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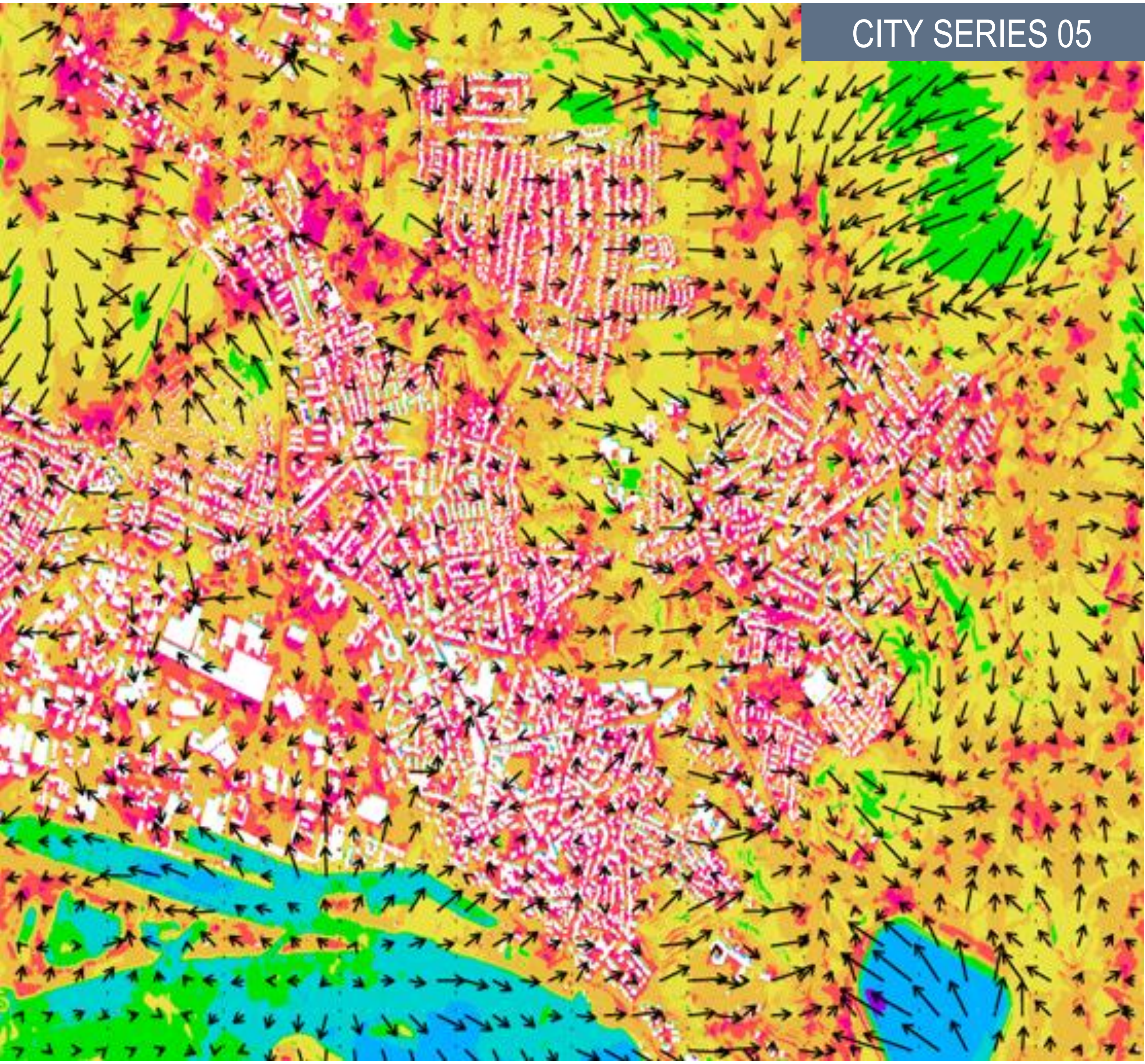
Urban Climate Modeling for Central Areas of the City of Geesthacht Using the PALM-4U Model

CITY SERIES 05



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Urban Climate Modeling for Central Areas of the City of Geesthacht Using the PALM-4U Model

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1. 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). In the course of 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, with 2023 as the warmest year on record (Copernicus Climate Change Service 2024). Temperature distributions are also shifting throughout Germany towards higher values as a result of climate change, increasing the occurrence probability of extreme heat (Deutschländer & Mächel 2017). For example, regional climate change information for Geesthacht project a future increase in the number of summer days (daily maximum temperature above 25°C), hot days (daily maximum temperature above 30°C) and tropical nights (daily minimum temperature above 20°C) (Pfeifer et al. 2021).

In general, the impacts of increasing heat vary, depending on how vulnerable the affected people, urban districts or regions are (IPCC 2014). For example, 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, in particular, 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 only slowly, and which are often not highly discernable. 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).

Not least due to these serious impacts, legal issues (Groth et al. 2021) and concerns regarding the protection of monuments (Groth et al. 2022) are also raised more frequently. These issues must be included in the practical discussion and consideration of how to deal with increasing heat stress caused by climate change in the future.

From an urban planning perspective, provisions in the German Building Code (BauGB), for example, are pertinent and must be taken into account against this backdrop. Section 1 (5) of BauGB stipulates that urban land-use planning should contribute to promoting mitigation and adaption to climate change impacts, particularly in urban development. Section 136 (2) BauGB even states as follows: "Deficits in respect of urban development occur where 1. in its existing state of physical development or condition, an area fails to meet the general needs of the people living or working within it in respect of healthy living and working conditions and general safety." This means that heat stress, which is already discernable and measurable in many locations (Bender et al. 2022), can also be accompanied by urban planning deficiencies that must be recognized and tackled through suitable adaptation measures addressing climate change impacts (Groth et al. 2022).

Long-lasting heatwaves increase heat stress, especially in cities, as urban areas only cool down again slowly. This applies not only to large cities, but also to smaller ones. This is due to the following: the construction materials used, which can store a great deal of heat; a high degree of sealing, which results in less evaporative cooling; and waste heat from technical systems or traffic. The population increase in cities and related construction activities also increase the risk of further overheating (Offermann et al. 2022). In general, many city systems react sensitively to changes in the climate. In order to counteract climate change impacts through construction measures, longer time periods must be taken into consideration. On the one hand, this is because the stages from planning to implementation often take several years and, on the other, because buildings and structures are expected to retain their functionality for several decades, even under changing climatic conditions. From an urban planning perspective, the expected climate changes must therefore already be included in today's planning to facilitate adaptation to climate change impacts (Bender et al. 2022).

Regarding questions on potential heat stress, urban climate models form a vital basis for planning decisions. They can be utilized to create a digital model of the municipality to simulate current or future urban climate, including areas where they are possibly affected markedly (hot spots). The calculated urban climate describes the climatic situation, considering interactions with open spaces, developed areas, building structures, water bodies, traffic and urban greenery (Matzarakis 2018). For example, structures that heat up over the course of the day release their heat at night, which reduces cooling in the city during the night. The higher the proportion of building structures and the degree of sealing in a city, the greater this effect becomes. Furthermore, the building structure, building height and the arrangement and density of buildings influence the supply and circulation of cold air.

Against this background, it is becoming increasingly important for municipalities to be aware of future climatic challenges and adaptation measures that reduce or avoid the negative impacts of climate change. To support municipalities here, new modules for the GERICS Adaptation Toolkit for cities (Bender et al. 2017)[1] are under development and are implemented in collaboration with the city of Geesthacht as part of the prototype product development. The aim is to demonstrate to smaller municipalities that digital models of a municipal area can be valuable planning tools for assessing possible climate change impacts.

The freely accessible and freely available urban climate model PALM-4U is utilized as an example for answering questions regarding "heat stress and thermal comfort" – this is a municipal challenge that is often considered vital (Bender et al. 2022). In consultation with the city of Geesthacht's Environment and Construction Department, the current heat stress situation in the central area of the city is under examination with a focus on the model's sub-regions "Geesthachter Straße" and "Hansastraße".

[1] Further information and publications on the GERICS Adaptation Toolkit for cities are available online: https://www.climate-service-center.de/products_and_publications/toolkits/stadtbaukasten/index.php.en

The primary intent of urban climate modeling is to answer the following questions:

- Which areas of the city are already experiencing high levels of heat stress today?
- Are there urban structures that possess more favorable thermal comfort?
- Which influence can be expected from possible redensification in the model's sub-regions under consideration and how could adaptation measures be designed there?

2. Methodology

2.1. Urban Climate Modeling

The high-resolution urban climate model PALM-4U (**Pa**rallelized **L**arge-eddy Simulation **M**odel **for U**rban Applications) developed at Leibnitz University in Hanover (Maronga et al. 2020; Steuri et al. 2019) was utilized to simulate the current thermal comfort and heat load in the city of Geesthacht. PALM-4U is the enhanced version of the basic PALM model (Raasch & Schröder 2001), which has already been utilized 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 biometeorological parameters. These parameters always relate to humans and provide information on human well-being and physiological heat stress (Fröhlich & Matzarakis 2019, Kuttler 2009). PALM-4U employs the two commonly utilized thermal indices to do so: Physiological Equivalent Temperature (PET) (Matzarakis et al. 1999) and the Universal Thermal Climate Index (UTCI) (Błażejczyk et al. 2013).

For the urban climate modeling carried out here, 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” (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.

2.2. "City of Geesthacht" Simulation Setup

Urban climate modeling for the "thermal comfort" use case is calculated for the Geesthacht urban region at a resolution of 5 m x 5 m (Large Eddy Simulation [LES]) using the PALM-4U-Model. 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 (Fig. 1).

