The Contribution of Urban Climate Models for the Adaptation to Heat Stress – Lessons Learned from three Transdisciplinary Case Studie

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1 ABSTRACT

Climate change poses significant multiple challenges to urban areas, affecting public health, infrastructure, and essential services through rising temperatures, increasing dry seasons, heavy rain events, and shifting precipitation patterns. In response, cities must develop climate adaptation strategies and implement adaptation measures to create climate resilient infrastructures, adopting green urban planning, and fostering community engagement. One of the most pressing concerns is the intensifying impact of extreme heat, particularly during summer months, which is aggravated by both climate change and human activities. In urban environments, where the landuse is characterized by extensive impervious artificial surfaces and heat-retaining structures like buildings and roads, extreme heat events contribute to the Urban Heat Island (UHI) effect. In order to meet these challenges, city planners need useful tools that allow the modeling of different city development scenarios and the related effects on the environment. Against this background, the paper presents and discusses the practical use, main results and lessons learned from transdiciplinary case studies using three different urban climate models in three German cities. The “PALM-4U” model was employed to analyze heat stress in Geesthacht's city center, while the “FITNAH 3D” model by GEO-NET was applied to the entire urban area of Boizenburg/Elbe, including surrounding green and water spaces. Additionally, the "ENVI-met" model was used to simulate the effects of greening strategies on microclimates at four heat-stressed sites in Lüneburg.

Although all models have the focus on the temperature field and the thermal well-being of the citizens, the model approaches – including the needed model input – differ from model to model. These different model applications – conducted in close transdiciplinary collaboration with local key stakeholders – and the specific results, highlight the differences of model outcomes. This paper gives an overview of the main model characteristics. Furthermore, it discusses the typical information gained from such modeling approaches in the context of open questions related to the transfer of model results into administrative processes. Hence, our research can help urban planners, architects, and policymakers seeking to design and retrofit urban environments to improve thermal comfort and sustainability.

Keywords: urban climate models, heat stress, climate change adaptation, case studies, transdisciplinarity

2 INTRODUCTION

Climate change caused by human activities has far-reaching impacts. Extreme weather events, such as heatwaves, forest fires, floods and droughts are occurring more frequently and with increasing intensity in Europe as well (IPCC 2022). During these events, increasing heat stress, which is also becoming far more noticeable in Europe and Germany, is one of the societally most important impacts of climate change. In a direct comparison, for example, Europe is warming more rapidly than the global average (Copernicus Climate Change Service 2024). Temperature distributions are also shifting throughout Germany towards higher values because of climate change, increasing the occurrence probability of extreme heat (Deutschländer & Mächel 2017).

In general, the impacts of increasing heat vary, depending on how vulnerable and affected the regions, urban districts and people are (IPCC 2014). The GERICS-Klimaausblicke (climate oulooks) show for example for 401 German areas on the district level how the temperature and heat periods may change in the future (Pfeifer et al. 2021). Regardless of the location, older people, children, groups with low socio-economic status and individuals with health problems tend to be more vulnerable to the impacts of climate change than the general population (GERICS 2020). The health of individuals with certain illnesses (e.g. cardiovascular and respiratory diseases or diabetes) is also more affected by heat, which is often associated with a higher risk of heat-related death (European Climate and Health Observatory 2022; EEA 2018). Pregnant women are likewise more susceptible to heat stress. Overheating and dehydration can lead to premature labor (WHO

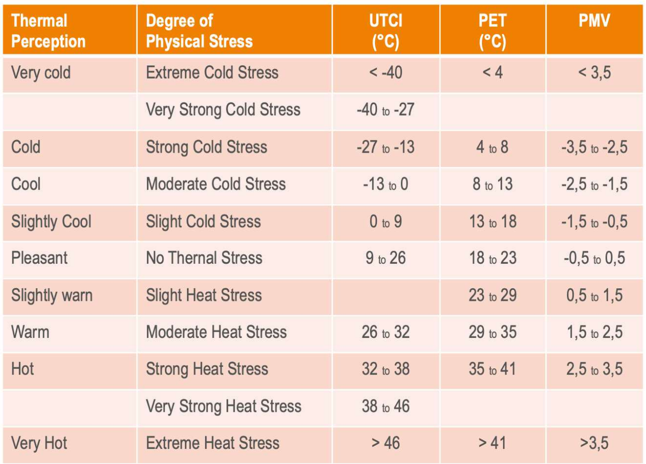
Europe 2021). Of great importance is that the combination of an increasing number of individuals over the age of sixty-five and the higher summer temperatures has led to an increase in the overall exposure of older people to heatwaves since 1980 (European Climate and Health Observatory 2021).

Altogether, the negative impacts of heat on human well-being and health are clearly documented (GERICS 2020; Hanefeld et al. 2019; Muthers et al. 2017), whereby very warm nights can lead to the body’s inability to regenerate properly, thereby increasing the general risk of illness. Heat has not only been proven to lead to decreased labor productivity overall, but also to additional and sometimes serious economic consequences, resulting in associated costs that develop subtley and slowly, so they often remain unnoticed. In summary, heat events are responsible for approximately 99% of at least 30,000 extreme weather-related deaths in Germany since the year 2000 (Trenczek et al. 2022a; Trenczek et al. 2022b).

The impacts of increasing heat in the city vary widely, depending on the proportion of sealed areas, building development, and the the degree of cold air venilation. In addition to its direct health impacts, heat stress can lead to damages of different parts of the critical infrastructure, such as roads, the power supply, or the IT infrastructure, causing significant economic repercussions (Groth et al. 2023). But not only extreme events have to be considered. The gradually changes are similar problematic, because their effects are not immediately apparent.

