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# Measures against heat stress in the city of Gelsenkirchen, Germany

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***Abstract***

*In the near-surface atmosphere, heat waves during the summer cause situations that may lead to human-biometeorological impairment. Because of their high population density, overheated cities are particularly strongly affected by heat stress. In the future, due to the effects of climate change, heat stress will increase in terms of its intensity and spatial expansion in the areas of concern. Taking the example of the city of Gelsenkirchen, Germany, this article presents a method for the identification of areas requiring adaptation or protection. A scenario of the future increase of heat stress events is presented, based on data of the German climate change model STAR II. For the identification of areas requiring adaptation and protection, spatial analyses of the urban heat island, land use and demographic aspects were performed using GIS tools. The application and assessment of adaptation measures is investigated for an urban quarter using the microscale numerical model ENVI-met. Finally adaptation measures in urban planning against heat stress are discussed. The relevant urban planning adaptation measures, which are also important in view of climate change, not only involve heat stress reduction in the residential areas already affected, but also involve the protection and optimisation of existing favourable and compensation areas.*

**Zusammenfassung**

Hitzewellen rufen für den Menschen Situationen hervor, die insbesondere in der sommerlichen bodennahen Stadtatmosphäre zu human-biometeorologischen Belastungen führen können. Überwärmte Städte sind dabei aufgrund der hohen Bevölkerungsdichte besonders betroffen. Der Klimawandel wird zukünftig die Wärmebelastung bezüglich Intensität und der räumlichen Ausdehnung verstärken. Am Beispiel der Stadt Gelsenkirchen wird eine Methode zur Lokalisierung urbaner Schutz- und Anpassungsgebiete vorgestellt. Die quantitative Zunahme von zukünftigen Hitzeereignissen wird anhand des regionalen Klimamodels STAR II aufgezeigt. Zur Identifikation anpassungs- und schutzbedürftiger Stadtgebiete werden mittels GIS-Werkzeugen Raumanalysen der städtischen Wärmeinsel, der Flächennutzung und der demografischen Situation durchgeführt. Anhand eines Modellquartiers wird die Anwendung und Bewertung von Minderungsmaßnahmen mittels des mikroskaligen numerischen Modells ENVI-met untersucht. Schließlich werden städtebauliche Anpassungsmaßnahmen gegen Hitzestress erörtert. Hinsichtlich der städtebaulichen Anpassung an den Hitzestress werden geeignete Minderungsmaßnahmen empfohlen, die sich nicht nur auf die Wärmereduzierung in bereits betroffenen Wohnquartieren, sondern auch auf den Schutz und die Optimierung vorhandener Gunst- und Ausgleichsräume beziehen.

**Keywords** Urban climate, urban heat island, thermal comfort, climate change, adaptation, land-use management

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## 1. Introduction

In addition to the scientific aspect, understanding the phenomenon of urban excess heating and the associated heat stress on city-dwellers, especially during hot spells (*Mayer* 2006), is of considerable practical relevance for urban planning (*Allen* 2012; *Gill* et al. 2007). Mandated by European and German environmental legislation (BauGB 2011, UVPG 2012), urban planners are required to optimise the climate in towns and cities on the basis of human–biometeorological factors (*Helbig* et al. 1999). The primary causes of excess heating, which may cause temperature increases that reach several Kelvin in central European cities, are a high degree of sealing, a lack of cooling by evaporation, inadequate ventilation and technical process heat (*Kuttler* 2010a).

The optimisation of the urban climate must not only take into consideration the current situation of heat stress, but also the additional effects to be expected (*Kuttler* 2012, The Federal German Government 2008) as a result of projected climate change (IPCC 2007). In this context, not only the areas currently affected by heat stress must be considered, but also the growth of areas affected by heat stress from the addition of areas where heat stress is currently assessed as slight to moderate, but may become severe in the future (*Kuttler* et al. 2012a, 2013).

Taking the example of the city of Gelsenkirchen, Germany, this article indicates the expected effects of climate change, in terms of heat stress, on the thermal comfort of the inhabitants, the means of identifying the urban areas affected and the means of selecting the appropriate urban planning adaptation measures. Adaptation to heat stress not only involves reducing the heat stress on the areas affected, but also protecting and optimising the existing compensation areas and the areas that provide a favourable impact on heat stress. The results presented in this paper are based on previously unpublished investigations and research reports for the municipality of Gelsenkirchen, Germany (*Kuttler* et al. 2011a, 2011b, 2012a, Stadt Gelsenkirchen 2011, 2012).

## 2. Investigation area

The city of Gelsenkirchen is located in the centre of the German Ruhr agglomeration (5.2 million inhabitants (RVR 2012)) in an area with a slightly pronounced relief of elevations between 25 m and 95 m above sea level. The characteristics of the industrial city, with an area of 105 km$^2$, are its bipolar structure (two city centres "Altstadt" and "Buer") and its extensive industrial and commercial areas (*Fig. 1*).

With 259,000 inhabitants, Gelsenkirchen is a medium-sized German city. The average population density is 2,470 inhabitants/km$^2$, rising to over 15,000 inhabitants/ km$^2$ in the city centres. The residential areas relevant for possible heat stress may be assigned to the climatopes "town centre" and "agglomerated urban buildings" (VDI 3787, Part 1 (1997/2003)) or 'local climate zones' LCZ 2 and 3 (*Stewart* 2011) (as regards classification, see *Tab. 1*).

## 3. Methodology

The starting point for this study was a climate analysis of the entire city that was completed in 2011, which includes 1:20,000 scale climate function maps and planning information maps in accordance with VDI 3787, Part 1 (1997/2003), based on measurements. The maps present information on the current urban climate situation and the geographic location of the existing areas currently exposed to heat stress risk.

In the first stage, the future changes in temperature levels throughout the city were determined on the basis of the German regional climate change model STAR II (*Kreienkamp* and *Spekat* 2008). These changes were then projected onto the synthetic climate function map, with a view towards locating the future heat stress areas in addition to the areas currently affected.

In the second stage, the sections of areas with heat stress risk that required priority treatment were then determined by taking into consideration the social factors of population density and the demographic structure of the population in terms of areas with a high population density and areas with a high share of high-risk groups in terms of environmental health. For both indicator groups, data provided by the city of Gelsenkirchen for 2011 are available. The high-risk groups are represented by senior citizens, who are 65 years of age or older. For the assignment of priorities, the degree of excess heating, the population density and the share of senior citizens are each normalised based on z-transformation. Then the figures are added and normalised to percentage to form a quantitative measure of the adaptation requirement or vulnerability.

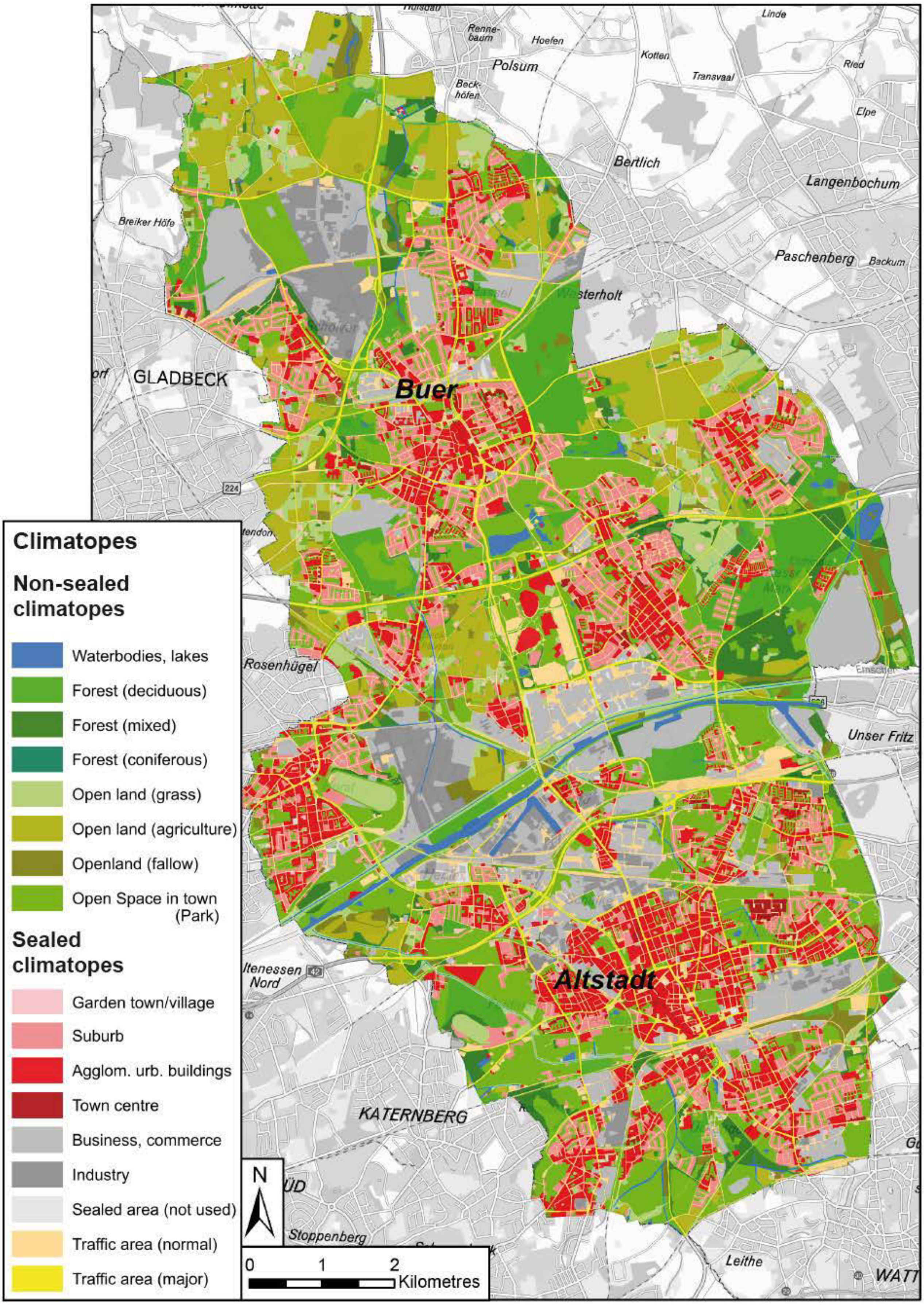


*Fig. 1 City of Gelsenkirchen: land-use map (climatopes)*

*Tab. 1 Comparison of the classification of land use that has an effect on climate: climatopes (VDI 3787, Part 1 (1997/2003)) and local climate zones (LCZ; Stewart 2011); * extended definition for local purposes*