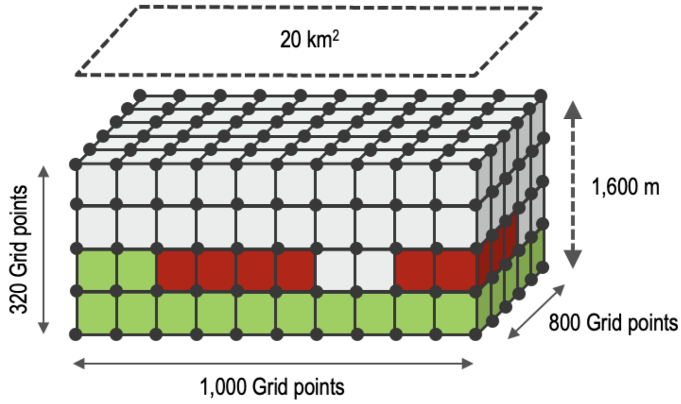

Fig. 1: The model area's geometry.

The assumed meteorological boundary condition is an autochthonous weather situation, as this is where the local climatic characteristics of a landscape can develop particularly well and the urban heat island – that is, the thermal load – is most heavily developed.

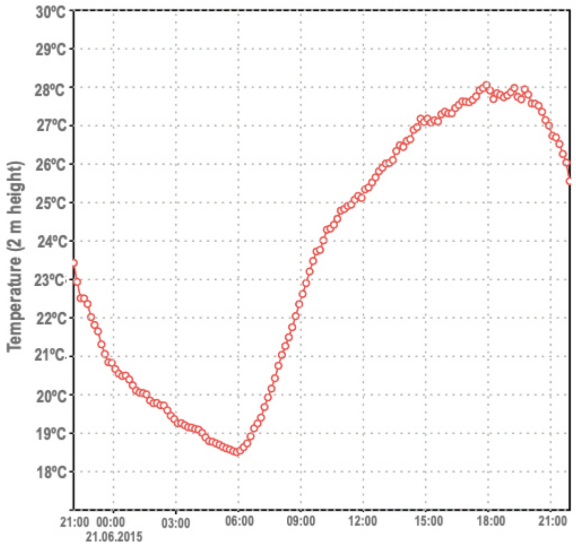

Fig. 2: Model input: temperature profile for the summer day used.

This weather situation is characterized by unobstructed solar radiation with little cloud cover and very light winds. 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 (Fig. 2).

The surface temperature, the air temperature at a height of 2 m, the "Physiological Equivalent Temperature" (PET) biometeorological index, the "Universal Thermal Climate Index" (UTCI) and the wind speed components u, v, and w are selected as output variables for this report, and output is provided for a daily cycle with a time span of 24 hours in one-minute time steps.

In the map views of the results, each map shows the wind speed at 10 m height in addition to the spatial distribution of a climate parameter or index. For all observations, the map views – screenshots from a video sequence – are compared for 04:00 (time of maximum cooling) and 16:00 (time of highest air temperature). A 5 m grid is used as the spatial resolution, which is a compromise between computing time and information quality. For a more detailed view of the model sub-regions, the "Geesthachter Straße" and "Hansastraße" regions are zoomed into the modeled maps of the "City of Geesthacht".

2.3. Thermal Comfort Assessment

Thermal comfort in public spaces is of great importance for the way in which these spaces are used as well as their attractiveness. High microclimatic and bioclimatic quality promotes healthy environmental conditions and well-being. Due to progressing climate change and further warming of cities as a result, the importance of climate adaptation at city level is growing in order to possess the capability to maintain or improve the quality of life for residents.

It is 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. In the approach used here, the "Universal Thermal Climate Index (UTCI)" and "Physiologically Equivalent Temperature (PET)" are applied (Box 1).

Box 1: Calculation of thermal comfort

The **UTCI** follows the concept of an equivalent temperature, using a reference environment with the following conditions: 50% relative humidity, no wind and the mean radiation temperature is equated to the air temperature (Jendritzky et al. 2012). This reference environment is compared to the current environment and its physiological effect on the human body. The UTCI calculation is based on a complex energy transport model (Fiala et al. 2012) and in simplified terms describes how the human body experiences wind, radiation, air temperature and humidity. It also takes into account the use of different clothing as a reaction to the actual ambient temperature (Havenith et al. 2012) (Fig.3). Stress is assessed using a 10-point scale (see Table 1).

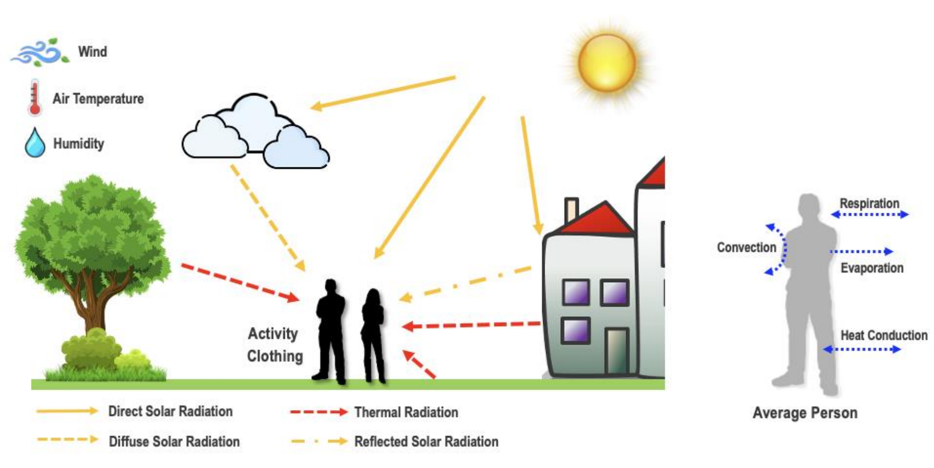

Fig. 3: Components for calculating thermal comfort.

PET is a commonly used index in the field of human biometeorology. It is based on the Munich Energy-Balance Model for Individuals (MEMI), which describes the thermal bioclimatic conditions in a physiologically relevant manner (Nastos & Matzarakis 2013). The PET is defined as the air temperature at which an individual possesses a balanced heat budget under identical sweat evaporation, skin surface and core temperature as caused by the conditions to be assessed (Höppe 1999, Matzarakis et al. 1999). Nine thermal stress classes are used for interpretation. Table 1 shows the classification based on the Matzarakis & Mayer's classification (1996) for Central Europe.

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

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

3. The Model Regions

The Model Region: "City of Geesthacht"

The PALM-4U model region is the central area of the city of Geesthacht, as shown in figure 4. The southern boundary is located in the area of Marschacht harbor, the western boundary follows approximately a line from the Hegeler Straße/Spandauer Str. intersection to Landhof Buhk. The northern boundary follows a line from the Mercatorstraße traffic circle to B404 and Wilhelm-Holert Straße. The eastern boundary lies slightly east of the reservoir (Berliner Straße).

Fig. 4: Aerial image of the "City of Geesthacht" PALM-4U-model region (image from 2018; City of Geesthacht and County of Herzogtum Lauenburg).

5A vital component for the following calculations is the geo-based information on land use, the type of land sealing and building structures. Figure 5 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).

For the detailed observations, two model sub-regions are investigated with a stronger enlargement to better visualize local heat hotspots. In all cases, the calculations are based on modeling the entire urban region.

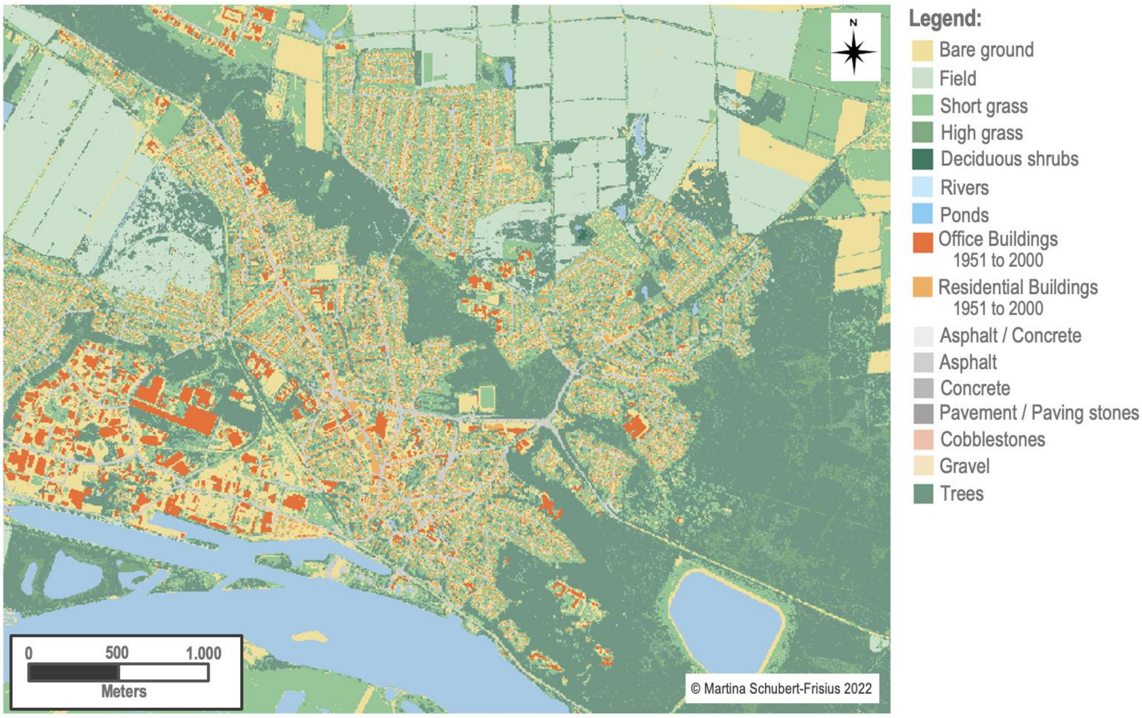

Fig. 5: Input data overview for the current land use in the “City of Geesthacht” modeling area (scale: 1:30,000).