Addressing the UHI effect requires a comprehensive understanding of how factors such as the building type, the spatial distribution of buildings, the location and functionality of ventilation corridors, and the extent of urban greenery influence local microclimates and heat dynamics. Related questions can be answered with urban climate models. They support urban planners when searching for the balance between functionality as well as sustainable development and minimal heat-related stressors, especially with regard to the effects of climate change. As the individual models are designed for different use cases, it should be clear to the processors in advance which model is best to be used.

It is also important to note in this context that an individual’s perception of warmth is not only determined by the air temperature. Rather, the complex interactions of meteorological (air temperature and humidity, wind speed, radiation influences) and non-meteorological factors (perspiration rate, work energy turnover, clothing) are responsible for thermal well-being. Various indices have been developed to estimate thermal sensitivity, like the “Universal Thermal Climate Index (UTCI)” (Błażejczyk et al. 2013), the “Physiologically Equivalent Temperature (PET)” (Höppe & Mayer 1987) or the “Predicted Mean Vote (PMV)” (Fanger 1972) (table 1). In this paper we focus for each case on results for the PET – an index based on the Munich Energy-balance Model for Individuals (MEMI) –, which provides a one-dimensional biometeorological measure that quantifies the perception of thermal comfort or discomfort (Höppe 2019). The PET is expressed in °C and is not to be confused with the de facto air temperature.



Thermal Perception	Degree of Physical Stress	UTCI (°C)	PET (°C)	PMV
Very cold	Extreme Cold Stress	< -40	< 4	< 3,5
	Very Strong Cold Stress	-40 to -27		
Cold	Strong Cold Stress	-27 to -13	4 to 8	-3,5 to -2,5
Cool	Moderate Cold Stress	-13 to 0	8 to 13	-2,5 to -1,5
Slightly Cool	Slight Cold Stress	0 to 9	13 to 18	-1,5 to -0,5
Pleasant	No Thernal Stress	9 to 26	18 to 23	-0,5 to 0,5
Slightly warn	Slight Heat Stress		23 to 29	0,5 to 1,5
Warm	Moderate Heat Stress	26 to 32	29 to 35	1,5 to 2,5
Hot	Strong Heat Stress	32 to 38	35 to 41	2,5 to 3,5
	Very Strong Heat Stress	38 to 46		
Very Hot	Extreme Heat Stress	> 46	> 41	>3,5

Table 1: Comparison of classification methods for describing thermal perception.

Against this background, the paper presents and discusses the practical application, main results and lessons learned using different urban climate models. The study is based on practical examples, whereby the focus of the model application is in general not on the exact numerical values but on the differences between scenarios or land use characteristics. For these reasons, and for cost aspects, it is not a common practice to compare results of different city climate models in one model site. It is therefore difficult to find such direct comparisons with the same scale in literature. For our study we use the following model approaches:

The "PALM-4U" model was employed to analyze heat stress in the central part of the city of Geesthacht (chapter 3), while the "FITNAH 3D" – used in a contract work by the company GEO-NET – was applied to the entire urban area of Boizenburg/Elbe, including surrounding green and water spaces (chapter 4). Additionally, the "ENVI-met" model was used to simulate the effects of greening measures on microclimates at four heat-stressed sites in Lüneburg (chapter 5). Based on these specific case studies, a brief model comparison will be carried out (chapter 6), followed by a summarizing conclusion (chapter 7).

3 THE GEESTHACHT CASE STUDY

3.1 General aspects – the PALM-4U modeling approach

The high-resolution urban climate model PALM-4U (Parallelized Large-eddy Simulation Model for Urban Applications) developed at Leibnitz University in Hanover (Maronga et al. 2019; Steuri et al. 2019) was utilized to simulate the current thermal comfort and heat load in the city of Geesthacht (33.000 inhabitants) in Northern Germany (Bender et al. 2024). PALM-4U is the enhanced version of the basic PALM model (Raasch & Schröder 2001), which has already been used frequently for urban climate analyses (Knoop et al. 2014; Letzel et al. 2012; Park & Baik 2012).

The Palm-4U model can be used to simulate entire cities as well as individual urban neighborhoods down to a resolution of one to two meters. Examples of weather situations are specified as external drivers for the calculations. The model requires geo-based information on terrain, building structures, vegetation, sealed surfaces and water surfaces as additional input variables (Heldens et al. 2020). As a result, the model provides spatial information on temperature, humidity and wind (speed and direction) as well as for biometeorological parameters. These parameters always relate to humans and provide information on human well-being and physiological heat stress (Fröhlich & Matzarakis 2019; Kuttler 2009).

For the urban climate modeling carried out here, the PALM-4U Version 21.10-rc1 was used with the following input data (sources specified):

- Aerial images (visible): resolution 0.2 m (Geesthacht City Administration).
- Aerial images (infrared) (County of Herzogtum Lauenburg).
- Surface model as raster data with a grid width of 1 m (digital terrain model: DGM1) (Geesthacht City Administration).
- Digital landscape model (DLM) to describe the landscape topography and relief of the earth's surface in vector format or digital surface model (DOM) with a grid width of 1 m (Geesthacht City Administration). The height accuracy for solid surfaces without vegetation is ≤ 0.3 m.
- Land use data as a shapefile or feature class (green areas, trees, traffic areas), based on data from Corine Land Cover (CLC) as well as from the Geesthacht City Administration.
- Building information from the official property cadastral information system (ALKIS): for example, information on the geometry, location, and shape of land parcels and buildings, type of use, terrain shape (Geesthacht City Administration).
- Digital 3D building models; “Level of Detail – refering to the level of complexity in a 3D-generated model” (LOD2): standardized roof shapes, building floor plans based on the official property map; the height accuracy is predominantly 1 m, information on the building function (County of Herzogtum Lauenburg).
- OpenStreetMap (OSM) data in 1 m resolution as input variables for determining sealing and location of bridges and water areas (rivers, canals and ponds). This information is from the year 2020.