| Climatope | Climatope* | Local climate zone (LCZ) | |
|---|---|---|---|
| Town centre | Town centre | 1 | Compact highrise |
| | | 2 | Compact midrise |
| Agglomerated urban buildings | Agglomerated urban buildings | 3 | Compact lowrise |
| Open space in towns | Park | | *– undefined –* |
| Suburb | Suburb | 6 | Open lowrise |
| *– undefined –* | *– undefined –* | 7 | Lightweight lowrise |
| Garden town, village | Garden town, village | 9 | Sparsely built |
| Business, commerce | Business, commerce | 4 | Open highrise |
| | | 5 | Open midrise |
| | | 8 | Large lowrise |
| *– undefined –* | Sealed area (not used) | | *– undefined –* |
| *– undefined –* | Traffic area (normal) | | *– undefined –* |
| *– undefined –* | Traffic area (major) | | *– undefined –* |
| Industry | Industry | 10 | Heavy industry |
| Forest | Deciduous woods<br>Mixed woods<br>Coniferous woods | A | Dense trees |
| Open land | Agriculture,<br>Grassland, Fallow land | B | Scattered trees |
| | | C | Bush, scrub |
| | | D | Low plants |
| | | E | Bare rock, paved |
| | | F | Bare soil |
| Waterbodies, lakes | Waterbodies, lakes | G | Water |

Finally, a numerical micro-scale model area was taken to illustrate how heat stress in residential districts can be analysed, assessed and then reduced, using the simulation model. The model area shown in the left-hand photo in *Figure 2* currently consists of an open space with an area of 5.3 ha surrounded by high-density buildings. The area includes a hospital with a care home.

The western and northern parts of the “Elisabeth-Stift Erle” have three- to five-story buildings with heights between 10 m and 15 m (corresponding to an aerodynamic roughness $z_0$ between 1.0 m and 1.5 m). To the east and south, there are mainly two to three-story semi-detached and detached houses (height 8 m to 10 m, $z_0$ between 0.8 m and 1.0 m). The actual condition of the area is characterised by the park at the hospital and the care facility, with an area of approximately 3.1 ha, which consists of open green spaces with individual groups of trees. To the west, the park is separated from the residential area on Voehdestraße by a row of trees that are approximately 10 m to 20 m high. Inside the park, the 18-m-high five-story main building of the hospital is the largest and highest building in the area.

Residences for senior citizens are planned to be built in the western part of the park on an area of approximately 0.4 ha (*Fig. 3*, left). This area corresponds to 13 % of the entire area of the park. The main buildings will be two large three-story residential blocks with courtyards and three smaller houses with two or three stories.


*Fig. 2 Aerial photograph (left) and building and vegetation model (right) showing the current situation of the ENVI-met model area "Elisabeth-Stift Erle" in Gelsenkirchen; source of aerial photograph: IT-NRW 2012*

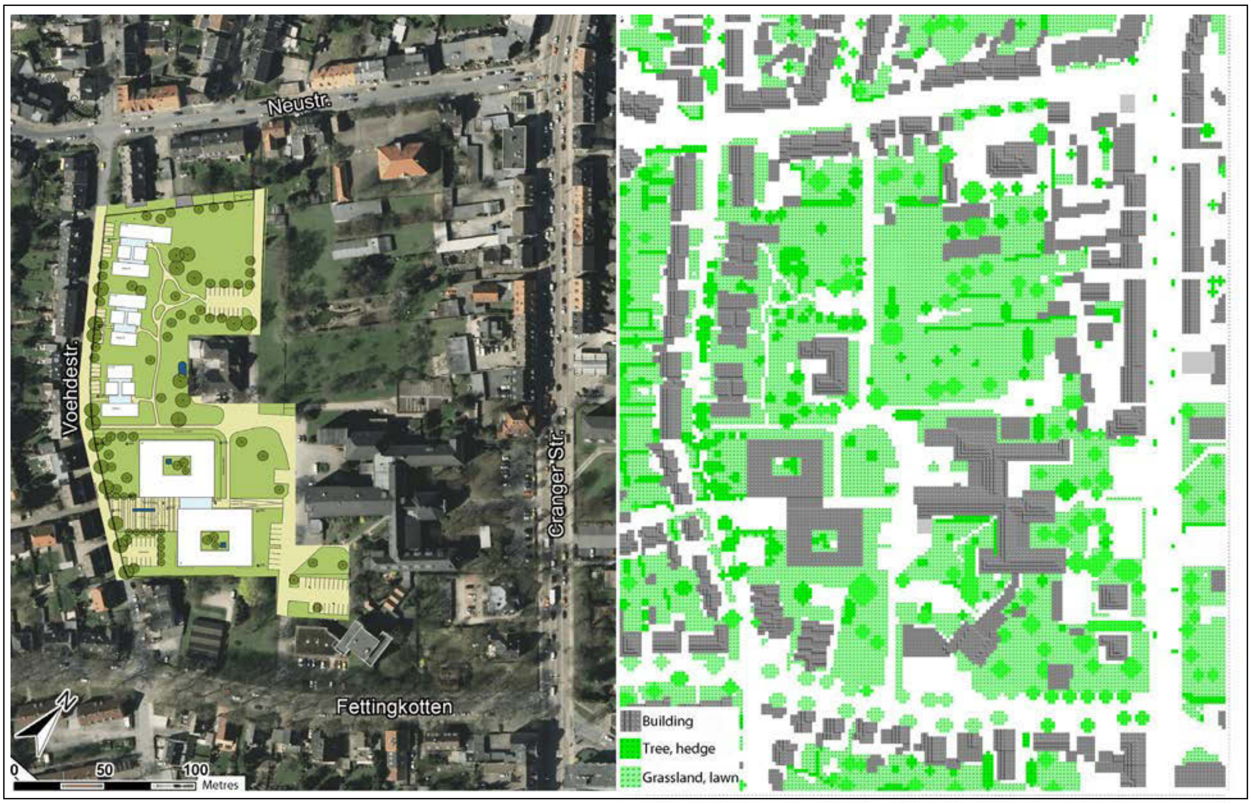


*Fig. 3 Aerial photograph (left) and building and vegetation model (right) showing the planned situation of the ENVI-met model area "Elisabeth-Stift Erle" in Gelsenkirchen; source of aerial photograph: IT-NRW 2012*

*Tab. 2 Initialisation parameters for the ENVI-met simulation model used to investigate climate change adaptation measures for the model area "Elisabeth-Stift Erle" in Gelsenkirchen*

| Parameter | Value | Notes |
|---|---|---|
| **Location** | | |
| Geographical location of Gelsenkirchen | 51.5°N, 7.04°E | Affects the radiation and energy balance |
| **Sizing (3D)** | | |
| Area size (x, y, z) (m) | 334, 428, 40 | |
| Number of grid lines (x, y, z) (n) | 167, 214, 20 | |
| Grid line spacing (x, y, z) (m) | 2, 2, 2 | |
| Nesting grids (x, y, z) | 10, 10, 10 | |
| Clockwise rotation of model (degrees) | -41.0 | For optimisation of building edges |
| **Meteorological conditions** | | Weather and meteorological situation |
| Duration of simulation run (h) | 36 | 24-hour diurnal course plus stabilisation period (12h) |
| Start of simulation on day (DD.MM.YYYY) | 20.06.2011 | Astronomic position of sun, affects radiation and energy balance |
| Start of simulation at local time (HH:MM:SS CET) | 05:00:00 | Starting point of stabilisation phase (11h) |
| Time steps of simulation run (h) | 1.0 | |
| Wind speed at 10 m above ground level (m/s) | 1.5 | Source: *Kuttler* et al. 2011a (stage I) |
| Upper wind direction (degrees) | 90 | Source: *Kuttler* et al. 2011a (stage I) |
| Roughness $z_0$ at reference point (m) | 0.1 | |
| Air temperature (2 m above ground level) (K [°C]) | 294.15 (21.0) | Source: *Kuttler* et al. 2011a (stage I) |
| Relative humidity (2 m above ground level) (%) | 68.0 | Source: *Kuttler* et al. 2011a (stage I) |
| **Cloud cover** | | Affects energy balance |
| Lower atmosphere (x/8) | 0 | |
| Middle atmosphere (x/8) | 0 | |
| Upper atmosphere (x/8) | 0 | |
| **Soil parameters** | | Affect energy balance |
| Soil type | Sandy soil | Standard input |
| Initial temperature of top layer (0-20 cm) (K [°C]) | 296.6 (23.4) | Source: *Kuttler* et al. 2012b |
| Initial temperature of middle layer (20-50 cm) (K [°C]) | 295.0 (21.9) | Source: *Kuttler* et al. 2012b |
| Initial temperature of bottom layer (> 50 cm) (K [°C]) | 291.8 (18.7) | Source: *Kuttler* et al. 2012b |
| Water content of top layer (0-20 cm) (%) | 45.0 | Source: *Kuttler* et al. 2012b |
| Water content of middle layer (20-50 cm) (%) | 45.0 | Source: *Kuttler* et al. 2012b |
| Water content of bottom layer (> 50 cm) (%) | 50.0 | Source: *Kuttler* et al. 2012b |
| **Building parameters** | | Affect energy buying |
| Building temperature (K [°C]) | 296.0 (23.0) | |
| Facade heat transfer coefficient (W/m²K) | 1.94 | Standard input |
| Roof heat transfer coefficient (W/m²K) | 6.0 | Standard input |
| Facade albedo (1) | 0.2 | Standard input |
| Roof albedo (1) | 0.3 | Standard input |
| **Thermal bioclimate (PET**, see *Tab. 3* **)** | | Affects metabolic energy balance |
| Speed of movement (m/s) | 1.0 | Movement mode: normal |
| Heat exchange (W/m²) | 116 | Metabolic heat exchange: normal |
| Mechanical factor (1) | 0.0 | Movement mode: normal |
| Heat transfer resistance of clothing, clo (1) | 0.5 | Clothing index: 0.5: summer clothes |