The Model Sub-Region: “Geesthachter Straße”

This model sub-region focuses on the area north of the Alfred Nobel School. It is bordered to the west by the old former railroad tracks and to the east by Richtweg. The area extends to the north as far as Timm-Kröger-Weg (Fig. 6). Distinctive areas are Geesthachter Straße, which runs through the entire area; the sports field on Silberberg, which forms a large open space; and the elementary school buildings at Silberberg in the central area.

The Model Sub-Region: “Hansastraße”

This model sub-region focuses on the upper portion of Hansastraße, from the Dösselbuschberg and Am Spakenberg intersection to the traffic circle at the highway junction. The region is bordered to the northwest by Uhrbrookring and its extension (in linear distance through the garden allotment site) as well as to the southeast by Barmbeker Ring (Fig. 7). The two water-filled depressions in the Immental and Farmenser Weg street expansions form distinctive regions.

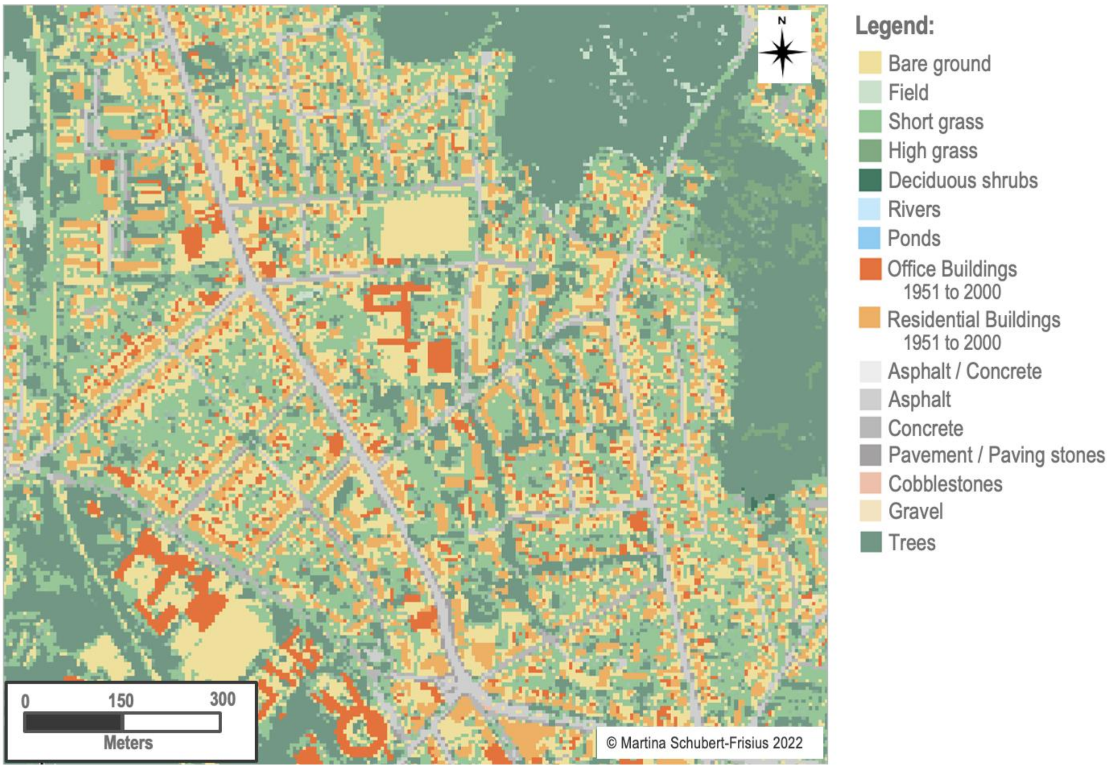

Fig. 6: Input data overview for current land use in the "Geesthachter Straße" model sub-region (scale: 1:7,500).

Fig. 6: Input data overview for current land use in the "Hansastraße" model sub-region (scale: 1:7,500).

4. “City of Geesthacht” Model Region: Results

4.1. Surface Temperature

The urban climate at times differs considerably from the climate of the surrounding region in terms of air temperature, humidity, radiation and wind. The primary reasons for the higher temperatures in urban areas are: a) storage of heat by buildings, squares, traffic areas and other infrastructure facilities, which is released again at night, and b) the reduced ventilation caused by a large number of flow obstacles such as building structures, noise barriers, trees and hedges. The urban heat island (UHI) is not only limited to the air temperature but can also be measured based on surface temperatures (Kottmeier et al. 2007) and partly in groundwater (Benz et al. 2016). In general, the UHI is most pronounced at night (Arnfield 2003). The surface temperature, however, must by no means be equated with the air temperature. It can rather serve as an indication of how much energy can be stored during the day and released again at night.

Looking at the simulation results for the “City of Geesthacht”, the spatial distribution of the surface temperature at 04:00 shows the lowest values (below 16°C) at the water areas (Elbe and reservoirs) and at the undeveloped areas near Düneberger Straße. While the temperature in the surrounding areas does not exceed 18°C, values of up to 22°C are simulated in some urban areas. A more varied picture emerges during the day (16:00). The model calculates the lowest surface temperatures (below 30°C) for the areas of water. In the surrounding areas, the values rise to 42°C and reach surface temperatures of up to 60°C in the urban region – particularly in the highly sealed areas (Fig. 8).

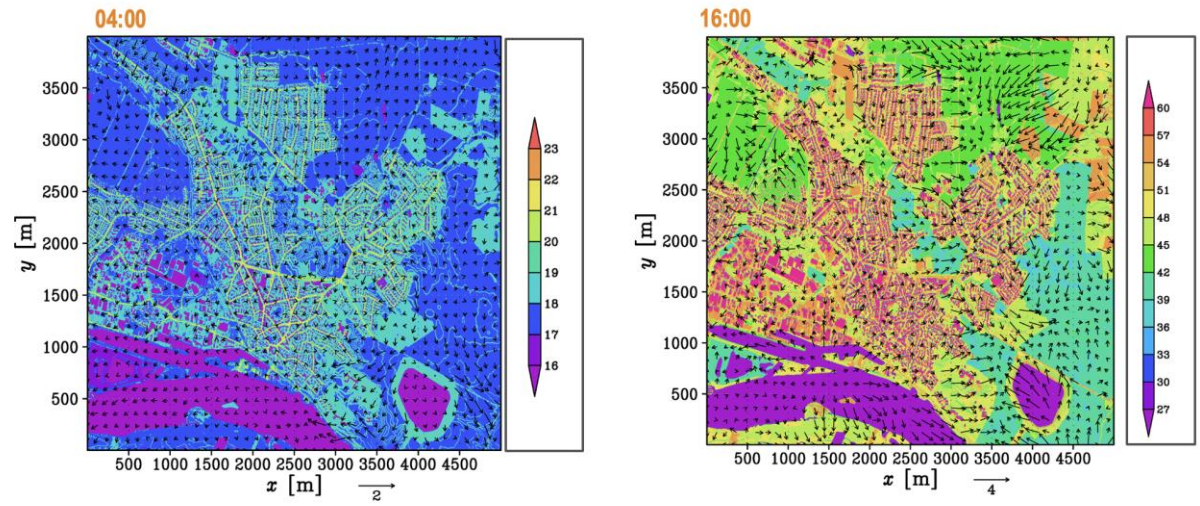

Fig. 7: Surface temperature and wind speed at a height of 10 m, at 04:00 (left) and 16:00 (right); “City of Geesthacht” model.

In summary, what is shown is that surfaces in the city – particularly traffic areas – can release more heat at night than surfaces in the surrounding countryside. The temperature differences lie at a maximum of 4°C, but mostly around 1°C to 2°C. During the day, the surfaces in the city heat up considerably more than the surrounding countryside. Here the model shows maximum differences of up to 15°C.

4.2. Potential Temperature at a Height of Two Meters

When considering the basic zone inhabited by humans (normally using the height of 2 m), the air temperature distribution shows considerably lower maximum values compared to the surface temperature (Fig. 9). With the air temperature spatial distribution at a height of 2 m, no pronounced urban heat island can be recognized at 04:00. The lowest temperatures, below 18°C, are modeled in the area of the Elbe and above open spaces near the Steglitzer Straße and Bauernvogtsweg areas. A dichotomy can be observed within the urban region: with lower temperatures in the western section (below 19°C) and higher temperatures (up to 23°C) in the neighborhoods to the north and east. The separating element here is the city forest, which runs from the northwest to southeast in the model area. The air temperature has risen significantly both in the city and in the surrounding area at 16:00. The lowest temperatures are found above the Elbe (21 to 25°C) and above the reservoir (25 to 26°C). Temperatures of up to 30°C can be observed above almost all traffic areas in the urban region. Temperatures vary between 27 and 29°C in the surrounding countryside to the north-east.

When comparing winds speeds at a height of 10 m, the speeds are considerably higher during the day than at night. The wind blows from the Elbe and from the open spaces in the surrounding north-western and north-eastern areas toward the city, whereby only very low wind speeds can be observed in the city center.