The thermal comfort was modeled at a resolution of 5 m x 5 m. A total of 1,000 x 800 x 320 grid points in the x, y and z directions are included in the model calculation. They describe a region with an area of 20 km² and a height of 1,600 m. The assumed meteorological boundary condition is an autochthonous weather situation – characterized by unobstructed solar radiation with little cloud cover and very light winds. Under these conditions local climatic characteristics of a landscape can develop particularly well and the urban heat island – the thermal load – is most pronounced currently. For initializing the calculation, a spatial constant temperature profile of a summer day (here June 20th, 2015) with an initial temperature of 23.4°C (296.5 K) at the surface for the start time of 21:00 CET (Central European Time) is specified. The PALM-4U model region includes the central part of the city of Geesthacht. Figure 1 provides an overview of the input variables used for the subsequent urban climate modeling. The map notably reveals the urban areas with office buildings and the surrounding areas characterized by agriculture and forests. In large portions of the city, the image is heterogeneous, with some green areas and large areas with little vegetation (assumed here to be bare ground).

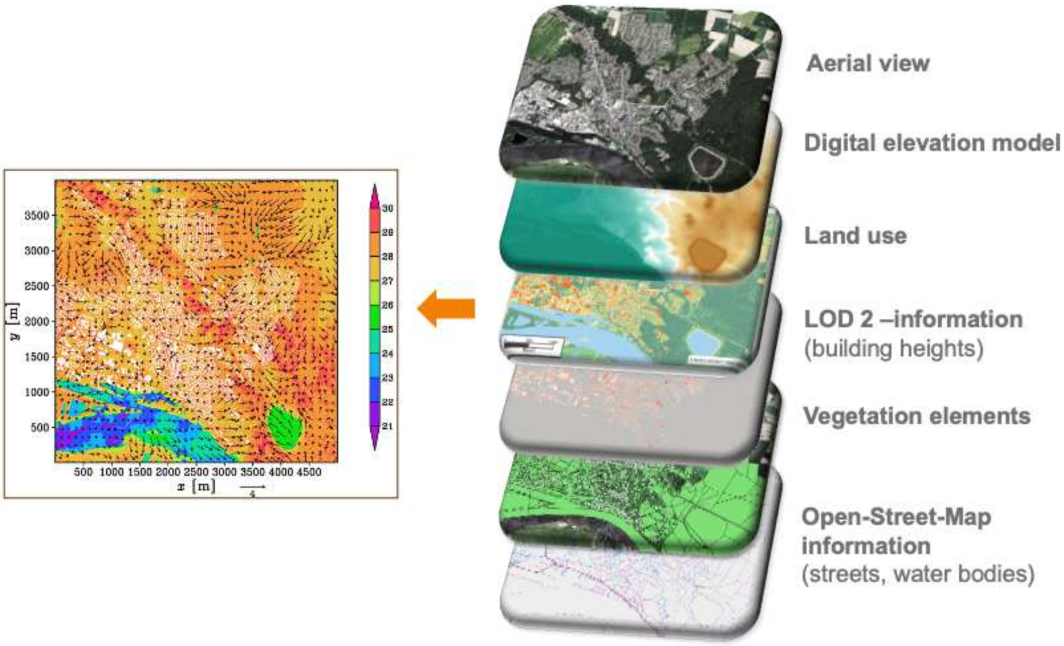


Fig. 1: Input data overview for the “City of Geesthacht” modeling area (scale: 1:30,000).

3.2 Map of the heat stress (PET-values) for the city of Geesthacht

The PALM-simulations show the daily course of the heat load, here displayed by the PET values, that correlates strongly with the short-wave solar radiation. Highest heat loads occur not only inside the city center over sealed surfaces without shading, but also in the surrounding open spaces. At nighttime (shown at 04:00 h) the PET value distribution shows that no thermal stress is to be expected. Rather, PET values below 18°C are found in the peripheral areas of the city, near the river Elbe, in the surrondings of the reservoir and in some parts of the city, which corresponds to “slight cold stress” according to the specific PET classification (figure 2). With increasing warming during the day there is a significant increase of the thermal stress, too, whereas the highest stress occurs at 16:00 h. At that time “moderate heat stress” only occurs around the Elbe and above the reservoir. Within the urban region, the PET values rise above 42°C in many areas, which corresponds to “extreme heat stress”. As with the air temperature at 2 m height, the urban forest is also the separating element here, with PET values between 39°C and 45°C. The lowest PET values (between 36°C and 39°C = “strong heat stress”) can be observed south of the Elbe, in smaller wooded areas on the eastern edge of the city, above the open spaces north of Narzissenweg, in the north-eastern outskirts and in the Börmweg area.

To summarize, the assessment based on the PET values shows that no thermal stress occurs at night in the whole urban area. In contrast, during the day, the heat stress is increasing to an extreme level in most parts of the developed parts of the city. Even though heat stress occurs at a lower level in the surrounding, it is still heavily pronounced there as well. Moderate conditions can be found near the water bodies and in shaded areas. With respect to increasing temperatures in the future, city administration should face this challenge in upcoming city planning processes.

