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Urban Thermal Comfort – Reality and Challenges

Komfort termiczny miasta – rzeczywistość i wyzwania

Aneta Afelt*[1,2], Wojciech Szymalski[3], Kamil Leziak[4]

[1] Interdisciplinary Centre for Mathematical and Computational Modelling, University of Warsaw, Poland

[2] Espace-DEV, French National Research Institute for Sustainable Development, France

[3] Institute for Sustainable Development, Warsaw, Poland

[4] Faculty of Geography and Regional Studies, University of Warsaw, Poland

ORCID AA https://orcid.org/0000-0001-8744-2992; WS https://orcid.org/0000-0002-5107-0223; KL https://orcid.org/0000-0003-0858-8163

• akafelt@uw.edu.pl

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Abstract: The city is characterised by a specific climate. Depending on the type of land use, the characteristics of the land cover, such as colour and the permeability of the surface, or the construction materials used in the urban space – there are locally large horizontal and vertical differences in air temperature in the city, defined by the local energy balance of the surface area. The varies are represented by the topoclimatic units. Each of the topoclimatic types can be characterised by a specific sensitivity to the occurrence of high air temperature, which has its direct impact on the parameters of thermal bioregulation of an individual living in the urban space. The analysis of topoclimatic conditions is presented on the example of two towns near Warsaw: Mińsk Mazowiecki and Wołomin. We then demonstrate the relationship between topoclimate and human thermal stress under conditions of high and extremely high air temperature. We present how targeted actions in urban space can shape topoclimates and consequently mitigate the effects of heat waves. These measures are of considerable importance in the context of adaptation to forecast climate change. In our opinion, modelling of human thermal stress should be one of the key parameters in spatial planning, among others, as a part of health risk management.

Keywords: city topoclimate, spatial planning, human thermal stress, adaptation to climate change, health-One Health

Streszczenie: Miasto charakteryzuje się specyficznym klimatem. W zależności od rodzaju zagospodarowania terenu, cech jego pokrycia takich jak m.in. barwa i przepuszczalność powierzchni, zastosowanych materiałów budowlanych w przestrzeni miejskiej – występują lokalnie poziome i pionowe różnice temperatury powietrza w mieście, określone przez lokalny bilans energetyczny powierzchni czynnej. Zróżnicowania te prezentowane są przez jednostki topoklimatyczne. Każdy z typów topoklimatycznych charakteryzuje się specyficzną wrażliwością na występowanie wysokiej temperatury powietrza, co ma swój bezpośredni wpływ na parametry bioregulacji termicznej człowieka w przestrzeni miejskiej. Analizę warunków topoklimatycznych przedstawiono na przykładzie dwóch podwarszawskich miejscowości: Mińska Mazowieckiego i Wołomina. Prezentowane są zależność między topoklimatem a stresem termicznym człowieka w warunkach wysokiej i ekstremalnie wysokiej temperatury powietrza. Wskazujemy, jak ukierunkowane działania w przestrzeni miejskiej mogą kształtować topoklimat i w konsekwencji łagodzić skutki fal upałów. Działania te mają szczególnie istotne znaczenie w kontekście adaptacji do prognozowanych zmian klimatu. Naszym zdaniem modelowanie stresu termicznego człowieka powinno być jednym z kluczowych parametrów w planowaniu przestrzennym, również jako element zarządzania ryzykiem zdrowotnym.

Słowa kluczowe: topoklimat miasta, planowanie przestrzenne, stres termiczny, adaptacja do zmian klimatu, zdrowie publiczne-One Health

Introduction

Quantitative research on the analysis of climate and bioclimate of cities – its distinctiveness and specificity – has a long history. In Poland, a good summary of the state of research is the 2008 publication of "Climate and Bioclimate of Cities" (Kłysik at al. 2008); the comprehensiveness of the issues in an overview is brilliantly characterised by Fortuniak et al. (2019). A good diagnosis of the influence of the urban form of land use on the modification of meteorological factors and the formation of distinctiveness of climatic conditions by urbanised areas makes it possible to conduct comprehensive biometeorological research in this space. Research in this area is extensive, addressing both (1) individual human conditionings – psycho-physical response to biometeorological conditions (Nikolopoulou et al. 1999; 2001; 2003), adaptation to outdoor biometeorological conditions (Nakano and Tanabe 2020) and (2) attempts to address the mitigation of adverse biometeorological conditions (Simath and Rohinton 2022) and (3) attempts to develop systemic solutions at the level of specific architectural and planning solutions (Ka-Lun Lau et al. 2022).