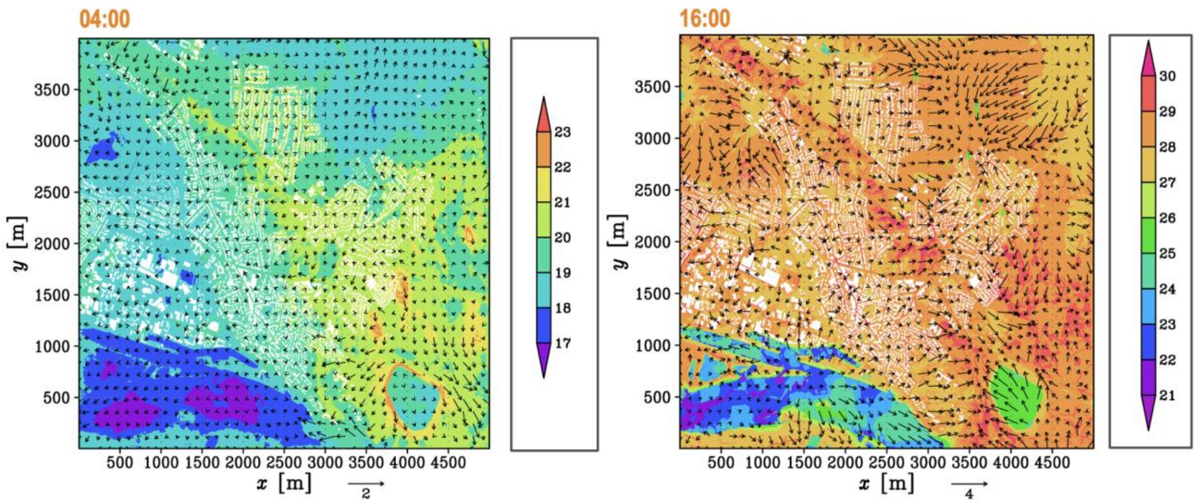

Fig. 8: Temperature at a height of 2 m and wind speed at a height of 10 m, in each case at 04:00 (left) and 16:00 (right); “City of Geesthacht” model.

In summary, the air temperature at a height of 2 m shows no clear difference between the urban region and the surroundings. Rather, a general temperature gradient exists at night, with low air temperatures in the south and west (up to 19°C) and higher values in the east (up to 23°C). Also in the day situation (16:00) there are no major differences between the urban region and the surroundings (both 27°C to 29°C). Exceptions are the water bodies with lower temperatures (22°C to 26°C) and several road and forest areas (central section and in the east) with higher temperatures (up to 30°C).

4.3. Universal Thermal Climate Index (UTCI)

The Universal Thermal Climate Index (UTCI) is a human biometeorological parameter that establishes a link between the outdoor environment and human well-being (Box 1). The term “universal” makes it clear that the index is suitable for many applications based on outdoor thermal environmental conditions, such as forecasts, warnings, bioclimate maps or climate impact research.

When observing the model results at 04:00, the UTCI values only show temperatures between 18°C and 22°C, which are in the “no thermal stress” range (Fig. 10). The lowest values occur in the Elbe area, in the open space near Bauernvogtsweg and on the northern edge of the model area. At 16:00, the thermal load has increased in all parts of the model and the inhabitants of Geesthacht are exposed to heat stress everywhere – with varying intensity. The lowest exposure ("moderate heat stress") can be seen around the Elbe and above the reservoir. In contrast, "strong" to "very strong heat stress" (37°C to 39°C) can be observed in almost the entire developed urban region (especially in the vicinity of traffic areas). Slightly lower values (33°C to 35°C), but still corresponding to "strong heat stress", can be found in the north-eastern surroundings, from where the wind moves towards the northern edge of the city.

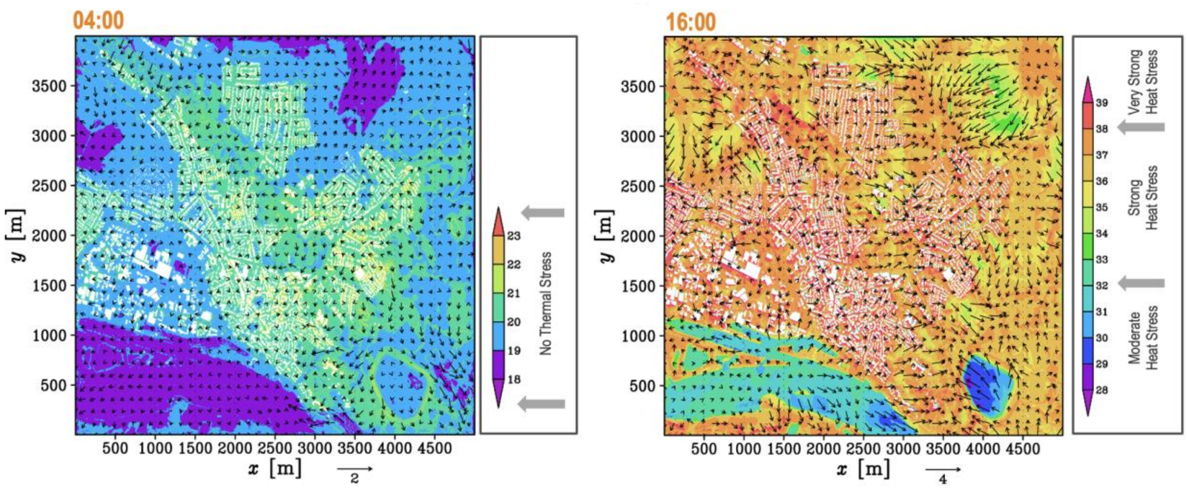

Fig. 9: Universal Thermal Climate Index and wind speed at a height of 10 m, at 04:00 (left) and 16:00 (right); “City of Geesthacht” model.

In summary, the modeling shows that based on the UTCI values, no thermal stress is to be expected in the urban region at night. During the day, however, the values increase considerably and the Geesthacht residents are exposed to heat stress throughout the model region, with the developed areas showing the highest levels of stress.

4.4. Physiological Equivalent Temperature (PET)

The physiological equivalent temperature (PET) is another universal thermal index that is often utilized for urban climatological studies (Matzarakis et al. 2010). It is used below to describe the heat load (Box 1). The level of PET values correlates strongly with the short-wave solar radiation. This means a high heat load occurs not only in cities – particularly on large, sealed surfaces without shading – but also in the surrounding open spaces. As with UTCI values, the PET value distribution shows that no thermal stress is to be expected within the model region at 04:00. Rather, PET values below 18°C are found in the peripheral areas of the city, above the Elbe and the reservoir and in the area of Düneberger Straße and Schäferberg, which corresponds to "slight cold stress" in the classification (Fig. 11). Thermal stress has increased in all parts of the model region by 16:00, in some cases significantly. "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.

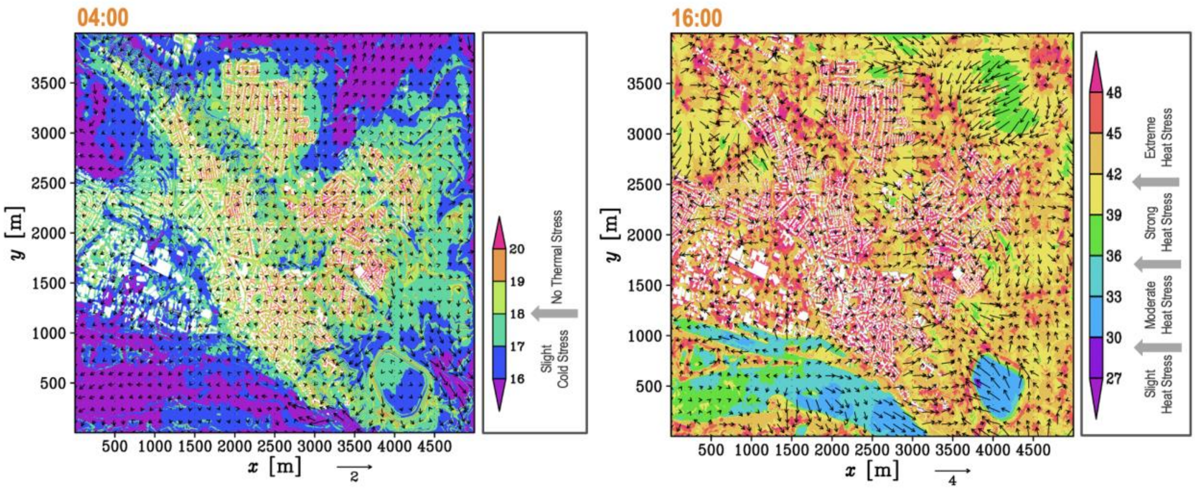

Fig. 10: Physiological Equivalent Temperature and wind speed at a height of 10 m, at 04:00 (left) and 16:00 (right); "City of Geesthacht" model.

In summary, the assessment based on PET values shows that no thermal stress occurs at night in the entirety of the urban region. In contrast, during the day within the developed urban region, areas with "extreme heat stress" are predominately found. Even though heat stress decreases in the surrounding areas and in the open spaces, it is still heavily pronounced there as well.

5. “Geesthachter Straße” Model Sub-Region: Results

5.1. Location

One focus of this study is on the Geesthachter Straße area between Silberberg and Gerstenblöcken streets (in short: the “Geesthachter Straße” urban district) (Fig. 12). The city of Geesthacht is planning to convert the urban district here including the construction of additional buildings as part of its inner-city development. While land use in the central section of this model sub-region is currently dominated by residential structures, the urban forest is the dominant land use in the northeastern area. Further characteristic areas are the sports fields on the streets Silberberg and Neuer Krug.

Because of an expected increase in summer days, hot days and tropical nights in Geesthacht and the surrounding area in the future (Pfeifer et al. 2021), urban climate modeling is to examine whether heat hotspots are already occurring in this area of the city. As it can be assumed that these hotspots will continue to exist or become even more pronounced in the future due to ongoing warming, they must be taken into consideration in subsequent planning so as not to further exacerbate the future heat situation. The following detailed maps for the model sub-region are each enlarged sections of the urban climate modeling that was carried out for the entire urban region.