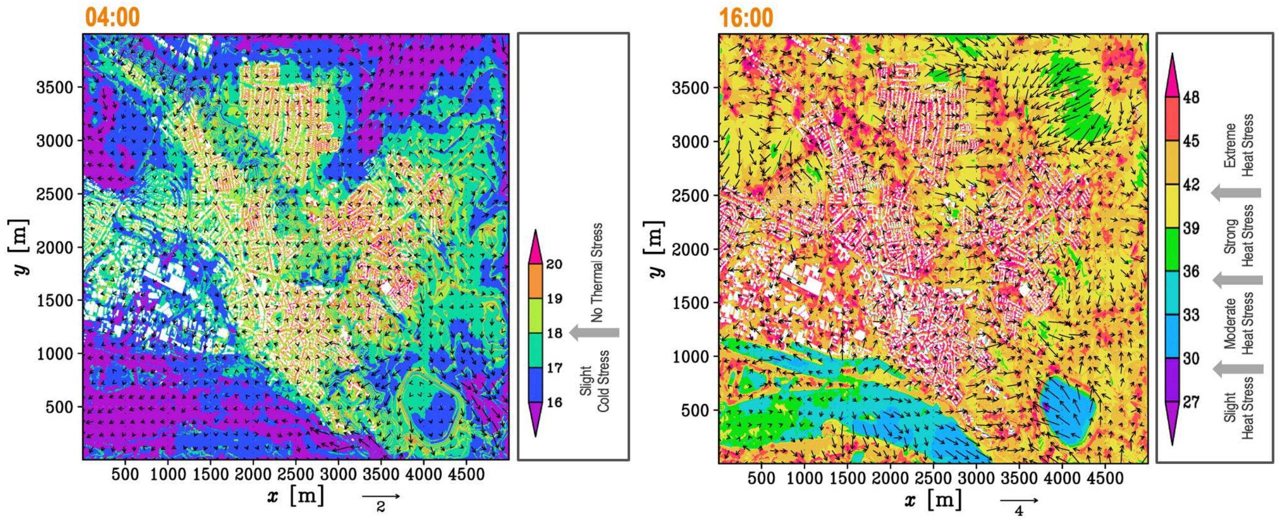


Fig. 2: Physiological Equivalent Temperature and wind speed at a height of 10 m, at 04:00 (left) and 16:00 (right); “City of Geesthacht” model.

4 THE BOIZENBURG/ELBE CASE STUDY

4.1 General aspects – the FITNAH 3D modeling approach

A model frequently used in Germany for urban climate assessments is FITNAH 3D from the company GEO-Net (Gross 1993; GEO-Net 2013). An area-wide model analysis was conducted for the city Boizenburg/Elbe (7,500 inhabitants) with a spatial resolution of 5 m x 5 m (GEO-Net 2021). For the detailed modeling, the following input data was needed: aerial images or topographic maps, DGM, DOM (LOD 0 or LOD 1), land use data. Building geometries, provided by the city of Boizenburg/Elbe in the form of a 3D model, were integrated into the analysis. The detailed information of structural heights (buildings and green structure) enables a realistic representation of flow barrier impacts on the air exchange together with the influence of urban morphology on the local microclimate. Typically, assessments with FITNAH 3D encompass both nighttime conditions – with the focus on cold air production and associated flows – and daytime bioclimatic loads, providing a comprehensive assessment of the microclimatic characteristics across the urban area (figure 3).

The model area of Boizenburg/Elbe covers approximately 121 km². The peripheral areas are dominated by open and green spaces (total area of 47.4 km²), which makes these parts very important for the cold air production at night and the cooling of the city. The climate analysis was based on the meteorological framework of an autochthonous summer day, which serves as a representative condition for the model calculations. Autochthonous weather patterns occur in Boizenburg on 5 to 7 days per month during summer (June, July, August). These conditions are characterized by clear skies and minimal synoptic wind influence, allowing the local climatic features of the town and its surrounding region to be distinctly observed. A hallmark of such high-pressure weather conditions is the formation of surface winds, driven by temperature gradients between cooler open spaces and warmer built-up areas. An autochthonous summer day typically results in the highest thermal loads due to intense solar radiation and limited air exchange, therefore this modell situation can be seen as a worst-case scenario. It is important to note that this climate analysis provides a snapshot of the urban area's microclimatic conditions under specific meteorological scenarios.

4.2 Map of the heat stress (PET-values) for the city of Boizenburg/Elbe

In general, for commissioned expert opinions mostly the PET index is calculated for the time with the maximum air temperature (normally 16:00 to 17:00 h) or for the maximum intensity of solar radiation (normally 13:00 to 14:00 h). In our case, the map with the PET index at 14:00 h is used. Compared to the nighttime air temperature with a maximum difference of 5 K, the PET exhibits a greater range across the study area (18 K) at daytime. The lowest PET values are observed over wooded areas, ranging from approximately 26°C to 28°C. In these areas, individuals at a height of 1.1 meters above ground level are situated beneath the tree canopy, which provides protection from direct solar radiation. As a result, forests and parks with dense tree coverage can serve as vital refuges, offering only moderate heat stress.

Comparable PET values are achieved locally within urbanized areas beneath individual trees, such as those in the church and town hall square. These locations, which otherwise experience extreme heat loads exceeding 41°C PET due to the absence of shading, benefit significantly from the presence of tree cover (Groth et al. 2022). Relatively low heat loads, with PET values between 28°C and 32°C (slight to "moderate heat stress"), are observed over larger water bodies, including the harbor at the river Boize and in the surroundings of the Elbe River. All these areas benefit from the cooling effect of the water, experiencing lower thermal loads compared to areas further away from these watercources. By contrast, maximum PET values exceeding 42°C ("extreme heat stress") are recorded over open meadows and farmland in the surrounding regions. Highly sealed commercial areas in the eastern part of the city experience similar extreme heat stress. The absence of shading, combined with unimpeded solar radiation and limited evaporative cooling from sealed surfaces, contribute to these elevated thermal loads. A similar level of heat stress is widespread in the historic city center. While shading provided by trees and buildings locally reduces the heat load by 10 K, the prevalence of highly sealed and unshaded open spaces dominates the microclimate. Adjacent buildings reflect incoming solar radiation, further amplifying the heat load. Additionally, the dense spatial arrangement of buildings can reduce wind speeds, compounding the thermal stress.