The used model ENVI-met 3.2 (*Bruse* and *Fleer* 1998) is a three-dimensional linked flow and energy balance model that calculates and models the condition of the atmosphere over an area of the earth's surface with specific properties at a defined point in time. The physical principles of the model are based on the laws of flow mechanics (wind field), thermodynamics (temperature calculations), general atmosphere physics (e.g., radiation balance) and human thermophysiology (metabolic heat balance). For this simulation, the investigation area is modelled on a digital grid with a mesh of 2 m, in which the air temperature, thermal stress and flow fields are calculated for a defined weather situation. This study investigated the scenario of a clear hot day with low wind conditions. For the model, the plan area is extended at the borders to take into account the effects of the utilisation of the surrounding land on the area. The digital model therefore covers an area of 334 m × 428 m (14.3 ha) with 167 × 214 cells and a mesh spacing of 2 m. The digital models of the actual and planned situations are shown by the maps on the right-hand side of *Figure 2* and *Figure 3*. The calculations were performed for a hot day ($t_{max}$ ≥ 30 °C) with clear sky and a slight easterly wind with a speed of 1.5 m/s. The results were evaluated for the atmospheric situation on 21 June, as this is the day with the highest theoretical heat stress. Under these conditions, the air temperature only falls slowly at night-time in the densely built-up areas. Poor ventilation results in heat accumulation in the district, thereby leading to the occurrence of heat stress. The main model setup is shown in *Table 2*.

Thermal conditions, ventilation and heat stress were investigated. Heat stress was assessed on the basis of the thermal index PET (physiologically equivalent temperature; *Mayer* 2006; *Tab. 3*), which is also calculated by ENVI-met.

## 4. Results

To assess the requirements for the adjustments due to future hot spells, the expected future changes in the temperature levels in Gelsenkirchen are presented first (Section 4.1). The current and future thermal problem areas in the city are then identified, taking into account demographic factors (Section 4.2). The appropriate adaptation measures for reducing the risk of heat stress are presented in Section 4.3. Finally, the numerical simulation of the adjustment process is presented, taking the model district as an example.

### 4.1 Changes in air temperatures in Gelsenkirchen as a result of climate change

Calculations for Germany based on various regional models and IPCC greenhouse gas emission scenarios, which are normally considered together (IPCC 2007), are available for projections of future temperature changes. This study was based on the moderate IPCC scenario A1B for the German regional model STAR II, as this was the regional model with the greatest relevance to Gelsenkirchen. For this model, the calculation results up to the decade from 2051 to 2060 are now available; this decade was therefore used as a future scenario for this study. The decade from 1991 to 2000 was used to represent the current

*Tab. 3 Scale of the PET values for thermal perception and associated grades of physiological stress in accordance with VDI guideline 3787, Part 2 (VDI 2008) and Mayer (2006)*

| PET (°C) | Thermal perception | Grade of physiological stress | Physiological effect |
|---|---|---|---|
| | Very cold | Extreme stress | Cold stress |
| 4 | Cold | Strong stress | |
| 8 | Cool | Moderate stress | |
| 13 | Slightly cool | Slight stress | |
| 18 | Comfortable | No stress | |
| 23 | Slightly warm | Slight stress | Heat stress |
| 29 | Warm | Moderate stress | |
| 35 | Hot | Strong stress | |
| 41 | Very hot | Extreme stress | |

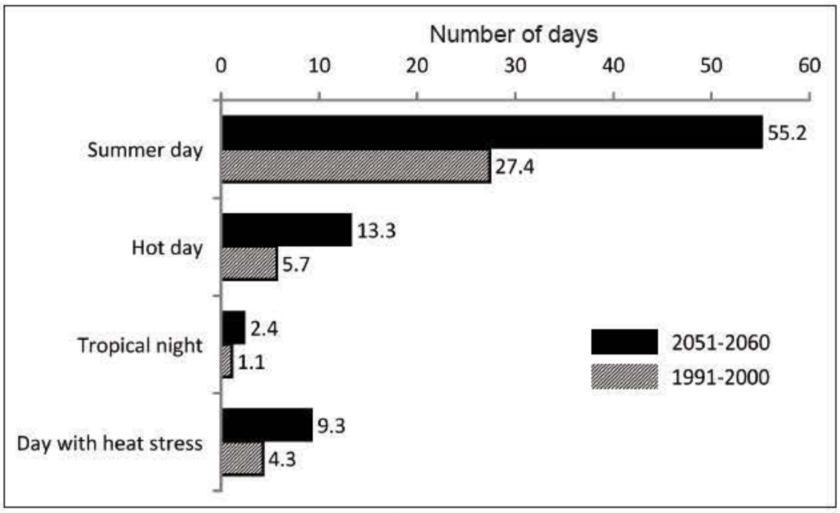


*Fig. 4* *Projected change in the average annual frequency of days with remarkable climate events for the Gelsenkirchen region in the decades 1991-2000 and 2051-2060 (IPCC greenhouse gas emission scenario A1B, model STAR II/ECHAM5; data source: PIK/CEC, Kreienkamp and Spekat 2008). Summer day: $t_{max} \geq 25$ °C, hot day: $t_{max} \geq 30$ °C, tropical night: $t_{min} \geq 20$ °C, day with heat stress: water vapour pressure $e \geq 18.5$ hPa*

situation for comparison purposes. In the period considered, ranging from 1991 to 2060, the annual average air temperature will rise by 2 K to 12.4 °C, with an associated increase in the number of days with remarkable climate events (*Fig. 4*).

The number of summer days will double from the present figure of 27 days to 55 days in the future, rising from 7.4 % to 15 % of the days of the year. There will also be a severe, more than twofold, increase in the number of hot days (13.3 days), days with heat stress (9.3 days) and tropical nights (2.4 days). Individual extreme years are expected to result in even higher frequencies of days with heat stress (comparable to the "summer of the century" of 2003 (*Schär* and *Jendritzky* 2004)).

Besides the number of heat events, the duration of these events is also significant because the

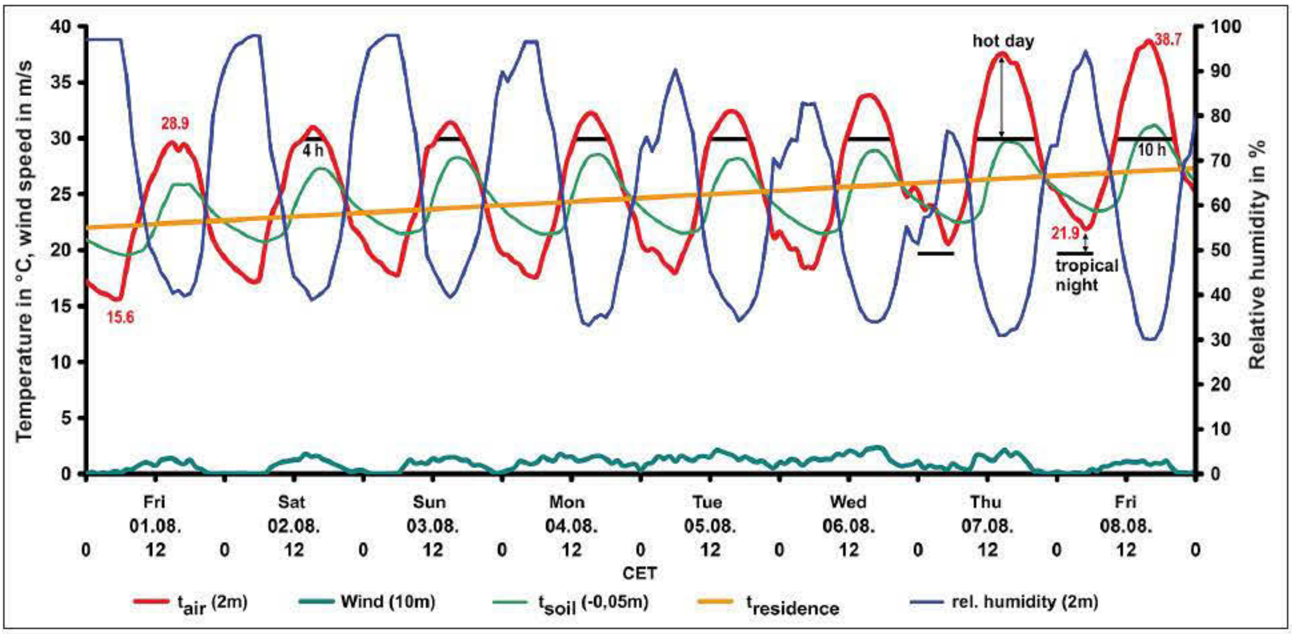


*Fig. 5* *Hourly average values of air temperature ($t_{air}$), relative humidity (rel. humidity), wind speed (Wind) and soil temperature ($t_{soil}$), as well as the estimated temperatures inside buildings ($t_{residence}$) during the heatwave from 1 to 9 August 2003 in the "summer of the century" 2003, at the campus station of the Department of Applied Climatology and Landscape Ecology of the University of Duisburg-Essen, located in the Essen city centre*

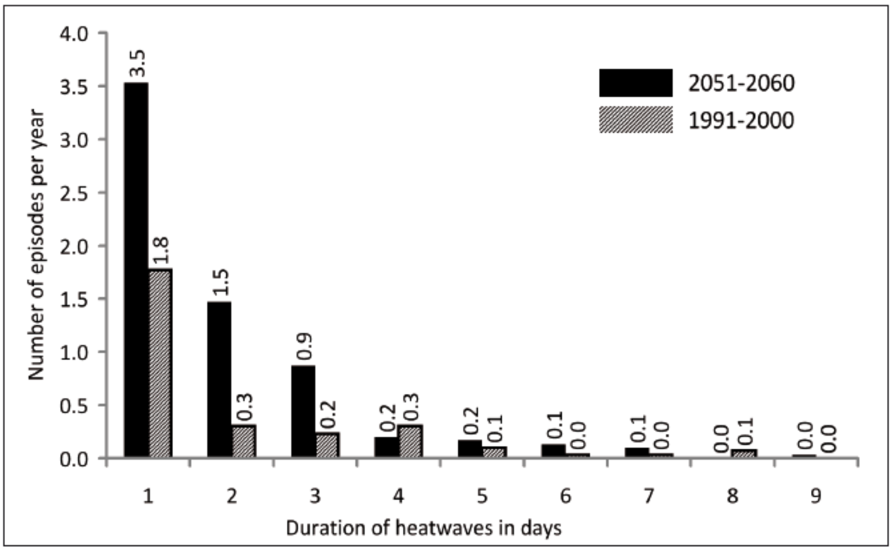


*Fig. 6 Projection of the average frequency of occurrence and duration of hot days and heatwaves for the region of Gelsenkirchen for the decades of 1991-2000 and 2051-2060. IPCC- IPCC greenhouse gas emission scenario A1B, model STAR II/ECHAM5 (Data source: PIK/CEC, Kreienkamp and Spekat 2008). Heatwave = uninterrupted sequence of days with $t_{max} \geq 30$ °C*

overheating of residential districts increases with the length of a heatwave, as shown for the example from August 2003 in the neighbouring city of Essen, located 12 km west of Gelsenkirchen (*Fig. 5*).