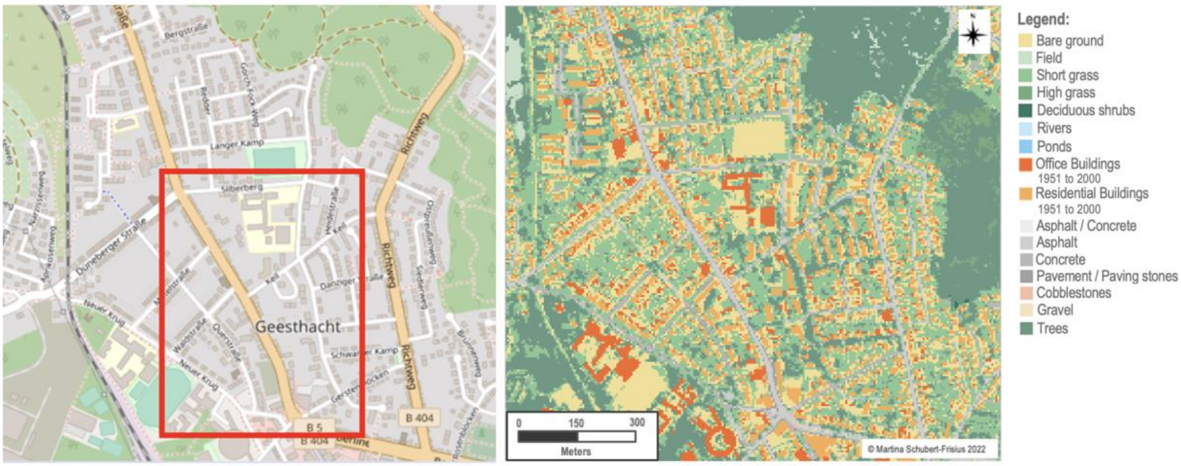

Fig. 11: Location in the model region (left) and land use (right) of the “Geesthachter Straße” model sub-region.

5.2. Surface Temperature

Looking at the surface temperature for the “Geesthachter Straße” area (5 m resolution) with a larger zoom factor, the model result for 04:00 highlights the buildings with very low surface temperatures (below 17°C) on the one hand, but also traffic areas with very high surface temperatures (up to 22°C) on the other. The open spaces between the buildings lie in a temperature range between 17 and 19°C. Within the “Geesthachter Straße” neighborhood, the slightly colder area can be observed on the west side. In addition, a larger cooler area can be observed in the southern section (Fig. 13).

The modeling shows significantly heightened temperatures at 16:00, with maximum values of over 60°C simulated on the building surfaces. As these temperatures depend heavily on the surface materials, differences are possible on site where the model assumptions deviate from the materials that were used. Streets and open spaces lacking shade also exhibit very high surface temperatures of between 48°C and 57°C. Only on the north and east sides of the buildings does the shade provide cooling, so that temperatures between 33°C and 39°C are modeled there.

When examining the wind flow field at a height of 10 m at 16:00, the currently existing buildings on Geesthachter Straße turn out to be a flow obstacle, so that a wind vortex is present in the central section of the neighborhood and the flow is deflected to the south in the southern section. In the northern section of the model area, the street Silberberg serves as an important ventilation route that channels wind into the northern section of the neighborhood. To the southwest, the Neuer Krug street is also important for ventilation, although it does not affect the “Geesthachter Straße” neighborhood.

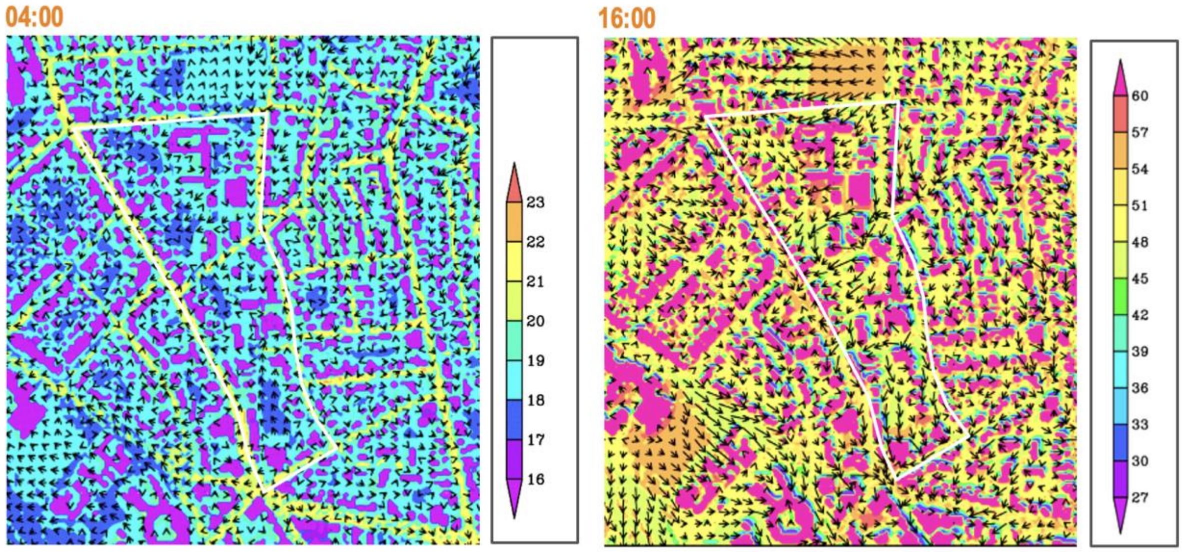

Fig. 12: Surface temperature and wind speed at a height of 10 m, at 04:00 (left) and 16:00 (right); “Geesthachter Straße” model sub-region.

In summary, the modeling shows the cooling influence of non-sealed surfaces at night compared to the warmer traffic areas. Even if the buildings appear very cool in the model, it can be observed during the day that the highest temperatures occur here and that the buildings therefore make a considerable warming contribution. In order to examine the effect in detail, the material properties of the individual buildings would need to be integrated into the model on a smaller scale and more precisely. The positive influence of shading on the buildings is particularly evident during the daytime.

5.3. Potential Temperature at a Height of 2 m

Examining the spatial distribution of the modeled air temperature at a height of 2 m, several cooler areas with temperatures below 19°C are noticeable at 04:00. A cooler area can be found on the west side of the district (1 and 2 in Fig. 14), where the buildings seem to prevent the cooler air from flowing away. To the west are other cooler areas, such as those above the large green spaces (gardens) on Querstraße (3) and above the open spaces between Neuer Krug and Grenzstraße (4). The general gradient is striking with low temperatures in the southwest and higher temperatures in the northeast.

At 16:00, the situation is more uniform with temperatures between 27°C and 30°C. The lowest temperature above and around the sports fields (Silberberg and Neuer Krug) (6, 8) as well as above the green areas on Querstraße (9) are striking. This indicates that warmer air tends to accumulate in densely developed areas due to the lack of adequate air circulation. In the Geesthachter Straße area, the model reveals the highest temperatures (around 30°C) south of buildings. There are no differences, however, in the urban climate compared to adjacent streets. Examining the wind direction and speed at a height of 10 m, wind flows from the outside over the northern area (6, 7) and the colder air in the southern section flows into the adjacent, warmer streets (5).

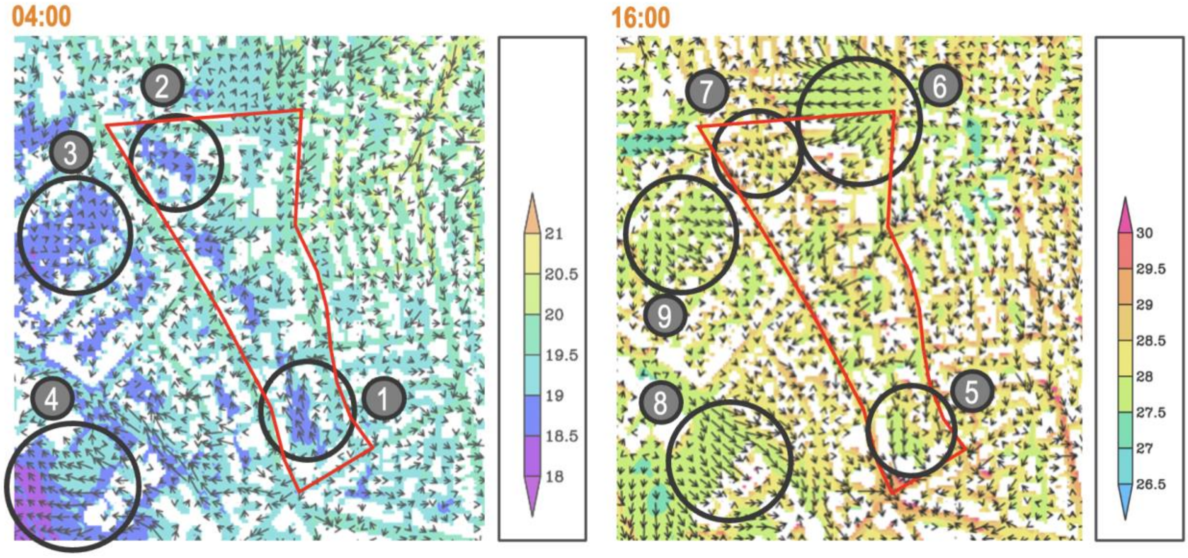

Fig. 13: Temperature (at a height of 2 m) and wind speed at a height of 10 m, in each case at 04:00 (left) and 16:00 (right); model sub-region “Geesthachter Straße”.

In summary, as lower temperatures occur above undeveloped areas both during the day and at night, the modeling proves the importance of such areas for the urban climate. In contrast, the air can heat up to a greater degree between buildings that are located closer together – that is, where the flow of air is severely restricted.