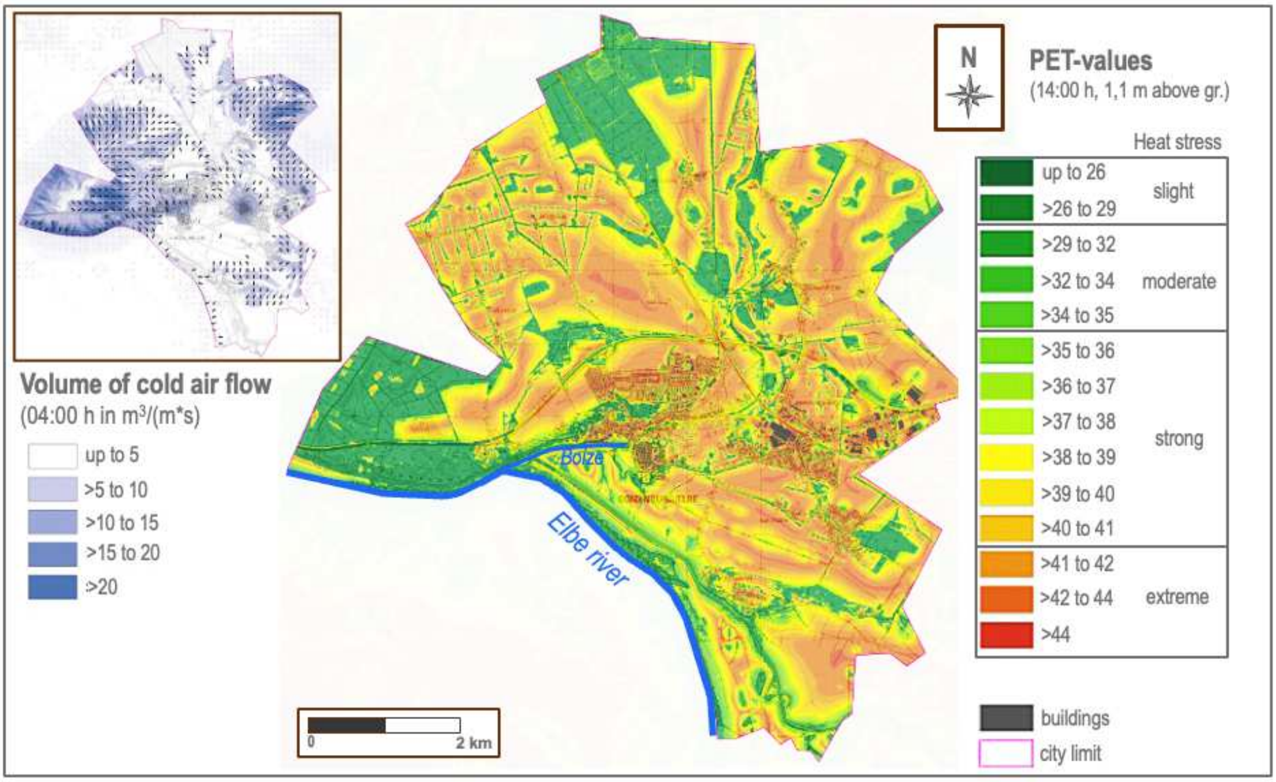


Fig. 3: Distribution of PET (14:00 h) in the "Boizenburg/Elbe"-model and a overview of the cold air flow (04:00 h).

To summarize, the settlement areas in the central part of the map experience relatively high thermal loads. Although these areas are characterized by loosely arranged single-family homes with a relatively high proportion of green spaces, some zones still face extreme heat stress due to the lack of shading. Individual trees in these areas, which were not explicitly considered in the modeling, provide cooling only locally and have limited influence on the overall heat load. The surrounding areas, mainly in the west and in the northeast, are important for the cold air production, but their impact is not big enough for the small city, so adaptation actions inside the residental areas are still necessary to lower the daytime heat stress.

5 THE LÜNEBURG CASE STUDY

5.1 General aspects – the ENVI-met modeling approach

The third microclimate model is ENVI-met (Bruse & Fleer 1998), a three-dimensional, geo-referenced, non-hydrostatic microclimate model, that can be used to calculate and simulate climatic parameters with high spatial (0.5 to 10 m) and temporal solutions up to 10 seconds. This model accounts for the intricate exchange of long-wave and short-wave radiation between surfaces, vegetation, and the atmosphere in urban environments. It is frequently used to assess the effectiveness of mitigation and adaptation strategies, e.g. by comparing the impacts of different potential measure packages. It calculates the microclimatical dynamics during a diurnal cycle using fundamental laws of thermodynamics and fluid dynamics.

