klushof’ by Zerhusen & Bauer (2025), which was developed as part of a joint project by the Climate Service Center Germany (GERICS), TAUW GmbH, and the City of Bremerhaven to create a new prototype module for the “GERICS Adaptation Toolkit for Cities”.

3 SOCIAL ASPECTS OF CLIMATE ADAPTATION

It is in general well understood that the impacts of climate change affect different population groups with varying intensity. Older people, individuals with pre-existing health conditions, and children are most frequently identified as vulnerable groups. In addition, pregnant women, people experiencing homelessness, and outdoor workers may also face elevated risks. Socio-economic factors such as low income, insufficient financial security, language barriers, and limited educational attainment further exacerbate individual vulnerability by constraining adaptive capacity. Given the high level of exposure and comparatively lower adaptive capacities of certain groups, socially equitable adaptation strategies should place particular emphasis on these vulnerable groups (EEA, 2025; Meer, 2025; Etzel et al., 2024; Prina et al., 2024; Proulx et al., 2024; IPCC, 2022; Swanson, 2021).

A key challenge lies in the fact that individual living conditions strongly shape exposure, and multiple vulnerabilities can overlap, making it difficult to derive generalized conclusions. Moreover, significant differences in adaptive capacities and needs exist both across the general population and within the different social groups. Evidence also suggests that insufficient consideration of social dimensions can further exacerbate existing inequalities within society (Spannagel & Brülle, 2024; IPCC, 2022; Swanson, 2021; Barnes et al., 2020).

Climate risk assessments, however, often focus primarily on exposure, overlooking social characteristics that critically influence susceptibility for climate change impacts. For example, Graham et al. (2018) demonstrate that risk assessments which fail to account for social factors may result in the relocation of socially connected, low-income communities without preserving their social networks – an outcome that could increase vulnerability, further marginalize these groups, and negatively affect their motivation to participate in political decision-making processes. Also the European Climate Risk Assessment (EEA, 2024), the European Commission′s Communication on Managing Climate Risks (EC, 2024), the EC′s Climate Action Progress Report (EC, 2023) and most recently the EU Preparedness Union Strategy (EC, 2025) stress the need for adaptation strategies that prioritise and focus on vulnerable populations to ensure that justice is integrated more broadly into efforts towards adaptation and societal preparedness. This highlights the critical importance of integrating socio-economic contexts alongside physical risks in assessment processes, to effectively reduce vulnerability and lower the escalating risk of maladaptation (EEA, 2025; IPCC, 2022; Shi et al., 2016; Ribot, 2014).

Despite these clear insights, recent research on subnational adaptation plans in Europe conducted by the European Environment Agency (EEA, 2025) illustrates for example a significant gap between recognition and implementation of measures with respect to social vulnerability. The study found that socially vulnerable groups are most frequently acknowledged during the early stages of the adaptation policy cycle, particularly in climate impact and risk assessments, with 68% of local adaptation plans including such considerations. However, this attention declines substantially in later stages: only 45% of plans incorporate socially vulnerable groups into specific adaptation actions, 7% monitor progress related to these groups, and 4% directly involve them in the planning process. Furthermore, only 3% of the plans examined include one or more adaptation goals explicitly addressing climate justice.

Interpreting the outcomes of urban climate analyses presents another specific methodological challenge, as these analyses typically rely on anonymized representations of cities, neighborhoods, and buildings without demographic or socioeconomic context. Nevertheless, empirical evidence indicates that heatwaves disproportionately affect socioeconomically disadvantaged urban areas (Yin et al., 2023). Income-based spatial segregation is also increasingly observable in Germany: lower-income households frequently reside in substandard housing conditions (e.g., insufficient thermal insulation, absence of air conditioning) and have limited access to cool refuges during extreme heat events. Furthermore, access to urban green infrastructure exhibits a strong socioeconomic gradient (Schüle et al., 2017; Wüstemann et al., 2017). For instance, the walking distance from residential locations to the nearest public park, tends to increase as household income decreases (Rehling et al., 2021). Overall, neighborhoods characterized by socioeconomic disadvantage demonstrate below-average provision of open spaces (Senatsverwaltung für Mobilität, Verkehr, Klimaschutz und Umwelt Berlin, 2025).

To assess local vulnerability within impact analyses, a top-down approach is commonly applied, using various indicators and local data to determine exposure. However, a key challenge lies in capturing social aspects based on specific and reliable data, as standardized indicators and externally defined descriptions of vulnerability often fail to adequately reflect the root causes and lived realities of vulnerability (Teebken & Schipperges, 2025).

To design effective adaptation and avoid exacerbating social inequalities, it is therefore essential to integrate social dimensions and justice already at the stage of vulnerability assessments. Early and inclusive stakeholder engagement in planning, design, and implementation is a central component for ensuring socially just climate adaptation (Leuphana University Lüneburg, 2024; Teebken, 2024; Teebken & Schipperges, 2024; Juhola et al., 2022; Breil et al., 2021; Fedele et al., 2019; Shi et al., 2016). Through this bottom-up approach, local knowledge and diverse perspectives can inform the characterization of local vulnerability. Consequently, both approaches – top-down and bottom-up – are crucial for capturing social vulnerability.

4 MODEL REGION AND MODELING APPROACH

4.1 Model region: destrict Goethestraße

The district Goethestraße is predominantly characterized by dense, impervious residential areas with multi-story perimeter block development. In the northwestern section, there are several sealed residential areas with multi-story linear buildings. North of Frenssenstraße, commercial areas and some vacant lots are located. The eastern Hafenstraße features mixed residential areas combined with commercial premises. Within this district, there are vacant multi-family buildings in need of renovation – some of these so-called "junk properties" have been closed for safety reasons. Most residential buildings are privately owned, with owners often residing outside the city.

A site inspection by the project team in May 2025 revealed a significant need for heat protection measures in public recreational spaces. Although some new trees have been planted and older street trees exist along the Goethestraße and adjacent streets, there remains a considerable need to provide adequate shading for pedestrian and cycling paths. This also applies to public recreational areas. For example, the Zollinlandplatz offers only limited shaded areas, and the Leher Pausenhof consists largely of sealed surfaces with a playground lacking sufficient shade.