5.4. Universal Thermal Climate Index (UTCI)

The modeled UTCI values in this model sub-region lie between 19 and 22°C at 04:00. According to the classification, there is therefore no thermal stress (Fig. 15). As with the air temperature at a height of 2 m, the lowest temperatures are also observed in the southwest of the model area (sports field, Neuer Krug). Within the “Geesthachter Straße” neighborhood, four cooler areas occur in a stretch running from northwest to southeast (blue areas with temperatures below 20°C).

At approximately 16:00, the urban district and the surrounding area heated up considerably, which correspondingly increased the heat stress (UTCI values of 36°C to 39°C). At the northeast corners of the building structures, the heat stress drops noticeably, albeit on a small scale (30°C: "moderate heat stress"), which can presumably be attributed to the shading effect of the buildings. Comparing the “Geesthachter Straße” urban district with its surroundings, only the areas around the two sports fields show a certain heat reduction (UTCI: 35°C to 37°C), although the heat stress there can still be classified as severe.

In summary, the modeling of the “Geesthachter Straße” urban district shows that, based on the UTCI, there is currently no thermal stress at night and that cooler zones can be observed in the garden areas. Nevertheless, these zones heat up quite considerably during the day, which can be attributed to the lack of shading.

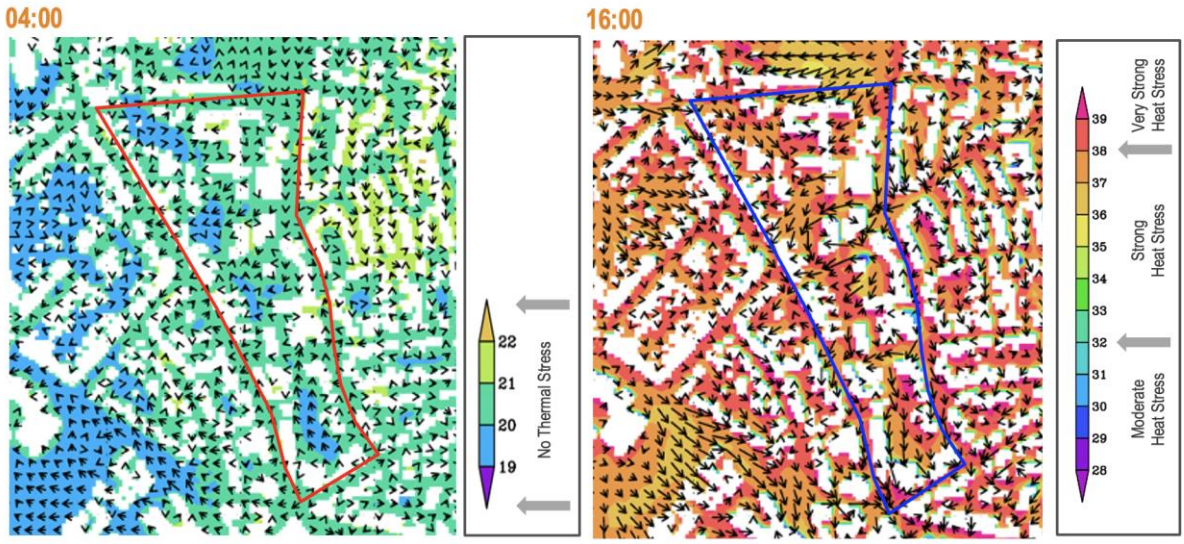

Fig. 14: Universal Thermal Climate Index and wind speed at a height of 10 m, in each case at 04:00 (left) and 16:00 (right); “Geesthachter Straße” model sub-region.

5.5. Physiological Equivalent Temperature (PET)

If PET is used to describe thermal comfort, a more differentiated image emerges compared to the UTCI. At 04:00, the model calculates areas with a "slight cold stress" (PET values below 18°C) in the central section of the urban district and above the sports field (Neuer Krug) (Fig. 16). On the east side of Geesthachter Straße and east of the city neighborhood, areas with a temperature above 19°C can be observed, but this still does not correspond to thermal stress. Within the “Geesthachter Straße” area, the lowest PET values (16°C to 17°C) occur above the large open space in the south (1) and above the undeveloped areas south of the Silberberg elementary school (2). A comparison of the PET values with the neighboring area along Danziger Straße (A) (up to over 20°C) shows the cooling influence of open spaces and effective ventilation.

This difference is much less pronounced during the day. At 16:00, heat stress has increased across the entire model sub-region due to advanced large-scale warming. The lowest temperatures occur at the northeast corner of building structures (PET values: 35°C to 30°C, "moderate heat stress"). The highest heat stress levels (PET values above 45°C) are observed both in most traffic areas as well as in the central area of the urban district (4, 5). Slightly cooler, but still heat-stressed areas (PET values: 39°C to 45°C) are located above the two sports fields (3, 6). In the northern section, the air from the sports field on Silberberg is directed into the city district (3), but this does not result in a considerable cooling effect. The air flow calculated in the southeastern section at a height of 10 m also has no influence on the wind field (6), which is probably due to the closed row of houses.

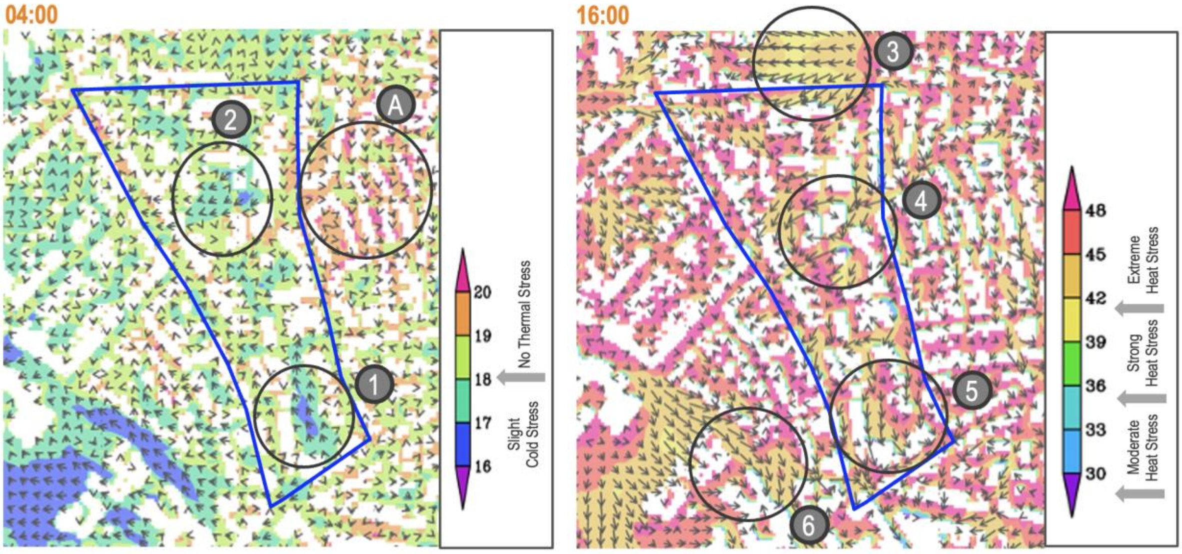

Fig. 16: Physiological Equivalent Temperature and wind speed at a height of 10 m, in each case at 04:00 (left) and 16:00 (right); model sub-region "Geesthachter Straße".

In summary, the modeling for the "Geesthachter Straße" urban district shows that no thermal stress currently occurs at night based on the PET. The gardens produce cooler areas compared to neighboring streets lacking open spaces. The lack of shading, however, means that the areas heat up considerably during the day.

6. “Hansastraße” Model Sub-Region: Results

6.1. Location

The model sub-region in the “Hansastraße” urban district can be divided into different zones with different land use variants relevant for interpreting general impacts of land use, building density and type of development on thermal comfort in the city of Geesthacht. Southeast of Hansastraße is the “Hansastraße” neighborhood, which is characterized by multi-story buildings arranged in rows and groups. The area is surrounded by detached single-family homes and an expansive wooded area (Fig. 17). Northeast of Hansastraße, in addition to detached single-family homes and apartment buildings, there are two wooded areas connected to each other and to the surroundings via undeveloped areas.

The following detailed maps for the model sub-region are each enlarged sections of the urban climate modeling that was carried out for the entire urban region.

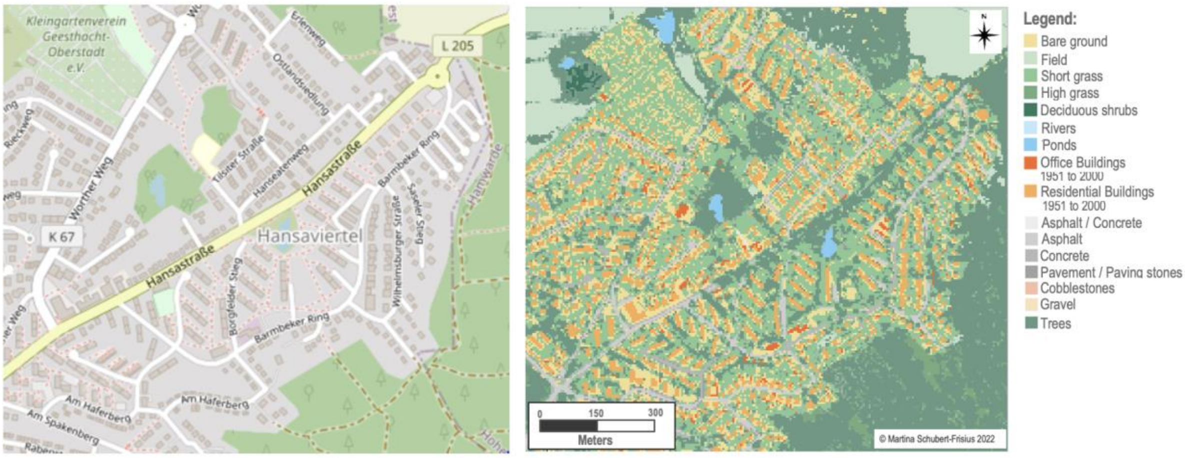

Fig. 15: Location in the model region (top left) and land use (right) of the “Hansastraße” model sub-region.