After the analysis of the urban climate for the whole city of Lüneburg (80,000 inhabitants) with FITNAH (GEO-Net 2019) the question, how can greening reduce the microclimatic stress at different sites in the city center, was posed. To address this question, a project exploring potential adaptation strategies to the impacts of climate change in Lüneburg was launched in collaboration with the project "Zukunftsstadt Lüneburg 2030+ (City of the future Lüneburg 2030+)".[1] Four prominent locations were selected for the modelling, to be simulated in three different scenarios each. Whereas the baseline scenario (s-quo) on a hot summer day with approximately 30°C – representing the current state of these sites – is characterized by minimal greenery, high degrees of surface sealing, and low albedo due to artificial materials, two potential greening scenarios should analyze the effects of urban green. The moderate greening (s-mod) seeks to strike a balance between preserving site usability and enhancing thermal comfort. Measures include partial surface unsealing and the incorporation of large plants for shading, while maintaining most of the existing site infrastructure. The maximum greening scenario (s-max) represents a more intensive application of greening measures, involving major structural modifications including vertical and roof greening that substantially alter the appearance of the sites. While disregarding legal and social constraints, this scenario aims to illustrate the maximum possible cooling effects of urban greening interventions. The steps represented by s-mod and s-max serve as benchmarks for future greening strategies, offering an evidence-based framework to estimate the expected cooling effects at the studied locations.

Analyzed key parameters include potential air temperature, mean radiant temperature, and PET – as the indicator for thermal comfort. The selected four locations represent a diverse range of site sizes, structural characteristics, and greening potentials, spanning enclosed small courtyards (375 m2) to partially open urban squares (6,750 m2). All of these locations hold direct relevance to inner-city development in Lüneburg.

5.2 Map of heat stress (PET-values) for the Marienplatz

The second largest location (4,875 m2) – the Marienplatz – serves as an example to show the procedure of a scenario analysis done in this project. Two times were used for the comparison of the heat stress (calculated as absolute PET values): 13:00 h and 17:00 h (figure 4). These parameters were visualized for all locations in bird's-eye-view maps, customized to the relevant area. A black arrow indicates the orientation of north, while a red arrow shows the angle of solar incidence. It is important to note that only values within the modeled site are interpretable. The microclimate of Marienplatz in its current state (status quo) is predominantly characterized by direct sunlight and relatively high PET values. The existing groups of trees play a critical role in shading the square, particularly during the afternoon hours. In the shadow-free majority of the square the mode shows an extreme heat stress, with PET values of around 56°C at 13:00 h (A1), rising to over 57°C at 17:00 h (B1). By contrast, areas shaded by tree groups exhibit significantly lower PET values, ranging from 38°C to 48°C. This clear contrast highlights the critical role of shading in reducing thermal discomfort. However, across the entire site – even in shaded areas – the PET values remain within the highest physiological stress category, corresponding to extreme heat stress. The direct effects of further shading by more trees are shown by the differences of the PET values for the comparison of s-quo vs. s-mod (A2 and B2) and s-quo vs. s-max (A3 and B3). The implementation of both greening strategies demonstrates a substantial reduction in PET across many areas. In the s-mod scenario, the areas with reduced PET are more limited, but the PET values still decrease by up to 17 K. In the s-max scenario, significantly larger areas show a reduction of the PET-values at 13:00 h and 17:00 h, respectively. The maximum cooling effect relative to the baseline (s-quo) is approximately 20 K at 13:00 h and nearly 25 K at 17:00 h. The cooling effect is mostly pronounced under tree canopies, although it does not occur above water surfaces, due to the heat buffer effect of water bodies. Consequently, the physiological heat load is reduced by one PET-level when the s-max scenario is applied, offering theoretically a meaningful improvement in thermal comfort. However, the practical application must be critically scrutinized.

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[1] https://www.lueneburg2030.de/stadtklima/index.html