This need for adaptation is particularly relevant given the district's demographic and social characteristics. The population density in the Goethestraße district is approximately more than ten times higher than the average density in Bremerhaven. As a designated "arrival neighborhood", the proportion of residents with a migration background is around 51% (Magistrat der Stadt Bremerhaven, 2024), significantly exceeding the citywide average of about 17%. The share of children and adolescents is also higher at around 21% compared to the citywide average of 10%, with this group exhibiting a very high need for language support (over 80%). In general, residents of this district are heavily affected by unemployment and debt, with a substantial proportion of the working-age population (approximately 31%) receiving basic income support for job seekers (Proloco Bremen & plan zwei, 2023).

The social vulnerability of the district has been confirmed by recent monitoring efforts. As part of the social area monitoring conducted in 2023 (Magistrat der Stadt Bremerhaven, 2023), Bremerhaven's districts were analyzed and categorized based on their social situation. The classification was derived from an index value calculated using six indicators: i) need for language support, ii) proportion without a high school diploma, iii) child poverty, iv) share of employable residents receiving SGB-II benefits, v) unemployment rate, and vi) proportion of non-voters. The index value indicates the extent to which a district's social status deviates from the citywide average. The district with the lowest status value is Goethestraße, with a calculated value of -1.6. Finally, the interplay between social vulnerability and environmental stress also becomes evident by a comparative analysis of nine-year mean air temperatures (2017–2024) and the social index at the district level carried out as part of the case study. This analysis suggests a tendency for neighborhoods with lower social status to exhibit higher average air temperatures – and thus more heat stress (Klafka, 2025).

4.2 Heat stress modeling approach

To estimate where heat hotspots occur within the city and to learn about the possible effectiveness of adaptation measures, it is common practice to conduct model simulations using urban climate models. Scenario analyses allow the comparison of urban planning and meteorological scenarios based on high-resolution, spatially comprehensive data (Bender et al., 2025). A key criterion considered in these simulations is human thermal comfort, which can be assessed using various indices. These indices help to describe whether a given microclimatic situation is perceived as comfortable or uncomfortable. This perception is primarily determined by the human energy balance (Höppe, 1999), which is calculated using a combination of meteorological parameters (air temperature, humidity, wind speed) and human factors (clothing type, activity level) to quantify heat exchange at the skin surface and heat transfer within the body. One commonly applied index – also used in this study – is the Physiological Equivalent Temperature (PET), which expresses results in degrees Celsius, thereby facilitating communication (Matzarakis et al., 1999). The classification of PET values is provided in table 1.

PET-Range in °C	Stress level	PET-Range in °C	Stress level
> 41	Extreme heat stress	13 – 18	Slight cold stress
35 – 41	Strong heat stress	8 – 13	Moderate cold stress
29 – 35	Moderate heat stress	4 – 8	Strong cold stress
23 – 29	Slight heat stress	< 4	Extreme cold stress
18 – 23	No thermal stress		

Table 1: Influence of physiologically equivalent temperature (PET) on the modeled temperature stress on humans (based on Matzarakis et al., 1999).

The calculations used the urban climate model of the "Tygron Platform". To assess urban heat stress, the "Tygron Platform Heat Module" in combination with the "Heat Stress Overlay" was utilized. An autochthonous weather pattern at a summer day was selected for the analysis of urban heat exposure. This weather type is characterized by the formation of cold-air flows during nighttime and pronounced diurnal cycles of air temperature, humidity, wind speed, and solar radiation, which amplify the effects of urban climate phenomena (Oke et al., 2017).

The evaluation of urban heat stress was based on the indicators proposed by Kluck et al. (2020): i) PET, ii) walking distance from residential buildings to public recreational areas not affected by heat stress, and iii) the proportion of shaded areas on public traffic surfaces.

The calculation of shaded areas on public traffic surfaces consider terrain elevation and urban morphology. Walking distance was determined through a network analysis of streets, pedestrian paths, and cycle routes at the building level. This analysis incorporated previously calculated PET values, assuming a threshold of 29°C to define heat-unaffected areas – corresponding to the upper limit of slight heat stress according to established classifications. Additionally, a minimum size of 200 m² was set for potential recreational areas. Private spaces and areas outside the model boundaries were not considered in this approach.

In addition, and to assess local heat distribution based on the PET as well as the effectiveness of adaptation measures, the four scenarios defined in table 2 were devoped and used within the modelling framework.

Szenario	Definition
KliStaRef	Representative current summer day as a reference scenario for describing present urban heat stress. The basis is formed by data from the climatological standard normal period (1991–2020) recommended by the World Meteorological Organization.
KliWaMed	Representative average summer day in the near future, based on the median value of regional climate projections for the period 2036–2065, considering the intermediate emissions scenario (RCP4.5).
KliWaMax	Representative extreme summer day in the near future, based on the maximum value of regional climate projections for the period 2036–2065, considering the intermediate emissions scenario (RCP4.5).
HitAnK	Representative current summer day with adaptation measures to describe present urban heat stress while accounting for the effects of potentially implementable adaptation measures (a combination of e.g. green spaces, building greening, urban trees, and reflective surface materials).

Table 2: Simulation scenarios for assessing heat stress.