6.2. Surface Temperature

The highest surface temperatures for nighttime (04:00) are found above traffic areas (up to 22°C). Green areas (mainly gardens) show temperatures between 18°C and 20°C (Fig. 18). There are four cool areas below 18°C in the model sub-region that stand out: wooded areas southeast of Barmbeker Ring, the pond area on Hansastraße (at the Hanseatenweg entrance), the wooded area at the Immental street expansion and the open area in the northwest. At 16:00, the surface temperature within the entire urban area have increased considerably, with building structures heated up to the greatest extent (up to 60°C). Comparing the areas northwest and southeast of Hansastraße, lower temperatures (below 48°C) are noticeable in the southeastern section between the rows of buildings due to higher wind speeds. The shade cast by the building structures is also more pronounced there and reduces the temperatures in the northeastern area of the buildings to below 33°C.

Higher temperatures dominate the northwest of Hansastraße. This also applies to the open spaces of the Geesthacht Oberstadt e.V. Allotment Garden Association, as little or no shade from trees exists in this area. The cooling effect from water surfaces can be observed in the Immental area and near the pond area (Hansastraße) with temperatures below 30°C. Wooded areas also lead to a temperature decrease (33°C bis 45°C).

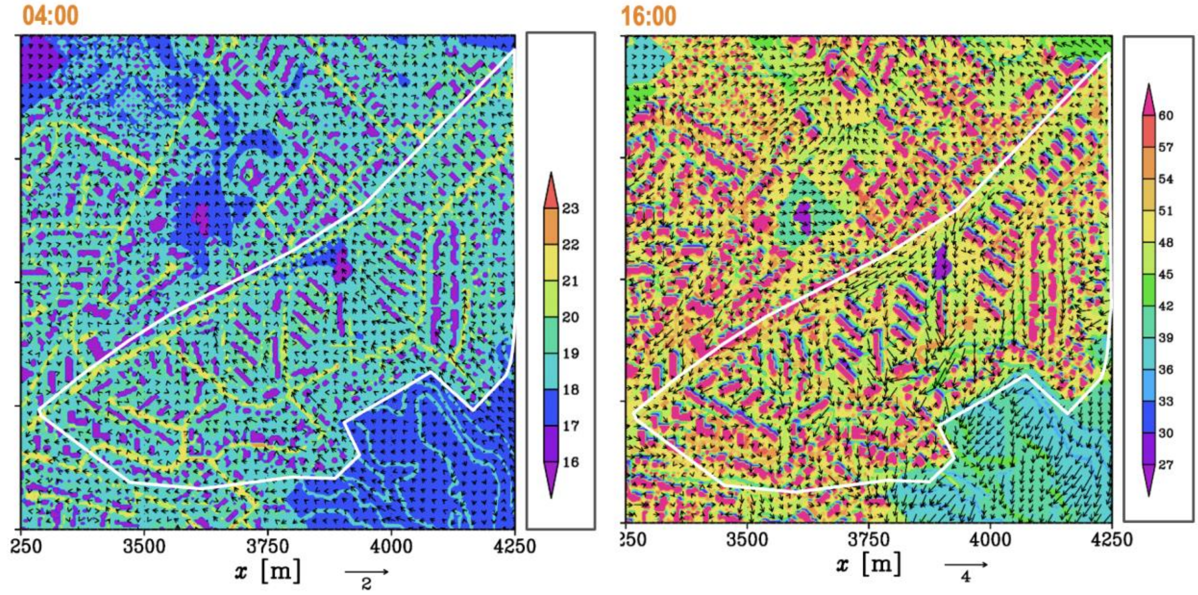

Fig. 16: Surface temperature and wind speed at a height of 10 m, at 04:00 (left) and 16:00 (right); "Hansastraße" model sub-region.

6.3. Potential Temperature at a Height of 2 m

As with the surface temperature, the highest air temperatures at night (04:00) are observed above the traffic areas (over 21°C). The model shows similarly high values between the rows of building structures and in the street areas southeast of Hansastraße as well as in an adjacent wooded area (Wandsbeker Stieg area) (4) (Fig. 19). The lowest temperatures in the model are seen where the degree of non-sealed areas is very high and there are few obstacles (trees) for the flow of cold air. The coolest locations with temperatures below 19.5°C are found in the water surface areas (2, 3), above the allotment garden area as well as over the open spaces adjacent to the north and northeast (1). At 16:00, the highest temperatures are simulated in the wider surroundings of the wooded area in the southeast of the model sub-region (7). This result, which may seem initially surprising for a wooded area, can be explained as follows: the course of the sun was simulated for a summer afternoon as part of the modeling. At this time, the slopes of the terminal moraines, which are located almost 30 to 40 m higher, are particularly illuminated by the sun shining from the southwest and are therefore heated up. From a physical point of view, more solar energy reaches these areas than a flat surface due to the exposed slope (southwest facing). This is also applicable to an area near the municipal forest north of the Besenhorst street. In addition, reduced flow of air masses in wooded areas is relevant. Forest areas essentially act as producers of cold air at night, whereby the cooling air volume does not reach such low temperatures as in open spaces. The tree canopy surface of the leafy forest or the evergreen coniferous forest shields the forest floor from the atmosphere and regulates the heat turnover in such a way that the trunk area generally does not heat up as much during the day as does the air layer near the ground above open spaces and does not cool down dramatically at night. The daily temperature curve in the forests is therefore more balanced. In the residential areas, the temperatures lie between 27°C and 29.5°C, depending on the distance between the building structures and the flow velocity, whereby the size of the open space has a reducing effect on the temperature. The lowest air temperature, with values below 25.5°C, occurs above the two water surfaces (5, 6). The cooling effect, however, has only a narrow reach.

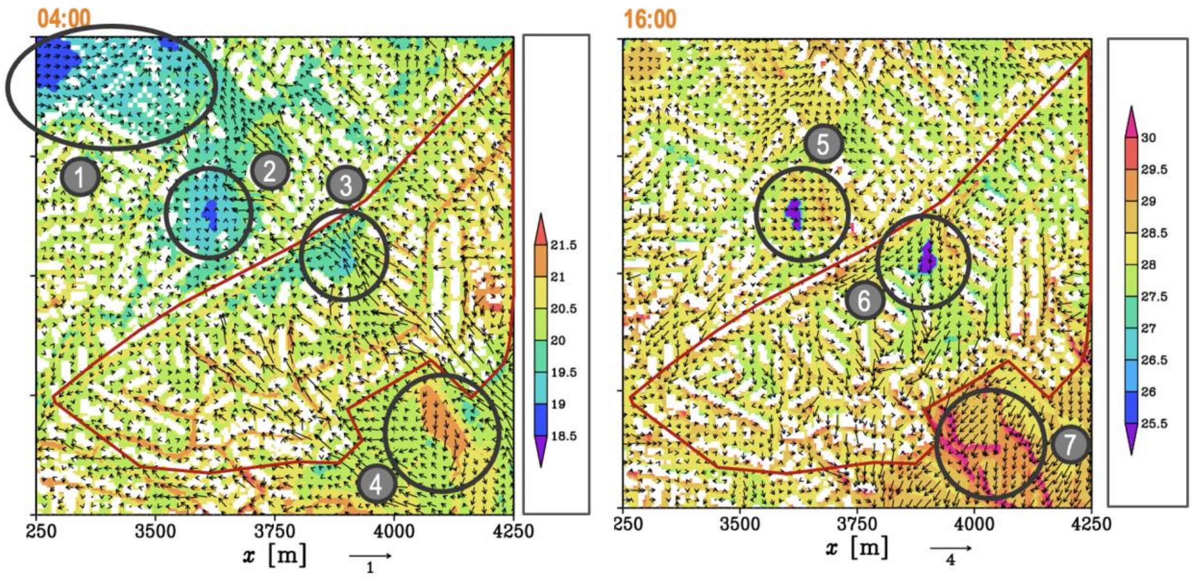

Fig. 17: Temperature (at a height of 2 m) and wind speed at a height of 10 m, in each case at 04:00 (left) and 16:00 (right); model sub-region “Hansastraße”.

6.4. Universal Thermal Climate Index (UTCI)

If the UTCI is used to describe the heat load, no thermal loads occur in this model sub-region at 04:00 (Fig. 20). The UTCI values vary between 20°C and 22°C in the developed areas and between 19°C and 21°C above the open spaces, water and forest areas as well as in the allotment garden area. At 16:00, the heat stress increased everywhere, but to varying extent. The highest UTCI values (over 38°C: classified as “very strong heat stress") are found on the southwest side of almost all building structures. In the street sections, where the buildings stand very close together, the heat stress is also very pronounced (36°C and higher). Lower UTCI values (up to 33°C), although still categorized as “very strong heat stress", occur above the water areas and in some wooded areas in the area’s southeast. The model results show "moderate heat stress" only in very small areas, each at the northeast corner of the building structures.

In summary, the modeling for the “Hansastraße” urban district shows that no thermal stress can currently be identified at night based on the UTCI. The coolest areas are located above water and open spaces. During the day, all areas of the city heat up and "strong" to "very strong heat stress" occurs, except for the small, shaded areas at the northeast corners of the building structures.