A factor that is forcing a modification of the approach to the issue of thermal comfort in urban areas is the progressive warming of the climate. The consequence of this process is not only an increase in the temperature, but also changes in related parameters such as evaporation, humidity, precipitation or wind speed and its direction and population health as well. Within urbanised areas – through the particularities of land use, the construction materials introduced, the permeability of the ground or the geometric configuration of the space – the dynamics of meteorological parameters are modified. UNEP and the Cool Coalition, in their report "Beating the Heat: A Sustainable Handbook for Cities" (Campbell et al. 2021), state that the projected increase in average urban air temperature will increase up to 40°C by the end of 2100, more than 2 times the Paris Agreement's goal of limiting global temperature rise to no more than 1.5°C.

From this point of view, it is necessary not only to consider the current thermal comfort in the daily life of the inhabitants in spatial planning, but above all to take into account future biometeorological conditions in current planning assumptions. Adverse biometeorological conditions, especially Universal Thermal Climate Index – UTCI *extreme and very strong heat stress* conditions are very dangerous to health, especially for children and the elderly.

A systemic approach to the problem of thermal comfort in urban space requires, instead of its general assessment (e.g., in relation to the urban heat island), conducting strictly local analyses – at the scale of the topoclimate. A topoclimatic unit can be understood as an internally coherent, homogenous area characterised by specific climatic conditions (topoclimate), which differ from the conditions prevailing in neighbouring units (Błażejczyk 2001). In each topoclimatic unit, the UTCI is then calculated according to the locally occurring meteorological parameters (Błażejczyk et al. 2010; Bröde et al. 2012). The result is a map of classified spatial diversity of thermal comfort for the inhabitants (Błażejczyk 2011). Mapping of UTCI in local scale makes it possible to diagnose the current variation in thermal comfort of a city – indicating hot-spots with unfavourable biothermal parameters. However, the main advantages of the method are: (1) the possibility of using air temperature values derived from climate predictions in the analyses and, further, (2) simulating the impact of land use changes on the improvement of human bioclimatic condition.

The aim of the work is to assess the comfort of city life from the perspective of its biothermal quality; to answer the question if and how high air temperature is linked with spatial city thermal comfort now and under future climate conditions. Differently than in mainstream data, research is focused on medium-size cities proving that it is not the size but the quality of the city fabric (topoclimates) that has an impact on the thermal comfort of society's life.

We present this approach on the example of research undertaken in two suburban towns, Mińsk Mazowiecki and Woomin, as part of the work on strategic documents for municipal climate change adaptation plans. The UTCI is used as an indicator for the delimitation of areas with biometeorologically unfavourable thermal conditions. The diagnosis covers the current state and future climatic conditions, defining the requirements for the need to introduce adaptation measures in the urban space.

The analysis has been conducted, as a general principle, for medium-sized cities (Mińsk Mazowiecki with approx. 40,000 inhabitants, Wołomin with approx. 50,000 inhabitants), for which detailed studies of thermal comfort are not usually conducted if they do not play a special role, e.g., as a health resort. The results clearly indicate the necessity of including a diagnosis of thermal comfort in spatial planning, also as a simulation of the influence of investment activities in the urban tissue on changes in the conditions of perceptible air temperature.

1. Methods

1.1. Study area

Thermal comfort has been evaluated for 2 medium-sized cities – Mińsk Mazowiecki and Wołomin. Both towns are located in the suburban zone of Warsaw; Wołomin, 20 km north-east of Warsaw, while Mińsk Mazowiecki, 30 km east of Warsaw, but are part of Warsaw conurbation zone. Both cities are characterised by a distinct separation of the urban from the capital. In terms of spatial functionality, typical for each city is: (1) the main transport artery running through the city centre, (2) concentration of service, commercial, public utility areas characterised by high activity of the inhabitants in the centre of the units, (3) the share of green areas in the urban fabric (parks, allotment gardens, agricultural areas, forests). Similarities were also shown for the general meteorological conditions typical of the region in which both cities are located. Both cities also perform similar administrative and educational functions for the local community in their regions. In terms of the general climatic conditions of the region, both towns are very similar.