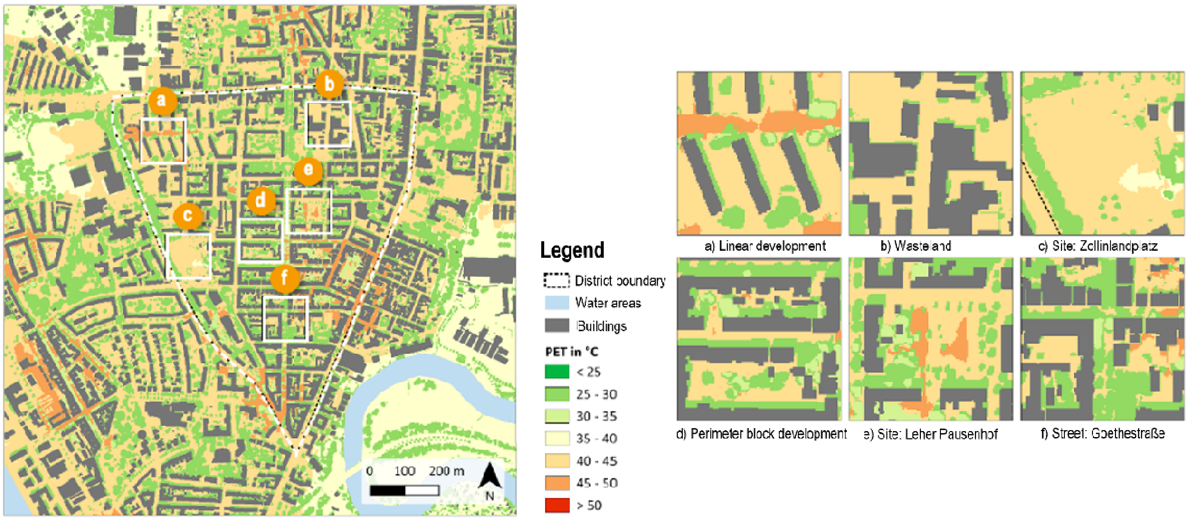
5 RESULTS

The assessment of urban heat stress in all scenarios is carried out at a pedestrian-relevant height of 2 meters, using the spatial distribution of PET values. To enable a clearer evaluation of the small-scale urban climatic structure, the district was subdivided into smaller subareas representing typical urban design patterns. For the Goethestraße district, the analysis highlights in detail the following elements: (a) linear development („Zeilenbebauung"), (b) wasteland („Brachflächen"), (c) Zollinlandplatz, (d) perimeter block development („Blockrandbebaung"), (e) Leher Pausenhof, and (f) Goethestraße.

5.1 Current situation – KliStaRef

5.1.1 Heat stress

At 2:00 p.m., the highest PET values (above 45°C) occur in the Goethestraße district between the linear building structures, in the central part of the Leher Pausenhof, as well as along the southern facades of buildings and within densely built street spaces (figure 1). The most favorable comfort conditions, characterized by slight to moderate heat stress (25°C to 35°C), are found on the shaded northern sides of buildings or beneath tall vegetation. Furthermore, the modeling results indicate that perimeter block development with a west–east building orientation generates significantly more shade compared to north–south oriented linear structures. An exception is the north–south oriented Goethestraße itself, where tree shading locally reduces PET values.



a) Linear development b) Wasteland c) Site: Zollinlandplatz

d) Perimeter block development e) Site: Leher Pausenhof f) Street: Goethestraße

Fig. 1: PET values during the peak heat stress around 2:00 pm in the Goethestraße district for the KliStaRef scenario.

5.1.2 Shaded areas on public traffic surfaces

Between 12:00 p.m. and 6:00 p.m., the proportion of shaded areas on public traffic surfaces in the Goethestraße district varies by subarea, ranging from 41.4% (Goethestraße-North) to 51.2% (Gnesenerstraße). A detailed analysis reveals that areas such as Zollinlandplatz, the central section of the Leher Pausenhof, and many inner courtyards of perimeter block developments lack any shading during this time period (figure 2). Favorable shading characteristics include multi-story buildings, tall urban trees with large crown diameters, and narrow street canyons.

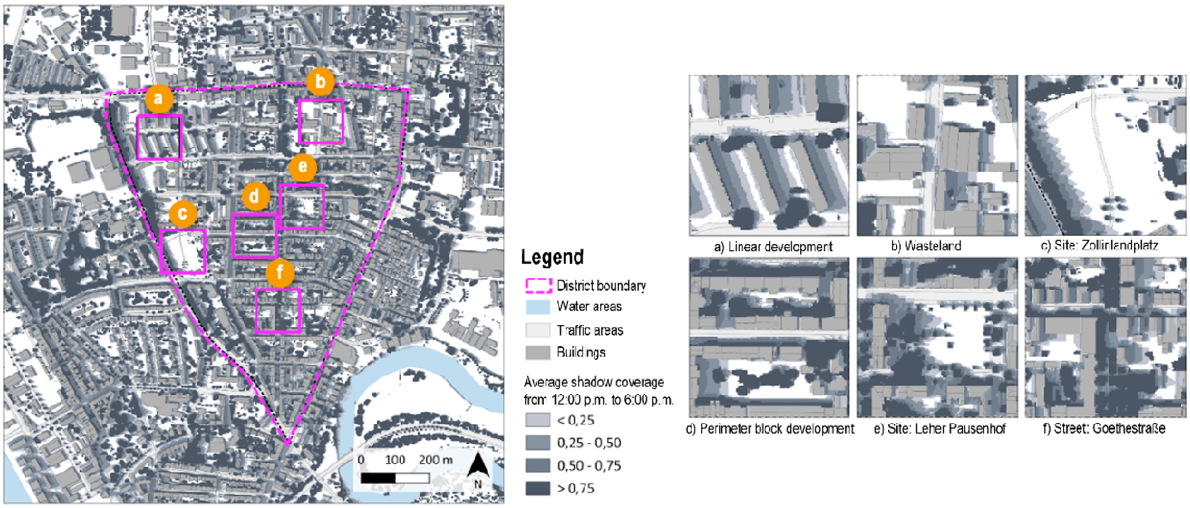


Fig. 2: Share of shaded traffic surfaces between 12:00 p.m. and 6:00 p.m. in the Goethestraße district, scenario KliStaRef.

5.1.3 Walking distance

The modeling of walking distances to heat-unaffected public recreational areas shows that in the Goethestraße district, distances of 400 m or more can occur in the northwestern and southern sections (figure 3). However, this result should be interpreted with caution, as areas with the highest values are located near the model boundaries, making it possible that recreational spaces in adjacent districts could reduce the actual walking distances.