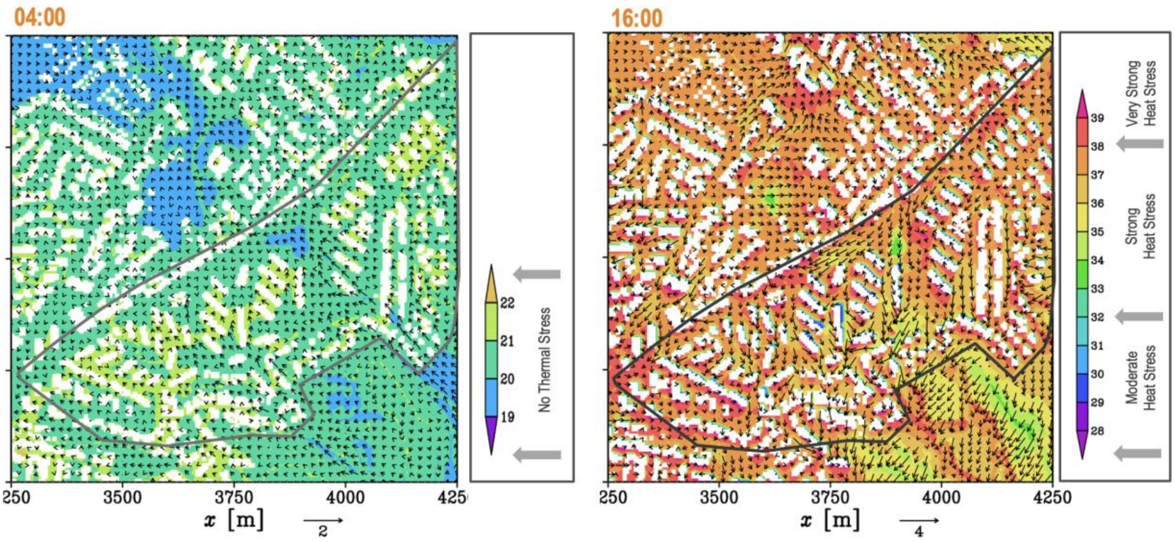

Fig. 18: Universal Thermal Climate Index and wind speed at a height of 10 m, at 04:00 (left) and 16:00 (right); model sub-region “Hansastraße”.

6.5. Physiological Equivalent Temperature (PET)

If the PET values are used to describe thermal comfort, the coolest places (below 18°C) at night can be found where there are no buildings but rather open spaces and water areas (1, 2, 3) or at the edge of wooded areas (4). The cold air flowing in can also provide cooling at the edges of the developments (17°C to 19°C). The penetration depth of the cold air into the developed area essentially depends on the building density and the building height. It should be noted here that the existence of trees and shrubs can also reduce the inflow. Due to the barrier effect, which makes it difficult for cold air to penetrate, temperatures of over 20°C can also occur at night (5). There is generally no thermal stress in residential areas at 04:00. Rather, "slight cold stress" can be observed in favorable locations (Fig. 21).

At approximately 16:00, the heat stress increased everywhere, with the highest values (45°C and more, which is classified as "extreme heat stress") found southeast of the building structures. Depending on the positioning of the buildings, these areas can overlap to form larger areas (7). Only where larger open spaces exist or good air flow is possible do the PET values fall slightly (39°C to 45°C), but they remain at a high heat stress level ("strong" to "extreme heat stress"). However, the allotment garden area, for example, shows high PET values (42°C and more), as the direct heat radiation is not reduced by shade. The coldest areas (36°C to 39°C) – although still exhibiting "strong heat stress" – are found in the vicinity of the water areas (6) and in the wooded areas in the southeast corner of the model sub-region (8).

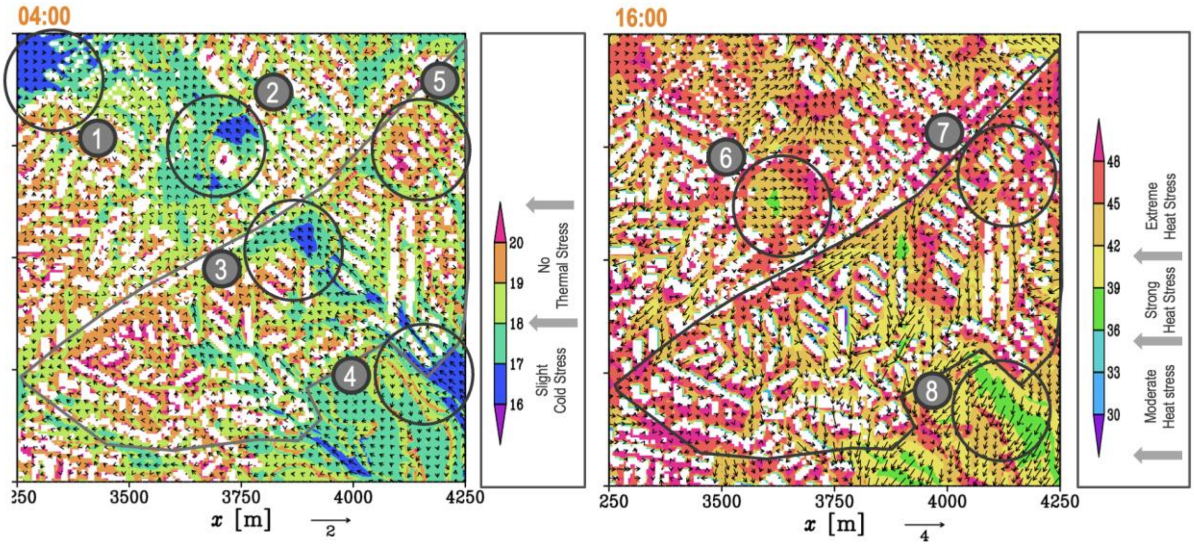

Fig. 19: Physiological Equivalent Temperature and wind speed at a height of 10 m, at 04:00 (left) and 16:00 (right); model sub-region "Hansastraße".

In summary, the modeling for the "Hansastraße" urban district shows that there is currently no thermal stress at night based on the PET values. The warmest areas are located between the building structures, where the warm air can accumulate. Heat stress increases considerably during the day, with the highest values between building structures or at the southeast of the structures. Open spaces and wooded areas, however, can also heat up substantially. The shade cast by trees or structures can nevertheless reduce the PET value. The resulting areas with only "moderate heat stress" are nevertheless relatively small.

7. Results at a Glance

As urban climate modeling with Palm-4U demonstrates using various indices, the location and extent of overheating are significantly influenced by land use, the type and positioning of building structures and the ability of cold air to flow through them. The modeling yields the following key findings for the urban area:

- Urban traffic areas heat up substantially during the day and emit heat at night.
- Geesthacht exhibits a temperature gradient at night in which the urban areas in the south and west are cooler than those areas in the east.
- When looking at the air temperature at a height of 2 m in general, there is no clear difference between the city and the surrounding area.
- The city is considerably warmer than the surrounding area when it comes to surface temperatures. Water surfaces are the coolest here and the overall temperature differences are the highest.
- When considering the thermal stress based on the PET values, no thermal stress can be seen in the model for the urban area at night (04:00). During the day, however, the areas with "strong" and "extreme heat stress" are prevalent. The lowest thermal stress is observed directly at the Elbe. It should be noted that many factors are included in calculating the PET values (see also Box 1). In this case, the surrounding area is somewhat cooler at night than the city. During the day, the forest heats up more rapidly, as the shade in the city initially offers more protection. Between 10:00 and 11:00, the city increasingly begins to heat up as the shade lessens (the PET value increases more rapidly). Between 12:00 and 14:00, the forest and city are still warmed to a similar degree, as it is the shade that is now primarily relevant. Between 14:00 and 18:00, the city is subject to greater stress, as the reflection from the buildings increases the thermal stress. Cooling occurs everywhere when the sun sets. The forest, however, remains more pleasant (lower PET value).

Based on a detailed assessment of the two model sub-regions (“Geesthachter Straße” and “Hansastraße”), the following findings can be determined:

- The greatest heat loads occur at night in traffic areas and during the day in the vicinity of building structures. The lowest thermal load is observed within the shade cast by buildings. Even if non-sealed open spaces (parks, sports fields, allotment gardens) with good air circulation are the coolest places at night, they often have a low livability quality (high PET values) during the day due to the direct insolation.
- On the one hand, the warming during the day should be counteracted by extensive shading in addition to planting more trees with large canopies; technical solutions such as sun sails can also be considered. On the other hand, it is important to ensure that there is sufficient air flow through the area so that the cool air can penetrate as far as possible into the city.
- With regard to developed areas and traffic areas, which heavily contribute to the daytime heating of the city, examination should be carried out as to whether providing shade through planting (façade or roof greenery, street trees) or technical solutions (reflective coatings on buildings or streets) can reduce heat storage which will reduce the heating of these areas. Although studies show that the cooling effect (reduction of 0.6°C to 1.5°C) of green roofs only works directly above the roof surfaces (Pfoser et al. 2013), it can also improve the indoor climate in the topmost apartments below the roof

(Groß 2012). Green façades are particularly effective on west and south-facing façades, as this is where the strongest insolation occurs, and the greening can reduce the heat radiation during the day.

- As investigations of the human habitable zone (2 m height) show, building construction that is too dense should be avoided, as this can cause the heat to accumulate and result in a lack of open spaces that can provide local cooling at night, albeit only to a limited extent. For this reason, sufficient potential for cold air flow should be ensured when planning a new urban district.
- Elements that facilitate cold air penetration are open spaces characterized by vegetation, garden allotments and wide streets. However, it is important to keep in mind that an excessively dense tree population can also act as a natural barrier. A low heat load is critical for the livability quality, which can be achieved even in the smallest spaces by unsealing, providing shade and greenery.
- Woodland and water areas also have a positive impact on directly adjacent neighborhoods during the day. They provide important balancing functions as a source of cold air and recreational space.

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