Thermal comfort of an urban area was defined as the value of the UTCI (Universal Thermal Climate Index) (Błażejczyk 2010; Bröde et al. 2012) on a local scale, with reference to the current topoclimatic conditions. For each city, a procedure to assess the spatial variation of the UTCI has been conducted. Then, the spatial sensitivity of thermal comfort was simulated in relation to threshold thermal air temperature conditions, successively for four predefined weather types that may occur during the warm season (20°C, 25°C, 30°C, 35°C). These simulations were linked to potential future climate conditions determined by simulations of climate change based in two scenarios RCP4.5 and RCP8.5 for the period 1981-2090 in both cities. The work was performed between 2018 and 2020. Spatial analyses were performed in QGIS and statistical analyses were performed using R software.

1.2. Climate conditions

Current climatic conditions were assessed based on survey data provided by the Institute of Meteorology and Water Management – National Research Institute (IMGW). Multi-year averages of air temperature, its annual amplitude, the number of days with temperature above 25°C, the number of warm and cloudy days, the number of cool days, the number of days with precipitation and its yearly distribution, the number of rain-free days, the average and maximum wind speed were determined for the 1990-2010 period.

1.3. Topoclimate classification

To determine the diversity of the local climate of Mińsk Mazowiecki and Wołomin, the ranges of topoclimatic units occurring in the city area were determined.

Table 1. Delimitation of topoclimatic units, Misk Mazowiecki and Wołomin

Distinguished topoclimatic groups		
11 – topoclimates with reduced (relative to standard surface) solar radiation inflow and reduced (relative to standard surface) reflected radiation	21 – topoclimates with average solar radiation inflow and reduced reflected radiation value	31 – topoclimates with an increased inflow of solar radiation and a reduced value of reflected radiation
12 – topoclimates with reduced solar radiation inflow and average reflected radiation	22 – topoclimates with average solar radiation inflow and average reflected radiation	32 – topoclimates with increased inflow of solar radiation and average reflected radiation
13 – topoclimates with reduced solar radiation inflow and increased reflected radiation value	23 – topoclimates with average solar radiation inflow and increased reflected radiation value	33 – topoclimates with an increased inflow of solar radiation and an increased value of reflected radiation
Thermal conditions in the respective topoclimate		
1 – cool topoclimate	2 – moderately warm topoclimate	3 – warm topoclimate
Anemological conditions in the topoclimate		
1 – a quiet topoclimate	2 – moderately windy topoclimate	3 – windy topoclimate
The topoclimatic classes (0-no, 1-yes)		
C1 – thermal inversions; C2 – radiation fog	C3 – air pollutants; C4 – anthropogenic heat stream	C5 – phytoncides

A topoclimatic unit can be understood as an internally coherent, homogenous area characterised by specific climatic conditions (topoclimate), which differ from the conditions prevailing in neighbouring units. The topoclimatic conditions were determined in accordance with the methodology of reviewing the topoclimatic map of Poland (Błażejczyk 2001), modified for the purpose of this study. The variation of topoclimatic conditions was defined in the basic resolution of 100 x 100 m. To examine the conditions prevailing at the border of the area in question in more detail, a zone delimited by the buffer of 100 m from the external borders of administrative borders were also included in the analysis.

Information on the characteristics of the natural environment influencing the structure of the heat and radiation balance of the active surface was used, in particular: (1) the terrain, its slope and exposure, (2) coverings and forms of land use, (3) moisture content of the substrate and its permeability. In each of the three categories, the values of the coefficients of change of the total solar radiation intensity, albedo, air temperature, relative humidity and wind speed were determined in relation to the so-called standard surface (flat air, grass covered with regular mowing).

Delimitation of topoclimatic units was made by groups, types, and classes of topoclimates and homogeneous topoclimatic units (Tab. 1). Numerical position codes were used to determine the topoclimatic units. The resulting map of homogeneous topoclimatic units is a synthetic illustration showing groups, types, and classes of topoclimates present in each field within the city.