While the number of hours (four) with $t_{max} \geq 30$ °C was relatively low at the beginning of the heatwave, and the nighttime temperatures were still relatively moderate at < 17 °C, up to 10 hours with $t_{max} \geq 30$ °C were recorded along with night-time temperatures that did not fall below 20 °C (tropical night) after the heatwave had continued for 7 days. Sample measurements of air temperature within residential buildings without air conditioning indicated that the increase from 22 °C at the beginning of the heatwave to up to 28 °C at the end caused increasing heat stress. This was especially the case in the nighttime despite the outdoor nocturnal cooling. Countermeasures to this effect will be discussed in the final section.

Compared with the reference decade, the average number of single-day heatwaves is expected to double from 1.8 to 3.5 by the decade from 2051 to 2060 (*Fig. 6*). In the case of heatwaves of a duration of over two days, the frequency will increase five-fold from 0.3 to 1.5 per year. This increase represents a rapid rise from one to five events in three years. On average, the frequency of three-day heatwaves, which currently occur approximately every five years, will increase four-fold. With an average of two events per decade (0.2 events per year), heatwaves with a duration of over four days are relatively rare, both in the reference decade and in the future decade studied. However, the maximum duration of heatwaves will increase from five to seven days.

## 4.2 Identification of present and future thermal problem areas in Gelsenkirchen

### 4.2.1 General procedure

To reduce heat stress not only at present but also in the future, it is necessary to identify not only areas in the city already affected by heat stress, but also areas where the heat stress is currently assessed as moderate and is expected to reach severe levels in the future. In addition to these areas where adaptation is required, it is also necessary to safeguard the areas requiring protection that are considered to be favourable or compensation areas, which may have a compensatory effect on the climate of the areas affected because of their positive contribution to climate and air quality. Such areas were identified on the basis of the climate analysis, which indicates climatopes in accordance with VDI 3787 Part 1 (1997/2003).

Severe heat stress already occurs in the town centre and urban climatopes. These severe areas account for 8 % (820 ha) of the city area (*Fig. 7*, left); the areas with the highest degrees of sealing and the most severe heat islands experience excess heating with temperature rises of up to 6.5 K (*Kuttler* et al. 2011a).

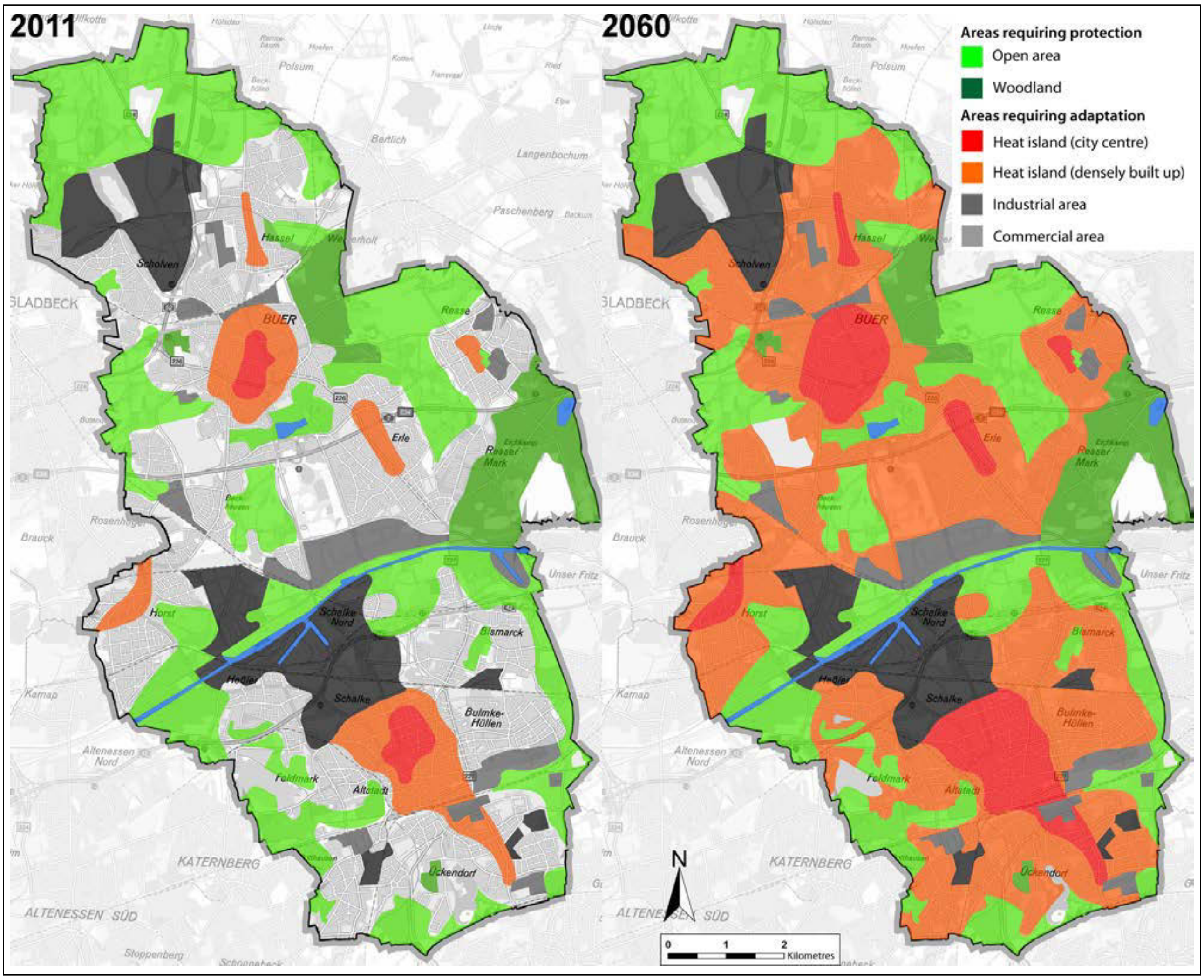


*Fig. 7 Current and future urban climate protection and problem areas with reference to heat stress in Gelsenkirchen (data basis: climate analysis of Gelsenkirchen)*

In the future, the temperature level throughout the city will be elevated, as the current average temperature differences between neighbouring climatopes, at < 2 K, are lower than the mean temperature increase expected in the future (≥ 2K). This expected temperature rise concerns the urban climatopes (*Fig. 7*, right). The presentation on the map is based on the assumption that the extended urban climatopes, as regards temperature conditions, will behave in the same way as the present densely built-up climatopes. Similarly, the present urban climatopes will reach the present temperature level of the town centre climatopes. By 2060, the area affected by heat stress within the city will reach 48 % of the total city area, i.e., approximately 5,000 ha. *Figure 7* also shows the climate compensation areas. These include all non-sealed climatopes (or LCZ A to G) with a total area of 3,700 ha (24 % of the total area of the city).

### 4.2.2 Priority areas

In view of the size of the areas affected, it would not be practical to implement all adaptation measures (see discussion section) throughout the complete city. Instead, the areas exposed to heat stress, which must be classified as severely affected in view of their demographic situation, will need to be given priority. *Figure 8* shows the current vulnerability or adaptation requirements of all the blocks used wholly or partly for residential purposes, where vulnerability was calculated from the susceptibility to heat, population density and share of senior citizens including priority areas in the city of Gelsenkirchen. Priority areas are identified by analysing the spatial distribution of the adaptation requirements on the basis of blocks. Areas with a strikingly high number and density of building blocks with high adaptation requirements of 50 % or