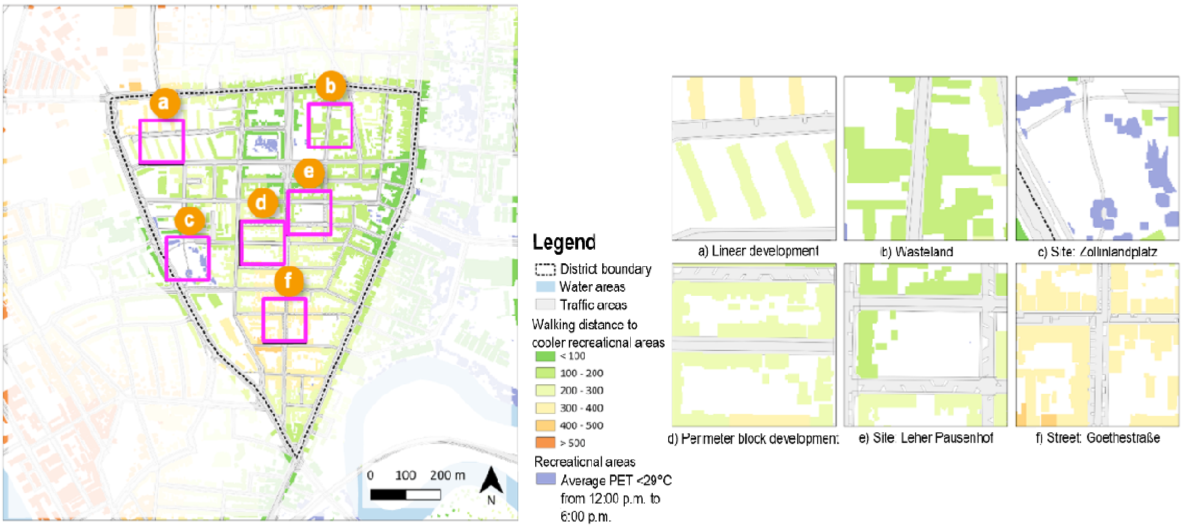


Fig. 3: Walking distance from buildings to heat-unaffected public recreational areas between 12:00 p.m. and 6:00 p.m. in the Goethestraße district, scenario KliStaRef. Areas outside the model boundary have been excluded.

5.2 Future scenarios – KliWaMed und KliWaMax

Both scenarios exhibit a comparable pattern of PET values, although thermal stress is consistently higher than in the reference scenario. Overall, PET values in KliWaMax are approximately 2°C higher compared to KliWaMed. When examining the spatial distribution of PET in the detailed subareas, heat stress in street spaces, inner courtyards, and between buildings increases further under KliWaMed (figure 4) and, in particular, under KliWaMax (figure 5). The contrast between shaded and unshaded surfaces also becomes more pronounced in these scenarios.

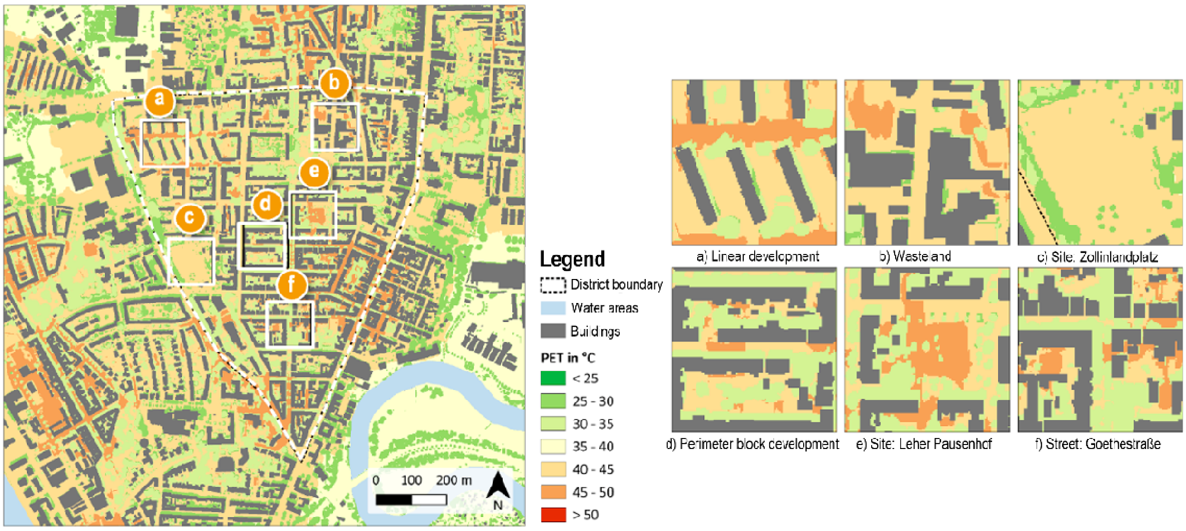


Fig. 4: PET values during peak heat stress around 2:00 pm in the Goethestraße district, scenario KliWaMed.

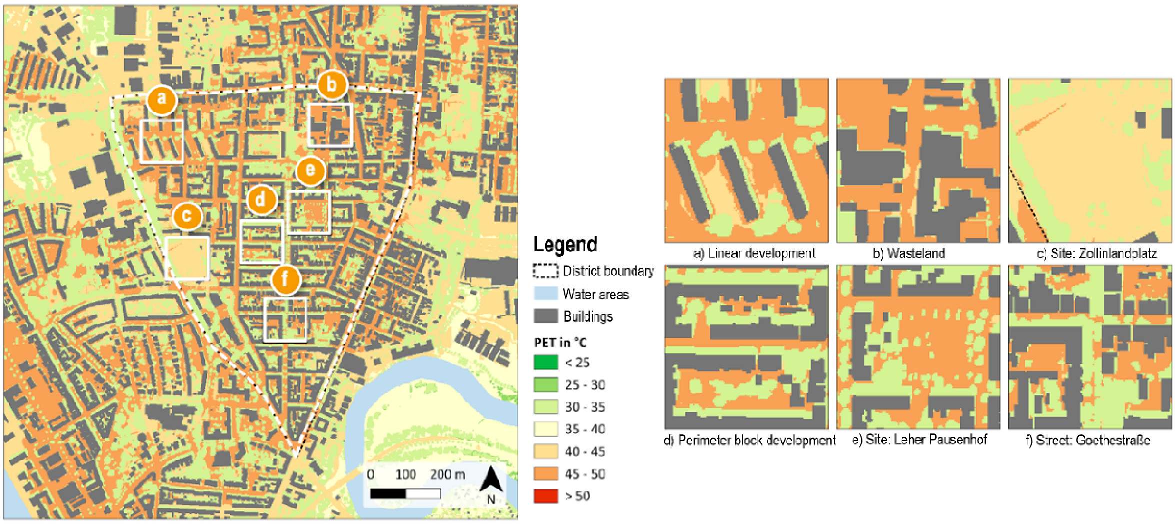


Fig. 5: PET values during peak heat stress around 2:00 pm in the Goethestraße district, scenario KliWaMax.