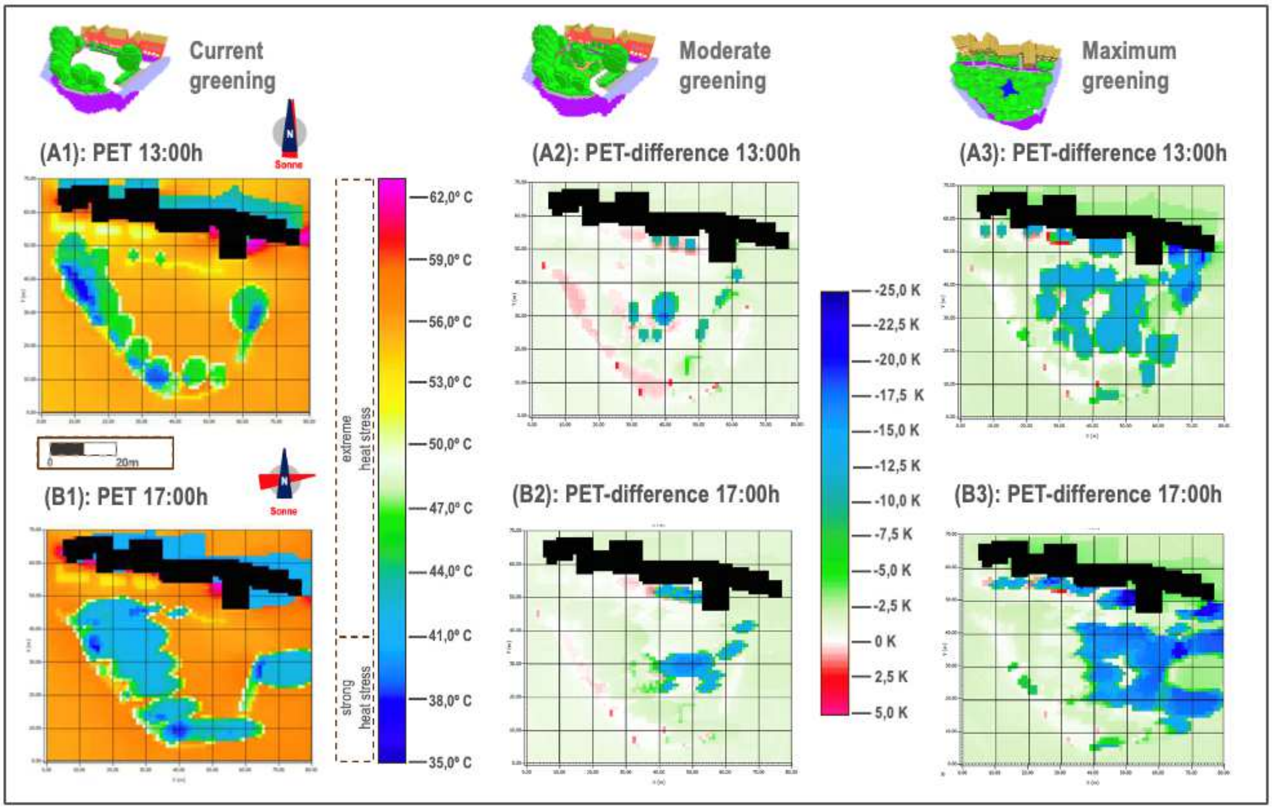


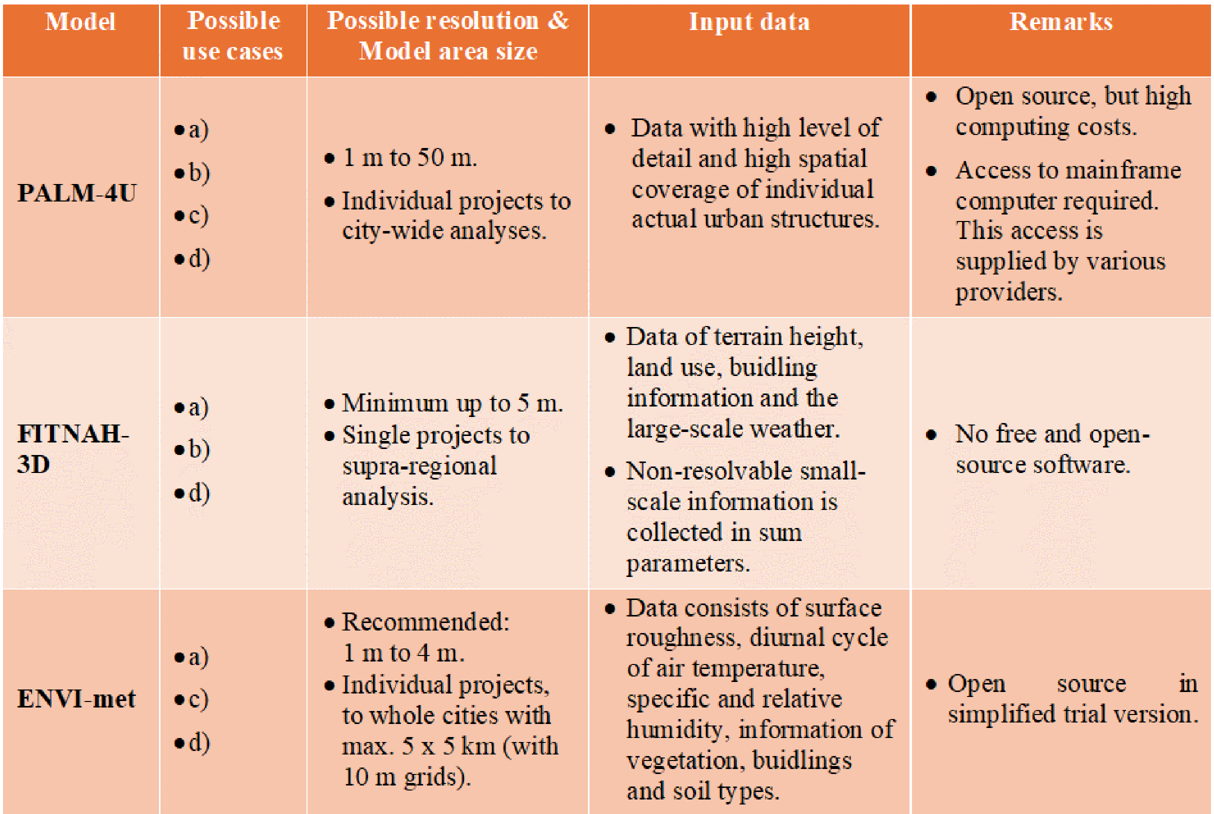
Fig 4: Distribution of PET (13:00 h (A1). and 17:00h (B1)) in the “Marienplatz”-model and the results of the comparison s-quo vs. s-mod (13:00 h (A2), 17:00 h (B2)) and s-quo vs. s-max (13:00 h (A3), 17:00 h (B3)). Buildings are shown in black.

The comparison of the three greening scenarios points out that PET values can be effectively reduced with the introduction of more vegetation. However, to fully evaluate the impact of these concepts, PET values must be analyzed in conjunction with the area of their effect. In general, the combination of greenery and water featueres, significantly reduces the thermal load. The quality of shade is particularly enhanced in areas featuring dense, multi-layered vegetation. Whereas the widespread shading of grassy areas is critical to ensuring their usability throughout the day. Therefore, an optimal design should incorporate strategically placed individual trees or groups of trees that provide a mix of extensive and partial shade. Additionally, larger clusters of trees with intensively planted understory vegetation could act as "cooling islands". The contribution of water features to thermal mitigation should not be underestimated. Integrating water elements into the design and creating an inner-city green oasis would further enhance the microclimate and improve thermal comfort. However, it should not be forgotten that the square is also intended for other uses in addition to its role as a “cooling island”. These must be reconciled as well, whereby previous prioritization of the desired types of use should set the framework for the redesign.