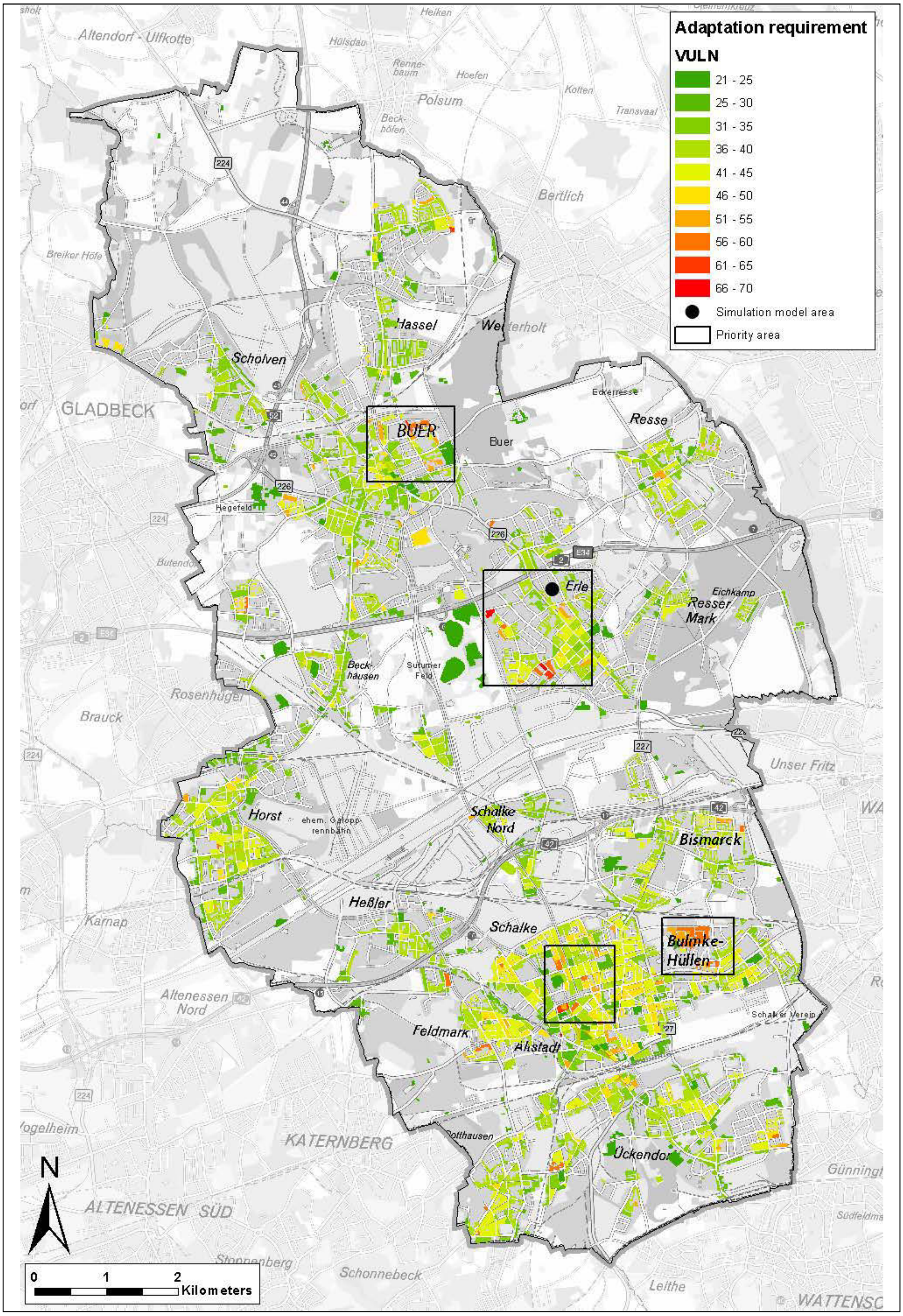


*Fig. 8* *Map showing the relative requirement (%) for adaptation measures according to heat stress as a result of climate change for building blocks, calculated from the susceptibility to heat, population density and share of senior citizens including priority areas in Gelsenkirchen; VULN = vulnerability; data basis: Gelsenkirchen climate management system*

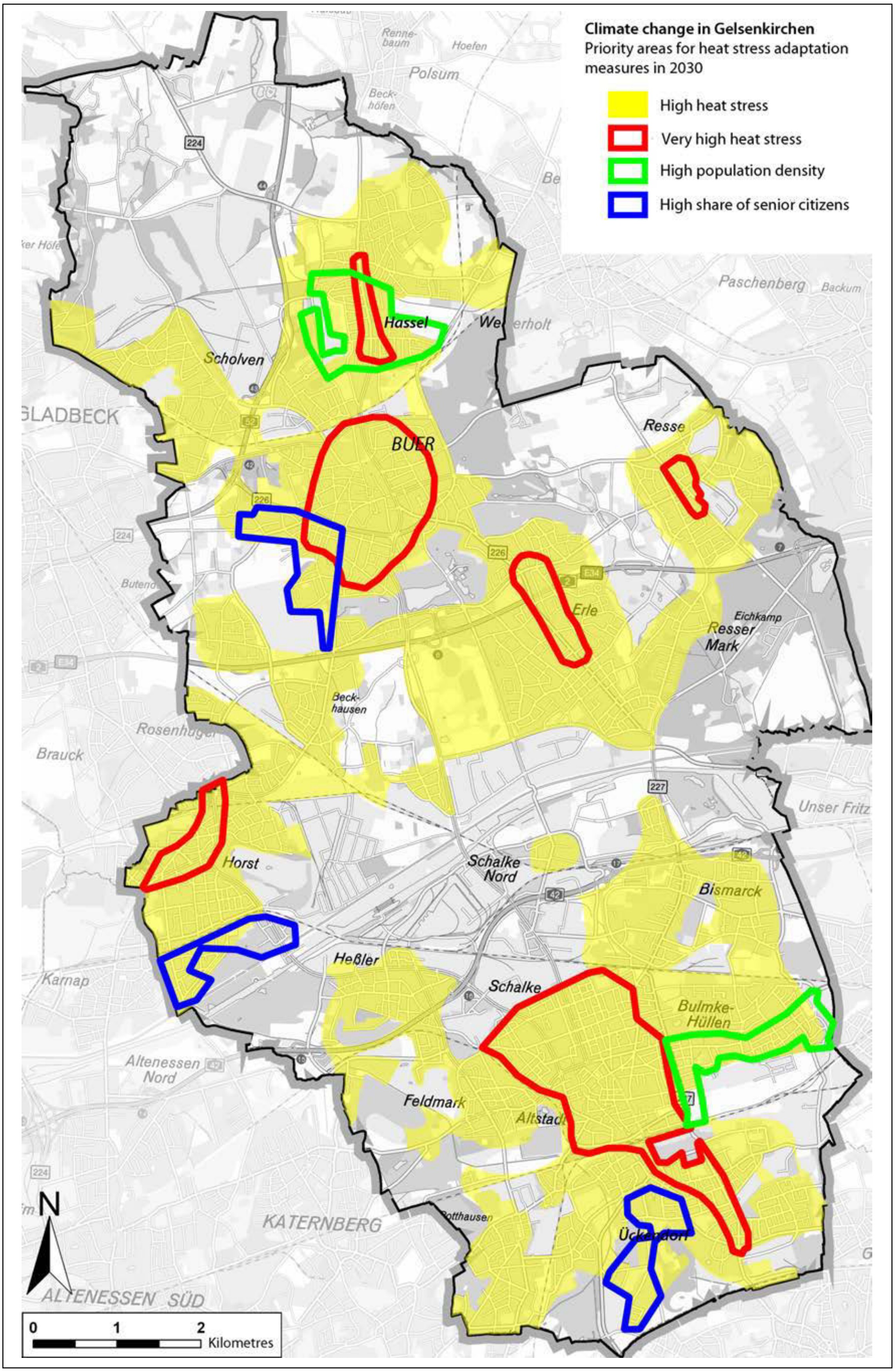


*Fig. 9 Priority areas for climate change adjustment in Gelsenkirchen in 2030; data basis: Gelsenkirchen climate analysis 2012 and Gelsenkirchen population atlas 2011*

higher are grouped together into clusters. Following this procedure, four priority areas were identified in Gelsenkirchen on the basis of the present-day conditions. These are assigned to the town centre and urban climatopes (VDI 3787, Part 1 (1997/2003)) or to LCZ 3 and 2 (*Stewart* 2011).

In the future, the priority areas are assumed to shift as a result of changes in land use, migration within the city or between cities and changes in the number of senior citizens. An initial rough estimate of the effects of these processes can made on the basis of demographic projections concerning the development of population density and the number of senior citizens (Stadt Gelsenkirchen 2011). However, such projections are only available for the medium-term future up to 2030. For the more distant future up to the end of the century, a further increase in the number of areas with a high share of senior citizens is expected. The areas affected shown in *Figure 9* represent the primary clusters where the criteria of heat stress, high population density and high share of senior citizens coincide.

### 4.3 Investigation of the selected model district by numerical simulation

Before applying urban planning measures to mitigate heat stress, urban planners need to make an assessment of the effects and to optimise the appropriate measures or bundles of measures (see Conclusions section). This assessment can be performed using micro-scale simulation models. The following paragraphs illustrate the use of a model of this type, ENVI-met (3.2), on the model area of Gelsenkirchen, where effects of new buildings on thermal conditions can be investigated on the basis of the planned situation. Here thermal conditions, air exchange and heat stress were investigated. The results are presented for the 2 m above ground level.