5.3 Current situation with adaptation measures – HitAnK

This scenario is based on the reference scenario and incorporates adaptation measures that are potentially feasible within the urban area to reduce heat-related impacts. Existing trees, buildings, and traffic surfaces were retained during implementation. Methodologically, the measures were realized by adding various green space configurations in areas such as vacant lots, parking spaces, sealed roadside strips, unused brownfields, sealed commercial fringe areas, and sealed recreational spaces. In some residential sections, tree density was increased (figure 6). In this scenario small trees (10 m height, crown diameter: 5 m), medium trees (15 m height, crown diameter: 10 m), and large trees (20 m height, crown diameter: 15 m) were included, whereas a minimum safety distance of 2.5 m between tree crowns and buildings was maintained. Planting distances were chosen based on two criteria: i) maximizing canopy closure and ii) preserving access points and parking spaces along traffic surfaces. As a measure with theoretically high visibility potential – but currently not beeing feasible in practise –, the former course of the Aue stream in the Goethestraße district was reconstructed in the model using historical city maps. This intervention widened the watercourse to 5 m and added 5 m-wide green strips with scattered tree groups on both sides of the stream. However, it has to be considered, that this model tool cannot calculate PET values above water surfaces, so that positive effects were minimal. In order to obtain a better direct comparison of all measures, another model that can calcluate PET-values over all surfaches has to be used for the modeling.

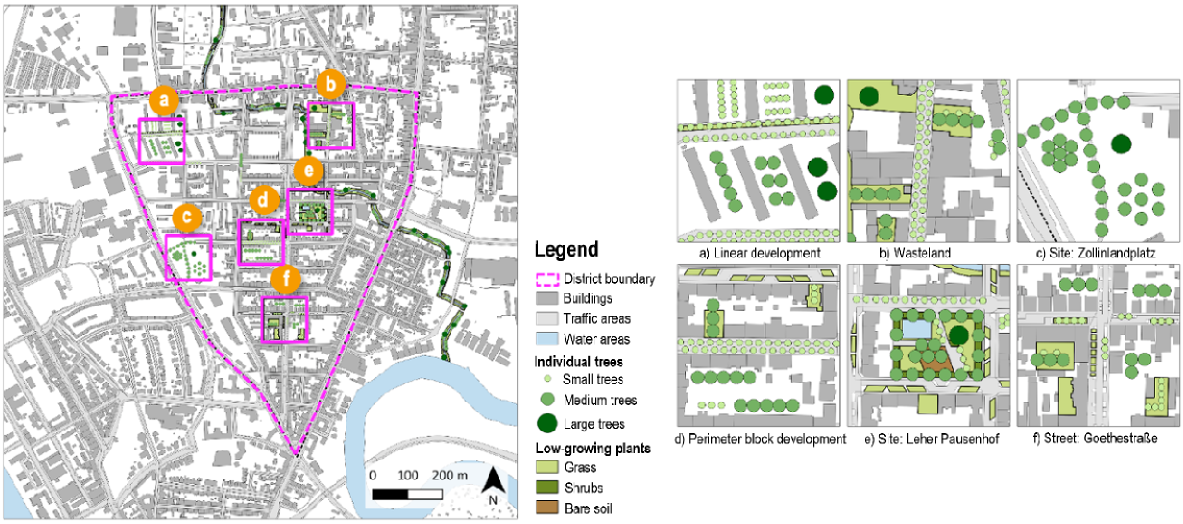


Fig. 6: Structure of the heat adaptation scenario (HitAnK) in the Goethestraße district.

When comparing the current thermal stress with a hypothetical situation in which numerous adaptation measures have been implemented throughout the model area, it becomes immediately apparent that heat stress has decreased by one to two PET classes in many locations. The expansion of shaded areas has improved conditions between linear and perimeter block developments, in street spaces near wasteland, at Zollinlandplatz, and at the Leher Pausenhof, reducing severe heat stress to moderate or slight levels (figure 7). However, the modeling also reveals that the increased tree cover locally reduces ventilation to such an extent that small areas – such as the wasteland subarea and some southern building façades (e.g., perimeter blocks or Goethestraße) – exhibit a narrowly confined increase in PET values.

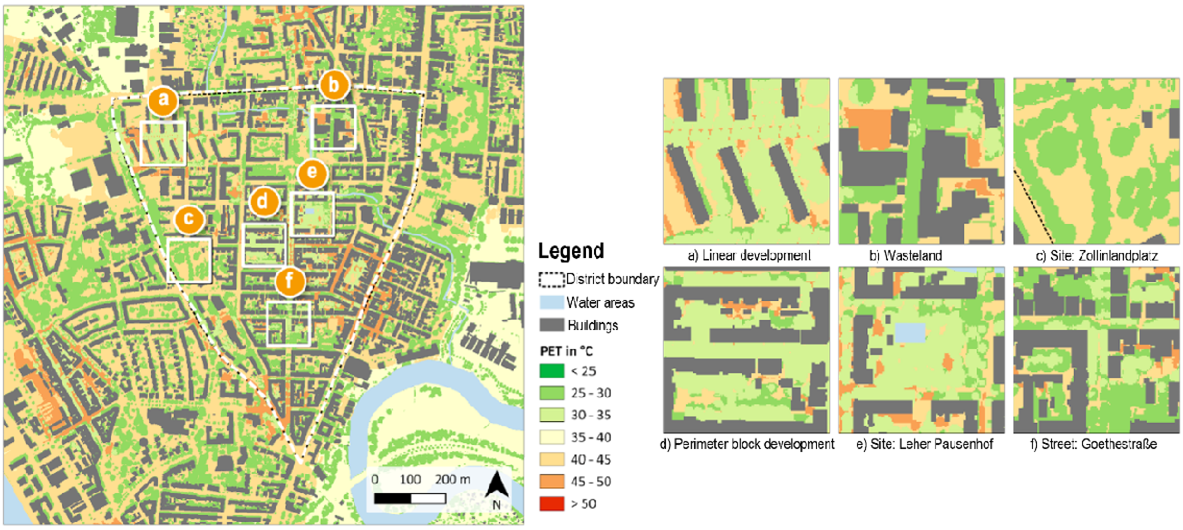


Fig. 7: PET values during peak heat stress around 2:00 p.m. in the heat-adapted Goethestraße district, scenario HitAnK.