6 MODEL COMPARISION

The three selected examples provide a good insight into the different modeling philosophies and the associated issues. While at first glance all urban climate models can be used to simulate heat stress in the city, a second look shows that the issues are much more complex in practice. Table 2 provides a brief overview of the three models.

For example, the PALM-4U model aims to enable city administrations to create a digital model of their own municipality almost independently (or with support). This type of condition should make it possible to update the current status at regular intervals and to model planning scenarios with associated impacts. Up to now, however, this has required a lengthy familiarisation period (assuming existing scientific knowledge) and access to high-performance computing. As the computing and processing times required are still very high, its use in practice is only a viable option for well-positioned local authorities, especially in view of shrinking financial and personnel resources.



Model	Possible use cases	Possible resolution & Model area size	Input data	Remarks
PALM-4U	• a) • b) • c) • d)	• 1 m to 50 m. • Individual projects to city-wide analyses.	• Data with high level of detail and high spatial coverage of individual actual urban structures.	• Open source, but high computing costs. • Access to mainframe computer required. This access is supplied by various providers.
FITNAH-3D	• a) • b) • d)	• Minimum up to 5 m. • Single projects to supra-regional analysis.	• Data of terrain height, land use, buidling information and the large-scale weather. • Non-resolvable small-scale information is collected in sum parameters.	• No free and open-source software.
ENVI-met	• a) • c) • d)	• Recommended: 1 m to 4 m. • Individual projects, to whole cities with max. 5 x 5 km (with 10 m grids).	• Data consists of surface roughness, diurnal cycle of air temperature, specific and relative humidity, information of vegetation, buidlings and soil types.	• Open source in simplified trial version.

a) Thermal comfort (Analysis of the heat load in urban areas), b) Cold air balance (Analysis of cold air production and functionality of cold air pathways), c) Wind comfort (Analysis of the effects of wind on buildings and the human perception of comfort), d) Pollutant dispersion (Analysis of pollutant dispersion from traffic and domestic fire emissions).

Table 2: The three city climate models at a glance (based on Pavlik et al. 2022; own modification).

Using the FITNAH-3D model is an approach including a commercial service provider, whereby the focus of the considerations is primarily on maintaining and improving the transport of cold air in and within the city. As practice has shown, questions of varying complexity can be answered, and options for action can also be developed, for example for the redesign of neighbourhoods. As every change in land use represents a new scenario to be analyzed – and payed for – the available budget limits the repeated use of the model.

The modelling approach with ENVI-met occupies a compromise from the operator's point of view. The model can be operated independently (with a certain familiarisation period) or by a commercial service provider. The focus of the application area is on the local level, such as the modeling of a city district, a street or a square. The fact that the calculations can be carried out relatively quickly on a standard computer means that it can be used easily to compare a higher number of different planning scenarios. However, it should be noted that the focus is only on local changes. Changes that take place in other parts of the city, but which can have an influence on the local urban climate (such as the development of fresh air corridors), can only be considered indirectly in the model layout.

Finally, it should be noted that the direct interpretation of the model results and the associated implications for the daily business can hardly be found in any final project report. For this reason, a basic prerequisite – regardless of the model results – is expert knowledge of what the maps and numbers mean or what can be derived directly from them. Even if some final reports provide recommendations, these still need to be translated into practical measures and understanding, to make the modeling results useful and applicable.

7 CONCLUSION

Climate change presents significant challenges to urban areas, with extreme heat, particularly during the summer months, being one of the most pressing impacts. Addressing the thermal comfort and heat stress in municipalities requires a comprehensive understanding of how factors such as ventilation corridors, urban greenery, building design, and spatial layouts have a combined impact on local microclimates and heat dynamics. Urban climate models are designed to tackle these challenges. They can also help to raise the awareness of specific challenges by visualizing current and future hot spots in city districts. This approach is particularly suitable for demonstrating the theoretical effectiveness of adaptation measures to increase the thermal well-being in a district. The focus is not on the exact extent of temperature reduction through individual measures, but rather on identifying potential challenges and possible solutions, and to raise awareness to pave the way for integrating adaptation into future city planning activities.

However, since the individual models are designed to address specific issues, they require different personnel and IT resources. Hence, it is essential for urban planners to identify in advance which model is most suitable for their needs and provides usable information for practical adaptation that is also fit for being seemlessly integrated in the city's existing data enquiry structure.

In general, urban development decision-makers should prioritize integrating microclimatic modeling as a fundamental component of planning measures. This approach could minimize, or ideally prevent, misinvestments in ineffective or counterproductive interventions. The model results can build a base to facilitate the efficient design of inner-city greening strategies and promote sustainable solutions for the municipality to tackle increasing heat-stress. They can also form an important building block for urban adaptation efforts to broader social goals and challenges beyond climate resilience.

Furthermore, it has to be considered, that adaptation in cities can be as diverse as projected climate change impacts. Each city has its own vulnerable sectors, places and infrastructure elements depending on the climatic, environmental and socio-economic frame. The keys for successful adaptation are scientifically based regional climate information and a holistic system understanding. Other important components for adaptation are an existing pressure to act, city needs, available knowledge, and accessible city specific information.

Therefore, adaptation is more than creating hot spot maps or developing adaptation strategies. For successful adaptation, communication is key. Therefore, only through the co-development and co-design with local decision-makers and local experts (such as urban planners, water and energy suppliers, etc.), the inclusion of local knowledge can be ensured. Communication is also the best tool to improve integrative system understanding, since the various expertise from all necessary areas can be incorporated. This not only benefits the success of the project but is also expected to increase the acceptance due to its local and individual character.

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