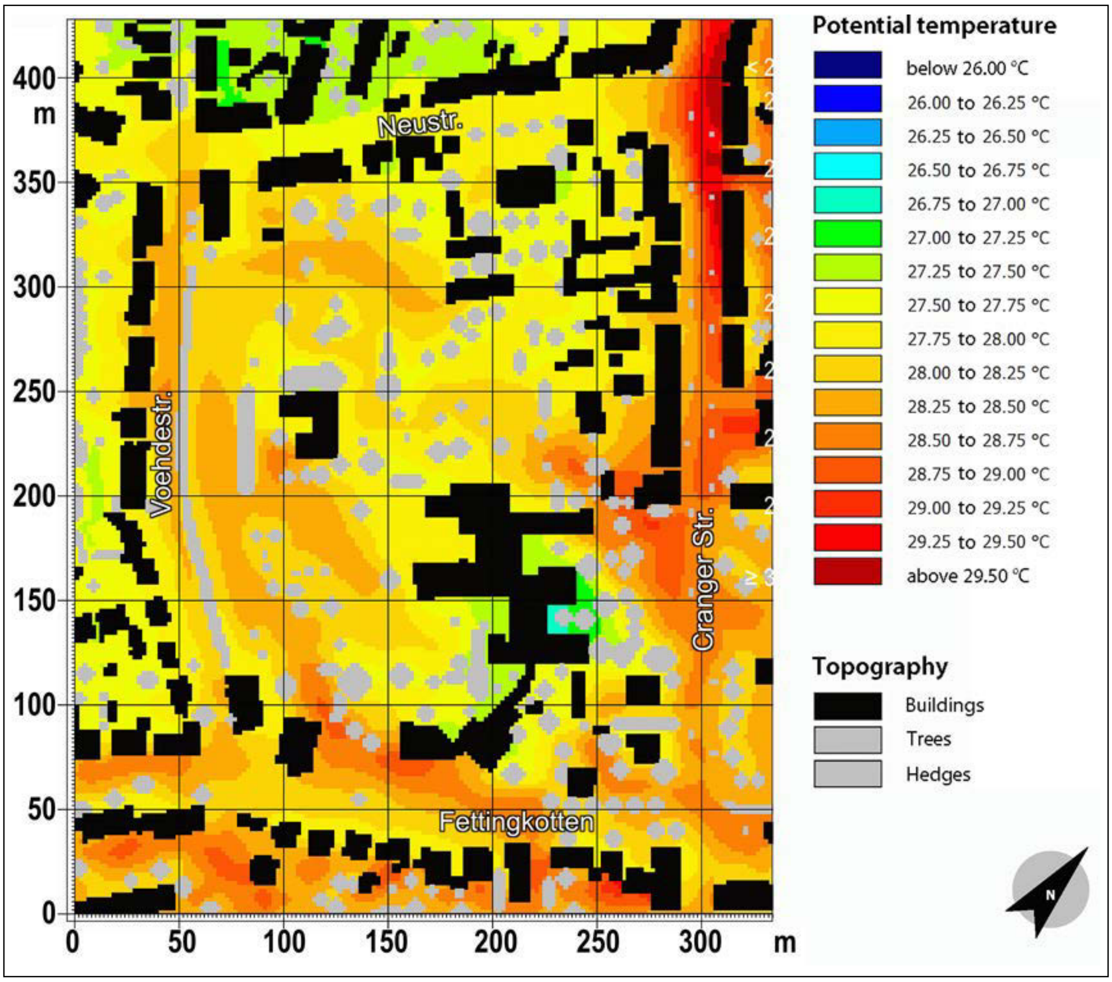


*Fig. 10 Distribution of the potential air temperature 2 m above ground level with the current situation of the model area "Elisabeth-Stift Erle" in Gelsenkirchen at 16:00 CET on a low-wind hot day ($t_{max}$ ≥ 30 °C) (21 June).*

### 4.3.1 Results for the current situation

The distribution of the potential air temperature at 2 m above ground level at 16:00 CET on a hot day ($t_{max} \geq 30°$), as this is the hottest hour of the day, is shown in *Figure 10*. At this time, the sun is shining from the south-westerly direction (240°). In the built-up areas to the north-east and south of the model area, the air temperatures are significantly above 28.5 °C. Especially in the street canyon in the northern part of Cranger Straße, temperatures above 29 °C occur on the sides of the street exposed to the sun. In the park of Elisabeth-Stift, at 27.5 °C, the temperature is approximately 1 K lower than in the surrounding area. In the area shaded by the western facade of the main building, the temperature is lowered a further 0.5 K to 27 °C. These data indicate that the greatest temperature contrast of approximately 3 K occurs over a relatively short distance of approximately 150 m between the main building and the northern section of Cranger Straße. However, the relatively small temperature difference does not indicate that there are only small differences in heat stress, as these differences are also affected by other factors, such as exposure to the sun. See the evaluation of the PET data below.

The wind field at 2 m above ground level, shown in *Figure 11*, indicates that high temperatures primarily occur in areas with high wind speed and are chiefly due to the advection of warm air from the eastern edge of the area (i.e., in accordance with the situation in the initial model atmosphere, see *Tab. 2*). The wind flows into the investigation area from a direction of 90°, i.e., from the bottom right of the simulation area, and is accelerated to speeds of up to 1.6 m/s, both in the open parking area (as a result of low roughness) and in the northern section of Cranger Straße (as a result of nozzle effects). The main buildings of the

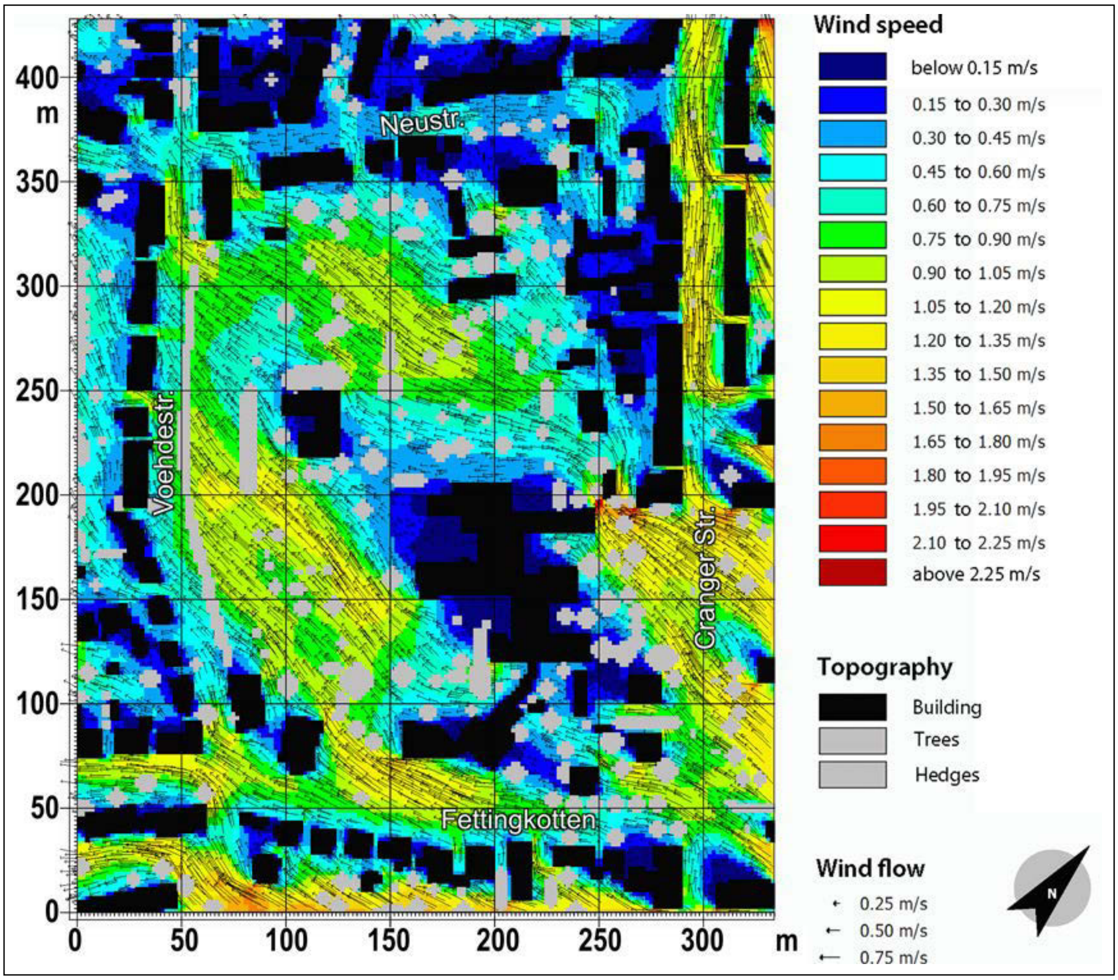


*Fig. 11 Distribution of wind field 2 m above ground level with the current situation of the model area "Elisabeth-Stift Erle" in Gelsenkirchen at 16:00 CET on a low-wind hot day ($t_{max} \geq 30$ °C) (21 June)*

facility and the rows of houses in Neustraße and Voehdestraße form obstacles or barriers to wind flow; on the leeward side of these rows of houses, the wind speed is reduced to less than 1 m/s.

*Figure 12* shows the distribution of thermal stress at 2 m above ground level at 16:00 CET in the model area. The PET values are very high (see *Tab. 2*), as this is the hottest hour of the day, when solar radiation is intense. Regarding the degree of such thermal stress, considerable differences are observed. In open areas without trees, conditions are hot to very hot, with PET > 35 °C, corresponding to strong to extreme heat stress. These large PET values also apply to the southern to western facades of all buildings, which are exposed to sunlight. In contrast, PET values of only 24 °C to 28 °C are observed in the shaded areas to the east of the trees and buildings. This range of PET values corresponds to a slightly warm perception, with only slight thermal stress. The difference between the PET at these shaded areas and the PET at areas exposed to sunlight is therefore 11 K. This large PET difference clearly demonstrates that thermal stress is chiefly caused by exposure to sunlight and that shading would therefore be the most effective mitigation measure.

### 4.3.2 Results for the planned situation

Due to greater clarity and comparability, the changes between the current situation (*Fig. 2*) and the planned situation (*Fig. 3*) are shown on differential maps that highlight the difference between the two situations. The differential maps shown below are designed in such a way that improvements are indicated by green markings and deteriorations by red markings.