The benefits of adaptation measures become evident when examining the difference map (figure 8). At the time of peak heat stress (2:00 p.m.), differences between the reference and adaptation scenarios range from -15.3°C to +2.3°C. Cooling effects in newly greened residential areas with low-growing vegetation reach -1.8°C (e.g., in the northern part of the vacant lots or the southern section of the Leher Pausenhof). In the shade of newly planted trees, PET values decrease up to -15.3°C, and in most cases around -10°C to -15°C. Areas planted with tree groups arranged in an east–west orientation and with close spacing provide more extensive cooling compared to tree groups oriented north–south with wider spacing. In contrast, the reconstructed course of the Aue stream appears to have a limited cooling effect in the Goethestraße district. This – as already mentioned above – can mostly explaint by specific limitation of the model approach.

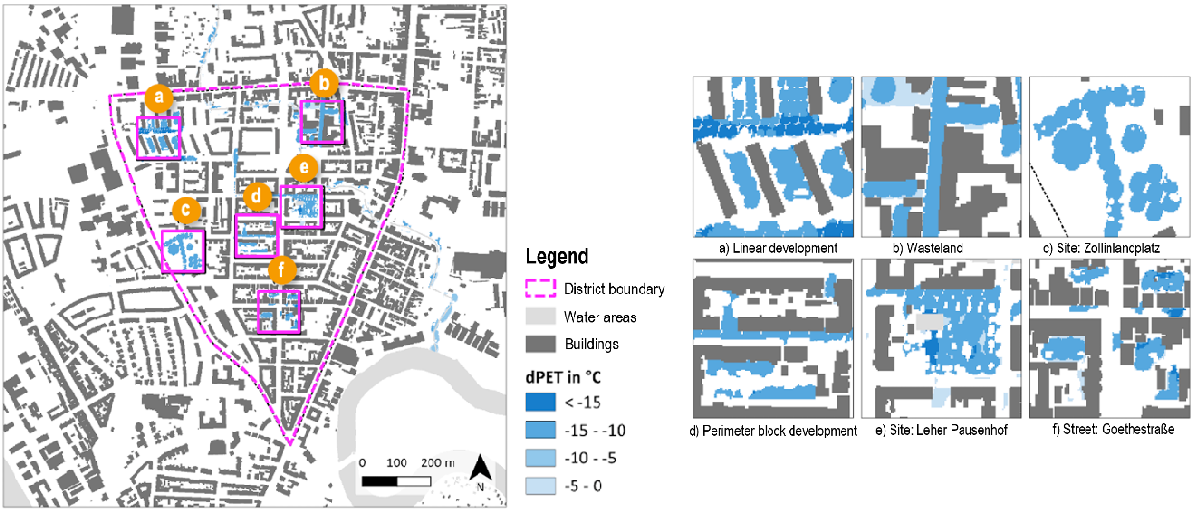


Fig. 8: Difference in PET values between the HitAnK and KliStaRef scenarios in the heat-adapted Goethestraße district during peak heat stress around 2:00 pm.

6 CONCLUSION

The modeling results indicate that the highest PET values occur around 2:00 p.m. on sun-exposed, south-facing sides of buildings or across built-up areas without any significant shading. The most favourable thermal conditions are found where surfaces are permanently – or at least for several hours – extensively shaded. Therefore, adaptation measures should primarily aim to increase shading during the midday and afternoon hours – especially on sun-exposed facades and roofs of buildings. In addition to the use of large-canopy urban trees and building greening, technical shading elements such as sun sails or parasols can make a valuable contribution.

To provide further cooling, the proportion of shade on public spaces should be examined in more detail by analysing people's usage patterns to answer the following questions: Which traffic areas are used most frequently at which times, and which recreational spaces are primarily visited for leisure activities? From this, one can prioritise the areas and routes that should be addressed first when implementing adaptation measures, in order to improve overall thermal comfort.

As the future scenarios show, heat stress will increase in the absence of adaptation measures. It is therefore advisable to consider improved shading in street space and on public recreational areas, so that these areas can be used during the summer months now and in the future, enabling people to avoid severe and extreme heat stress in other parts of the city. This also includes the routes leading to the recreational areas. It must be taken into account, in particular, that the full benefits of tree shade only materialise once the associated trees have reached the necessary size at the appropriate age, which means that action should start as early as possible.

The spatial distribution of PET values presented here provides initial indications of where high values are to be expected. The computed values are based solely on future changes in input temperatures. Therefore, it must also be assumed that humidity and other PET-relevant variables will change and PET values will additionally shift locally. Regardless of the exact values, however, the results indicate that – and where – increasing the share of shaded surfaces is an effective means of reducing heat stress.

Decisive for the degree of area-wide heat reduction are the planting distances between urban trees and the spatial orientation of tree rows. An east-west orientation has a greater effect than a north–south orientation. Green spaces can also contribute to increasing thermal comfort, but this requires adequate irrigation. Moreover, urban trees and green spaces provide additional ecological and health benefits and help reduce flooding by improving infiltration. To ensure that urban trees can cope with the consequences of climate change in the long term, site-appropriate, climate-resilient (Roloff et al., 2013) and allergy-friendly (Bergmann et al., 2025) tree species should be used. The construction of tree infiltration trenches has proven particularly advantageous, as they retain rainwater and increase water availability for the trees, thereby reducing irrigation effort (Szota et al., 2019).

The indicator “share of shade on public traffic areas” proposed by Kluck et al. (2020) offers, in contrast to the use of thermal indices, a simple approach to assessing heat exposure along streets as well as pedestrian and cycling paths. Its application in combination with an analysis of the time-of-day-dependent use of these areas is a good approach to planning and implementing targeted adaptation measures. By including different scenarios, the effectiveness of individual measures can be made more tangible and communicated more clearly. For this reason, it is recommended to calculate the share of shade not only at the social-area level, but for the entire urban area. It may also be helpful to consider the share of shade on residential buildings at different height levels and with a focus an apartments located under rooftops or with extensive south-facing exposure, frequently experience particularly high indoor temperatures during summer months.