The changes in the potential air temperature 2 m above ground level at 16:00 CET caused by the

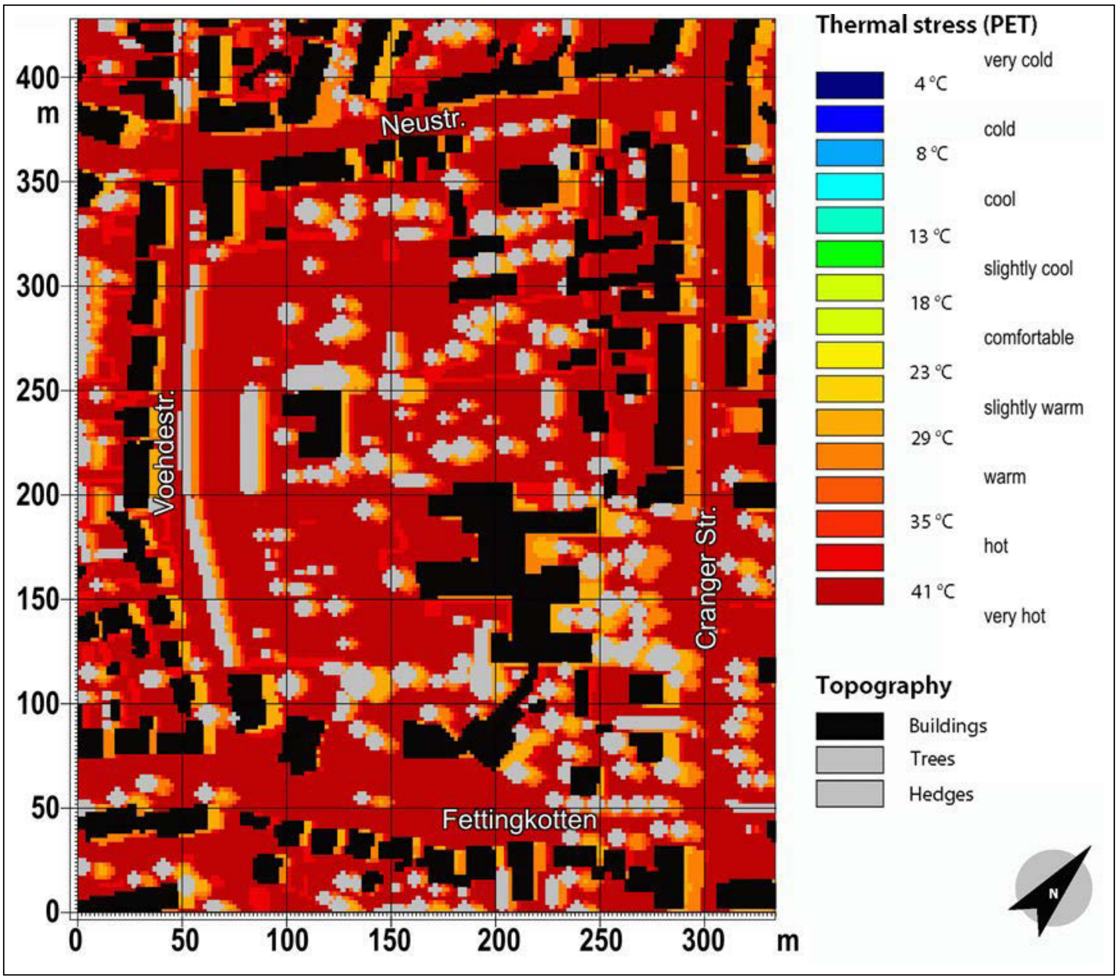


*Fig. 12 Distribution of the physiologically equivalent temperature (PET) 2 m above ground level with the current situation of the model area "Elisabeth-Stift Erle" in Gelsenkirchen at 16:00 CET on a low-wind hot day ($t_{max}$ ≥ 30 °C) (21 June)*

planned situation are primarily limited to slight reductions in temperature of less than 1 K in the area of the new buildings. However, as discussed below, the differences in thermal stress are considerably more pronounced, as other factors, such as solar radiation, air humidity and wind, have a significant impact on thermal comfort.

In terms of the wind field, the new buildings cause a reduction in wind speed of up to 0.5 m/s at 2 m above ground level (*Fig. 13*) on the leeward side at 16:00 CET. The resulting wind speed in this area is only between 0.3 m/s and 0.6 m/s. In the case of the two southerly blocks, the leeward side zone with a low-ventilation wind shadow can clearly be seen. This wind shadow extends up to the smaller new buildings, which form wind shadows of their own. Ventilation would be less restricted if the spacings between the buildings were increased.

Regarding the thermal stress at 16:00 CET, *Figure 14* shows that in the easterly shaded area of the new buildings and trees the situation improves by up to 3 comfort steps towards a "comfortable" or only "slightly warm" situation (reduction in PET by 6 K). However, the thermal stress increases by the same amount (6 K PET) in the areas where trees have been removed, resulting in "extreme thermal stress". Once again, this clearly shows that shading is a key factor in heat mitigation.

## 5. Discussion

One possibility of adaptation is to use urban planning measures with a view to reducing heat stress based on passive energy solutions that can achieve their effect without using additional energy. Energy-intensive technical solutions such as air conditioning are not

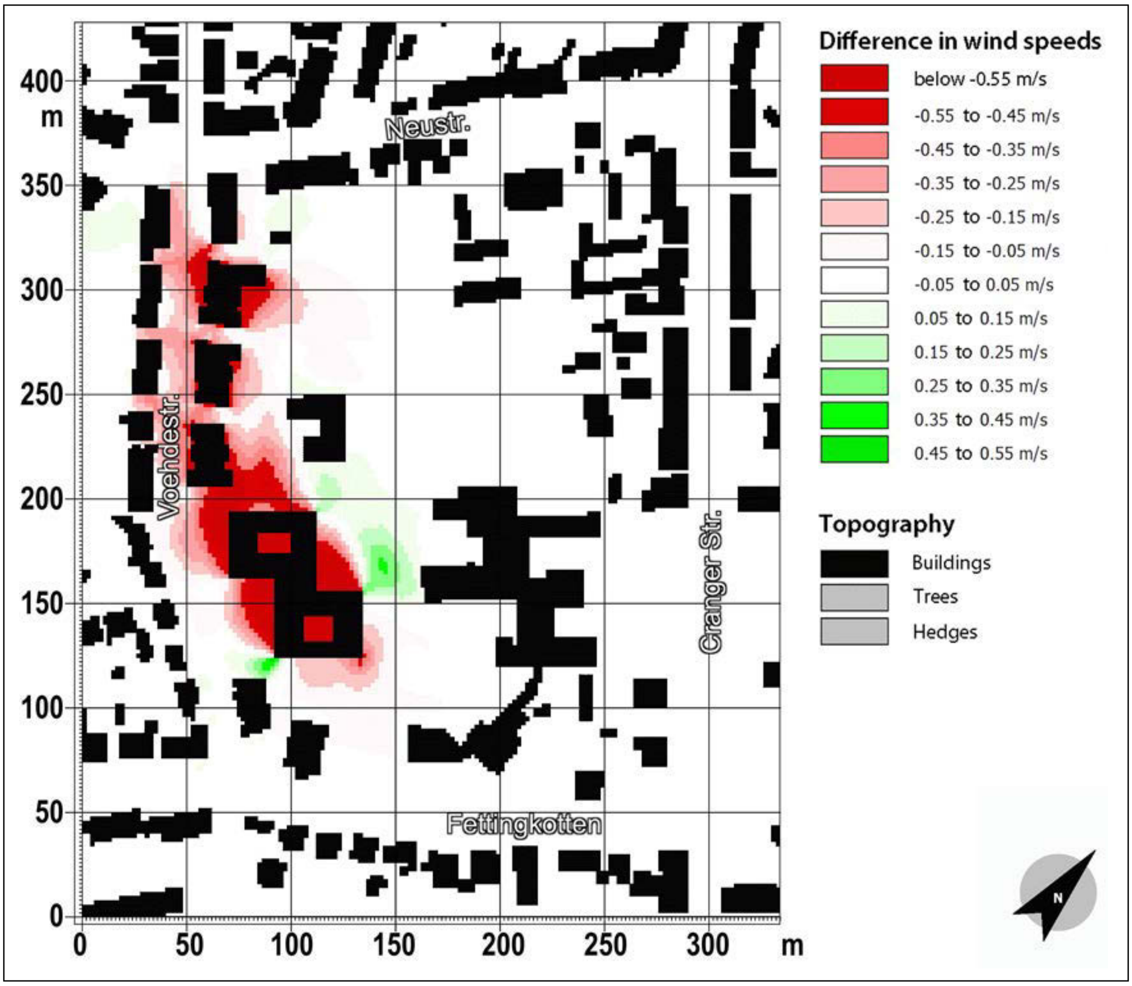


*Fig. 13 Difference in wind field 2 m above ground level between the planned and the current situation of the model area "Elisabeth-Stift Erle" in Gelsenkirchen at 16:00 CET on a low-wind hot day ($t_{max}$ ≥ 30 °C) (21 June)..*

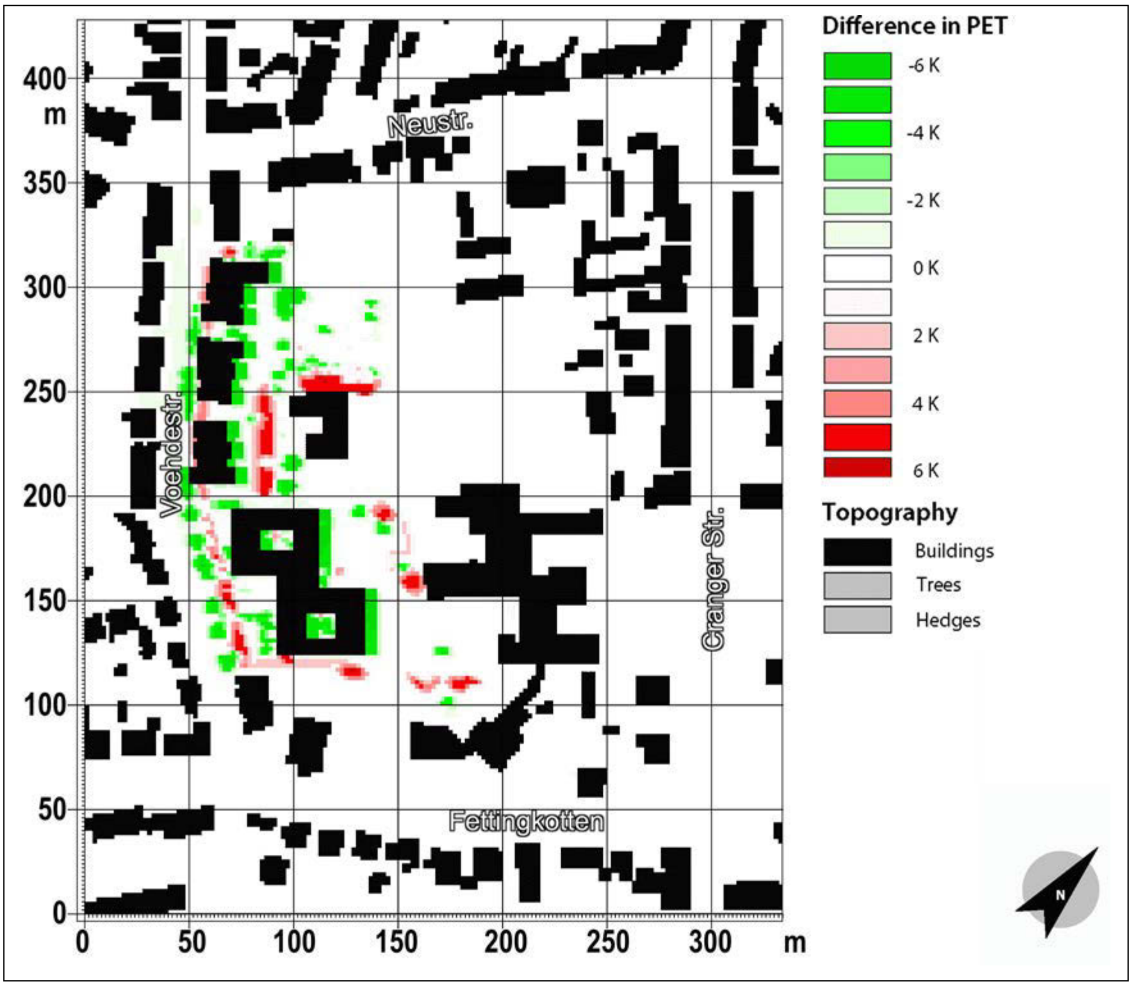


*Fig. 14 Difference in the physiologically equivalent temperature (PET) 2 m above ground level between the current and the planned situation of the model area "Elisabeth-Stift Erle" in Gelsenkirchen at 16:00 CET on a low-wind hot day ($t_{max}$ ≥ 30 °C) (21 June)*