Application of the indicator “walking distance to non-heat-stressed public recreational areas” proposed by Kluck et al. (2020) confirms the need for action identified during the site visit regarding the lack of shading in large recreational spaces, which are of great inportance for vulnerable residents to find cooling outdoors during heatwaves. This means in sum that residents are unable to find relief from heat at home or within walking distance of their homes. As the building-resolved analysis for the Goethestraße neighbourhood shows, there are currently only a few recreational areas with lower heat exposure during the time of day with the greatest heat burden. As a result, walking distances to cooler areas in the north-western and southern parts are in some cases more than 400 m. In particular, these areas should be considered for improving heat protection, including the provision of public buildings that offer thermal relief. The indicator should also be recalculated taking these facilities into account. Additionally, it could be discussed whether free drinking-water stations should be installed at some locations.

Overall, the study shows that the development of joint scenarios and the simulation of heat exposure highlight the necessity of specific adaptation measures for vulnerable groups. Exemplary approaches from the Netherlands can also provide valuable new impulses for planning in Germany. Furthermore, it becomes clear that the social dimension of climate adaptation must not be treated as an add-on, but should be considered from the outset and be an integral part of all planning phases. This also includes the early integration of social data into impact analyses. Only through the systematic consideration of social issues and the active involvement of vulnerable groups as well as practical decision-makers on site a just and sustainable urban climate adaptation can be achived.

7 REFERENCES

Barnes, M.L., Wang, P., Cinner, J.E. et al.: Social determinants of adaptive and transformative responses to climate change. In: Nature Climate Change, Vol. 10, pp. 823–828. London, 2020. https://doi.org/10.1038/s41558-020-0871-4.

Bender, S., Groth, M., Potyka, M. & Schubert-Frisius M.: The Contribution of Urban Climate Models for the Adaptation to Heat Stress – Lessons Learned from three Transdisciplinary Case Studies. In: Proceedings of REAL CORP 2025, pp. 895–905. Graz, 2025. DOI: 10.48494/REALCORP2025.1007.

Bergmann, K.-C., Straff, W., Mücke, H.-G., Stevanovic, K. & Zuberbier, T.: Empfehlung zur allergikerfreundlichen Bepflanzung von Städten unter Berücksichtigung des Klimawandels. In: Allergo Journal, Vol. 34, Issue 4, pp. 24–33. Berlin, 2025. https://doi.org/10.1007/s15007-025-6488-1.

Breil, M., Zandersen, M., Pishmisheva, P., Branth Pedersen, A., Romanovska, L., Coninx I., Rogger, M. & Johnson, K.: “Leaving No One Behind” in Climate Resilience Policy and Practice in Europe. ETC/CCA Technical Paper, No. 2021/2, Copenhagen, 2021. https://doi.org/10.25424/cmcc/justtrans_europe.

Creditreform: SchuldnerAtlas Deutschland 2025. Überschuldung von Verbrauchern. Neuss, 2025.

EC: Climate Action Progress Report 2023. In: European Commission Report. Brussels, 2023. https://climate.ec.europa.eu/document/download/60a04592-cf1f-4e31-865b-2b5b51b9d09f_en.

EC: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – Managing climate risks – protecting people and prosperity. COM(2024) 91 final. Brussels, 2024. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52024DC0091.

EC: Preparedness Union Strategy: Reinforcing Europe’s resilience in a changing world. EEAS Publication. Brussels, 2025. https://www.eeas.europa.eu/eeas/preparedness-union-strategy_en.

EEA: European climate risk assessment. Publications Office of the European Union. Luxembourg, 2024. https://data.europa.eu/doi/10.2800/204249.

EEA: Social fairness in preparing for climate change: How just resilience can benefit communities across Europe. EEA Report. Luxembourg, 2025. https://www.eea.europa.eu/en/analysis/publications/social-fairness-in-preparing-for-climate-change-how-resilience-can-benefit-communities-across-Europe.

Etzel, R.A., Weimann, E., Homer, C., Arora, N.K., Maimela, G., Villalobos Prats, E. & Banerjee, A.: Climate change impacts on health across the life course. In: Journal of Global Health, Vol. 14, Article 03018. Geneva, 2024.

Fedele, G., Donatti, C.I., Harvey, C.A., Hannah, L. & Hole, D.G.: Transformative adaptation to climate change for sustainable social-ecological systems. In: Environmental Science & Policy, Vol. 101, pp. 116–125. Amsterdam, 2019.

Graham, S., Barnett, J., Mortreux, C., Hurlimann, A. & Fincher, R.: Local values and fairness in climate change adaptation: Insights from marginal rural Australian communities. In: World Development, Volume 108, pp: 332-343, 2018. https://doi.org/10.1016/j.worlddev.2017.12.008.

Höppe, P.: The Physiological Equivalent Temperature – A Universal Index for the Biometeorological Assessment of the Thermal Environment. In: International Journal of Biometeorology, Vol. 43, Issue 2, pp. 71–75, 1999.

IPCC: Climate Change: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., 2022. doi:10.1017/9781009325844.

Juhola, S., Heikkinen, M., Pietilä, T., Groundstroem, F. & Käyhkö, J.: Connecting climate justice and adaptation planning: An adaptation justice index. In: Environmental Science & Policy, Vol. 136, pp. 609–619. Amsterdam, 2022. https://doi.org/10.1016/j.envsci.2022.07.024.

Klafka, R.: Auswirkungen des Klimawandels auf die Wohnbevölkerung in Abhängigkeit der Viertelstruktur in Bremerhaven. Unveröffentlichte Bachelorarbeit. Bingen, 2025.

Kluck, J., Klok, L., Solcerová, A., Kleerekoper, L., Wilschut, L., Jacobs, C. & Loeve, R.: De hittebestendige stad: Een koele kijk op de inrichting van de buitenruimte. Report, 127 pp. Amsterdam, 2020.

Konijnendijk, C.: The 3-30-300 Rule for Urban Forestry and Greener Cities. In: Biophilic Cities Journal, Vol. 4, Issue 2, pp. 12–15, 2021.

Konijnendijk, C.: Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: Introducing the 3–30–300 rule. In: Journal of Forestry Research, Vol. 34, pp. 821–830, 2023. https://doi.org/10.1007/s11676-022-01523-z.

Konijnendijk, C.: Rethinking Urban Green Spaces. In: Edward Elgar Publishing Ltd. Cheltenham, 2024.

Leuphana Universität Lüneburg: KlimaVielfalt: Gemeinsam klimafit in die Zukunft! Praxisleitfaden. Lüneburg, 2024. https://pubdata.leuphana.de/server/api/core/bitstreams/49420b78-dcc6-469f-8dd7-c256398f6c0c/content.

Magistrat der Stadt Bremerhaven: Sozialräumliches Monitoring Bremerhaven 2023. Bremerhaven, 2023.

Magistrat der Stadt Bremerhaven: Bericht 2023 – Über die Verwaltung und den Stand der Stadtangelegenheiten. Bremerhaven, 2024.

Matzarakis, A., Mayer, H. & Iziomon, M.G.: Applications of a Universal Thermal Index: Physiological Equivalent Temperature. In: International Journal of Biometeorology, Vol. 43, pp. 76–84. 1999.

Meer, N.: Social Policy and the Determinants of Vulnerability – Missing 'Race' in Climate Adaptation. In: Social Policy and Society, pp. 1–12. 2025. https://doi.org/10.1017/S1474746425000041.

Oke, T., Mills, G., Christen, A., & Voogt, J.: Urban Climates. 546 S., Cambridge University Press. 2017.

Prina, M., Khan, N., Akhter Khan, S., Caicedo, J.C., Peycheva, A., Seo, V., Xue, S. & Sadana, R.: Climate change and healthy ageing: An assessment of the impact of climate hazards on older people. In: Journal of Global Health, Vol. 14, Article 04101. 2024.

Proloco Bremen & plan zwei: Vorbereitende Untersuchungen Integriertes Entwicklungskonzept Lehe/Mitte-Nord. 2023.

Proulx, K., Daelmans, B., Baltag, V. & Banati, P.: Climate change impacts on child and adolescent health and wellbeing: A narrative review. In: Journal of Global Health, Vol. 14, Article 04061. 2024.

Rehling, J., Bunge, C., Waldhauer, J. & Conrad, A.: Socioeconomic Differences in Walking Time of Children and Adolescents to Public Green Spaces in Urban Areas. In: International Journal of Environmental Research and Public Health, Vol. 18, Article 2326. 2021. https://doi.org/10.3390/ijerph18052326.

Ribot, J.: Cause and response: vulnerability and climate in the Anthropocene. In: The Journal of Peasant Studies, Vol. 41, Issue 5, pp. 667–705. 2014. https://doi.org/10.1080/03066150.2014.894911.

Roloff, A.: Bäume in der Stadt. Verlag Eugen Ulmer. Stuttgart, 2013.

Schüle, S.A., Gabriel, K.M.A. & Bolte, G.: Relationship between neighbourhood socioeconomic position and public green space availability. In: International Journal of Environmental Research and Public Health, Vol. 18, Issue 5, Article 2326, 2017. https://doi.org/10.3390/ijerph18052326.

Senatsverwaltung für Mobilität, Verkehr, Klimaschutz und Umwelt: Umweltgerechtigkeitsatlas 2023/2024. Berlin, 2025. https://www.berlin.de/sen/uvk/umwelt/nachhaltigkeit/umweltgerechtigkeit/umweltgerechtigkeitsatlas/.

Shi, L., Chu, E. & Anguelovski, I. et al: Roadmap towards justice in urban climate adaptation research. In: Nature Climate Change 6, 131–137, 2016. https://doi.org/10.1038/nclimate2841

Spannagel, D. & Brülle, J.: Ungleiche Teilhabe: Marginalisierte Arme – verunsicherte Mitte. In: WSI-Verteilungsbericht 2024, WSI Report Nr. 98. Düsseldorf, 2024.

Statista: Die 25 kreisfreien Städte und Landkreise mit der höchsten Arbeitslosenquote in Deutschland im Jahr 2024. Hamburg, 2025. https://de.statista.com/statistik/daten/studie/1134691/umfrage/staedte-und-landkreise-mit-der-hoechsten-arbeitslosenquote/.

Swanson, K.: Equity in Urban Climate Change Adaptation Planning: A Review of Research. In: Urban Planning, Vol. 6, Issue 4, pp. 287–297. 2021. https://doi.org/10.17645/up.v6i4.4399.

Szota, C., Coutts, A., Thom, J., Virahsawmy, H., Fletcher, T. & Livesley, S.: Street Tree Stormwater Control Measures can reduce Runoff but may not Benefit Established Trees. In: Landscape and Urban Planning, pp. 144–155. 2019. https://doi.org/10.1016/j.landurbplan.2018.10.021.

Teebken, J.: Vulnerability locked in. On the need to engage the outside of the adaptation box. In: Global Environmental Change, Vol. 85. 2024. https://doi.org/10.1016/j.gloenvcha.2024.102807.

Teebken, J. & Schipperges, M.: Soziale Frage Klimawandel. Klimaanpassung als sozialpolitische Gestaltungsaufgabe. FES diskurs. Bonn, 2024. https://collections.fes.de/publikationen/content/titleinfo/1571663.

Wüstemann, H., Kalisch, D. & Kolbe, J.: Access to urban green space and environmental inequalities in Germany. In: Landscape and Urban Planning, Vol. 164pp. 124–131. 2017. https://doi.org/10.1016/j.landurbplan.2017.04.002.

Yi Yin, Y., He, L., Wennberg, P.O. & Frankenberg, C.: Unequal exposure to heatwaves in Los Angeles: Impact of uneven green spaces. In: Science Advances, Vol. 9, Issue 17. 2023. https://doi.org/10.1126/sciadv.ade8501.

Zerhusen, P. & Bauer, J.: Hitzemodellierung Bremerhaven – Ortsteile Goethequartier und Klushof. Unpublished report from TAUW GmbH for GERICS, 2025.