taken into consideration. These measures are based on the model of the climate-friendly city, which represents an optimum compromise between moderate building density, which helps saving natural areas with good climate conditions in the outskirts, and heat-reducing features, such as planting, watering, ventilation and shading. The possible solutions to heat stress are established in urban planning measures from the field of urban climatology relevant to planning (*Kuttler* 2011). *Table 4* provides an overview of 22 selected measures that are especially well-suited for reducing heat stress in cities and are recommended in the detailed adaptation study for the Ruhr area given in "Handbuch Stadtklima" (MUNLV 2010). The proposed solutions apply to different scales.

The smallest-scale solutions may be applied to specific urban planning projects, such as individual buildings (e.g., thermal insulation, planting or shading). To reduce the heating of buildings due to solar radiation, roof and facade greening and thermal insulation should be taken into consideration, in addition to facade shading. In the case of new buildings, the orientation of the building should be optimised to minimise exposure to sunlight. The measures taken at the small-scale level only have an impact on the microclimate over a limited area, as shown above by the results of the study area. Depending on the vulnerability or adaptation requirements of a specific city district, these small-scale measures should therefore be bundled and applied consistently over a larger area. The climatope types or LCZs found in an urban area lead to different adjustment or protection requirements, and the optimum bundles of measures will therefore include different projects (*Tab. 4*).

At the medium-scale level (level of city districts) urban planning measures, such as building arrangement or,

*Tab. 4 Overview of the urban development measures for adaptation to heat stress caused by climate change in Gelsenkirchen.*
*Note: The H figures refer to the detailed explanation of the measures in "Handbuch Stadtklima" (MUNLV 2010)*

| Measures ▶ | | Buildings | | | | | District design – urban infrastructure | | | | | | | District design – green spaces and vegetation | | | | | | General climate functions | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ▼ Level of action ▼ | | H8 | H10 | H14 | H18 | H15 | H5 | H12 | H13 | H22 | H24 | H23 | H26 | H6 | H7 | H19 | H20 | H21 | H28 | H4 | H11 | H16 | H17 |
| Planning note map<br>Scale 1:20,000<br>**Planning notes** | Actual land utilisation map<br>Scale 1:5,000<br>**Climatope / LCZ** | Roof planting | Facade planting | Wall shading and thermal insulation | Shading elements on buildings | Suitable building materials | Maintenance and creation of open spaces, removal of sealing | Creation of open water spaces | Optimisation of building orientation | Shading of relevant areas | Backfilling of pipeline trenches using materials with reduced thermal conductivity and heat capacity | Traffic surfaces using materials with reduced thermal conductivity and heat capacity | Utilisation of surplus water from local groundwater management | Creation, maintenance and redesign of parks | Roadside planting | Increased irrigation of urban vegetation | Planting of urban spaces using appropriate plant species | Soil-covering vegetation, avoidance or artificial coverage of non-planted areas | Planting of urban areas with a view to improving the permeability of the topsoil (root penetration) | Definition of development limits | Maintenance and creation of fresh air areas | Maintenance and creation of air paths | Avoidance of building strips parallel to slopes |
| Adversely affected climate area | Town centre / 1 & 2 | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | |
| Unfavourable climate area | Densely built-up area / 3 | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • | |
| Adversely affected industrial and commercial area | Industrial and commercial area / 4-8, 10 | • | • | | | • | • | | • | | • | • | • | | • | | • | • | • | | | • | |
| Transition between adversely affected and compensation areas | Garden city/ village/edge of urban area / 9 | • | • | • | • | • | • | • | • | • | | | • | • | | • | • | • | • | • | | • | • |
| Climate compensation area | Grassland, arable land, fallow land / B–F | | | | | | • | | | | | | | | | | | | | • | • | • | • |
| Inner-city green space | Parks and grassland with trees / undefined | | | | | | • | | • | | | | • | • | • | • | • | • | • | • | | • | |
| Woods and forests | Deciduous, mixed and coniferous woodland / A | | | | | | • | | | | | | | | | | | | | • | • | • | • |
| Bodies of water | Bodies of water / G | | | | | | • | • | | | | | | | | | | | | • | | • | |
| Waste heaps | – / – | | | | | | • | | | | | | | | | | | | | • | • | • | |
| Maintenance of air paths | – / – | | | | | | • | | • | | | | | | | | | | | • | • | • | • |
| Facilitation of air exchange | – / – | | | | | | • | | | | | | | | | | | | | • | • | • | • |
| Industrial/commercial area with potential networking | Fallow land, sealed wasteland | | | | | | • | | | | | | | | • | | • | • | • | | | • | |
| Traffic avoidance | Traffic area (major traffic route) | | | | | | • | | • | | | • | | | | | • | | | • | | | |
| No building or emissions | – / – | | | | | | • | | | | | | | | | | | | | • | | | • |
| Establishment of pollution control | – / – | | | | | | | | | | | | | | | | • | | | | | | |
| Areas with large numbers of flat roofs | – / – | | | | | | • | | | | | | | | | | | | | | | | |

open space design etc., may be applied. In the overall design of city districts, the orientation of the buildings should be selected to ensure improved ventilation (i.e., large spacing between buildings). Apart from the creation of shaded zones (*Oliveira* et al. 2011, *Streiling* and *Matzarakis* 2003), the measures available for mitigating heat accumulations in outdoor areas (street canyons, backyards and areas between buildings) include active evaporation areas, such as gardens, parks or bodies of water (*Goldbach* and *Kuttler* 2012, *Shashua-Bar* et al. 2011; *Spronken-Smith* and *Oke* 1999). When developing such areas, water supply to the soil should be ensured (MUNLV 2010), for example, by using rainwater systems or local groundwater.

When refurbishing gardens and parks, plants that can tolerate severe winters and long summer dry spells should be selected. It is also important to select plants with low emissions of biogenic volatile organic compounds (BVOCs), as these are highly reactive ozone precursors (*Tab. 5*).

The largest-scale measures include the utilisation of climate functions affecting several districts of the city, including interaction between rural or compensation areas and the affected urban areas, such as the maintenance of cold air paths. Investigations should be performed to determine whether the districts concerned can be connected to the existing networked green areas, fresh air areas or ventilation paths at the edge of the city.

## 6. Conclusions

As this study has shown, densely built-up urban areas are susceptible to high thermal stress. The problem

*Tab. 5 The ozone-forming potential (OFP) and drought resistance of selected trees and their suitability for higher temperatures (source: combined, after Benjamin and Winer 1998, Roloff et al. 2008, modified; here: after Kuttler 2012)*

| Scientific name | Common name | Low ozone-forming potential (OFP) | High drought tolerance (DT) |
|---|---|---|---|
| *Acer campestre* | Field Maple | ++ | ++ |
| *Acer rubrum* | Red Maple | ++ | ++ |
| *Carya ovata* | Shagbark Hickory | ++ | + |
| *Carya tomentosa* | Mockernut hickory | ++ | ++ |
| *Fraxinus pennsylvanica* | Green Ash, Red Ash | ++ | + |
| *Ginkgo biloba* | Ginkgo, Maidenhair Tree | ++ | ++ |
| *Malus tschonoskii* | Tschonoski Crabapple, Pillar Apple | ++ | + |
| *Pinus ponderosa* | Ponderosa Pine, Bull Pine, Blackjack Pine | + | ++ |
| *Pinus sylvestris* | Scots Pine | + | ++ |
| *Prunus avium* | Wild Cherry, Sweet Cherry, Bird Cherry, Gean | ++ | ++ |
| *Pyrus communis* | European Pear | ++ | + |
| *Pyrus pyraster* | European Wild Pear | ++ | + |
| *Quercus rubra* | Northern Red Oak, Champion Oak | + | + |
| *Sophora japonica* | Pagoda Tree | + | ++ |
| *Ulmus parvifolia* | Chinese Elm, Lacebark Elm | ++ | + |
| *X Cupressocyparis* | Leylandii Leyland Cypress | ++ | + |
| *Zelkova serrata* | Japanese Zelkova, Keyaki | ++ | + |

Low OFP: Isoprene emission of ≤ 2µg/(g•h). DT: ++ = very good, + = good.

of urban excess heating, especially during heatwaves, is currently occurring and will continue to occur in the future. In view of the high population density and other social indicators in the built-up areas, the possibility of implementing urban development adaptation measures is highly relevant. Therefore attention here was drawn to the application aspect in terms of discussing suitable countermeasures against heat stress in urban planning.

As the measures can only be implemented over the long term, urban areas on the outskirts of cities must also be considered, which are currently only moderately affected by thermal stress but will be more severely affected in the future as a result of the more frequent and more intensive heatwaves that will occur with climate change.

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