1.4. Determining the bioclimatic conditions

Bioclimatic conditions in the area of investigations were determined by means of the Universal Thermal Climate Index (UTCI). UTCI values are expressed in °C and objectively determined (i.e., independently of subjective perception of individuals) the thermal stress that the human body is subject to in given conditions. The UTCI takes into account physiological processes and physical heat exchange between the body and the environment. In order to calculate the UTCI value, a formula was used (Błażejczyk 2011):

$$UTCI = 3.21 + 0.872 \cdot t + 0.2459 \cdot M_{rt} - 2.5078 \cdot v_{10} - 0.0176 \cdot f,$$

where:
UTCI – Universal Thermal Climate Index [°C],
t – air temperature [°C],
M_{rt} – average radiation temperature [°C],
v_{10} – wind speed at 10 m above sea level [m s^{-1}],
f – relative air humidity [%].

In order to present more accurately the variability of the bioclimatic conditions in the study areas in different weather situations, it was decided to determine the UTCI value for the four predefined weather types that may occur during the warm season (Tab. 2). UTCI values allow to determine the thermal loads occurring in a given area, as shown in table 3.

The UTCI was spatially presented, according to the topoclimate conditions and under the thermal load classes after table 3. Long-term exposure to increased heat stress affects physiological processes in the body, causing increased sweat secretion or dysfunction of thermoregulatory functions (Błażejczyk et al. 2010).

1.5. Future climate modelling

Climate change calculations for Mińsk Mazowiecki and Wołomin were performed using two bundles of high-resolution 0.11 deg (c. 12 km) regional climate simulations for the European domain available from

Table 2. Summer weather types included in UTCI modelling

Type of weather	Radiation intensity [W m^{-2}]	Cloudiness [%]	Air temperature [°C]	Relative humidity [%]	Wind speed at 10 m above sea level [m s^{-1}]
Average	550	50	20.0	50	4.0
Warmth	850	10	25.0	50	4.0
Hot	850	10	30.0	40	1.0
Extremely hot	850	10	35.0	30	1.0

Table 3. Thermal load classes according to UTCI (*UTCI Assessment Scale* 2003)

UTCI [°C]	Thermal loads	Physiological reactions (in general) (Błażejczyk et al. 2010)
over 46	*extreme heat stress*	Increasing sweat secretion to > 650 g/hour., Increased rate of increase in rectal temperature. Gradual loss of the ability of heat transfer to the air.
from 38 to 46	*very strong heat stress*	Reduction within 30 min of the temperature gradient between the inside and body surface to < 1°C. Increase in rectal temperature after 30 min of exposure.
from 32 to 38	*severe heat stress*	Dynamic heat sensation after 2 hrs: "very hot." Average sweat secretion > 200 g/hour. Increase in rectal temperature after 2 hrs of exposure. Heat loss per evaporation after 30 min > 40W. Gradual increase in skin temperature
from 26 to 32	*moderate heat stress*	Change in sweat rate, skin temperature, rectal temperature and face and hand temperature. Appearance of sweating after 30 min of exposure. Gradual increase in skin hydration. Average sweat secretion > 100 g/hour. Dynamic sensation of heat: "heat."
12 to 26	*no thermal stress (comfort zone)*	Dynamic feeling of warmth: "comfortable." Heat loss for evaporation > 40W on average. No change in rectal temperature during 2 h of exposure. Dynamic sensation of heat after 2 h of exposure: "comfortable." Heat loss per evaporation > 40W after 2 h of exposure.

EURO-CORDEX (Tab. 4) for two greenhouse gas concentration scenarios (Representative Concentration Pathways, RCPs), RCP4.5 and RCP8.5.

The EURO-CORDEX simulation results were processed for both cities using quantile fitting methods (Gudmundsson et al. 2012). Temperature values from the CPLFD-GDPT5 interpolated historical data set were used as reference data (Berezowski et al. 2016). The use of interpolated data is due to the lack of direct measurement data of meteorological parameters for Mińsk and Wołomin or its immediate vicinity so as to represent the study area. As a result of the procedure of modelling the future climate, corrected series of daily values of average, maximum and minimum temperature were calculated for two scenarios RCP4.5 and RCP8.5 for the period 1981-2090.

2. Results

Basic meteorological metrics such as air temperature, its average, minimum and maximum values differ slightly (0.2-0.5°C). The dynamics and structure of precipitation are also twinned. In the case of Mińsk Mazowiecki, the differentiating feature is the greater influence of temperate warm continental air masses on the weather (Szymalski et al. 2018; 2020).

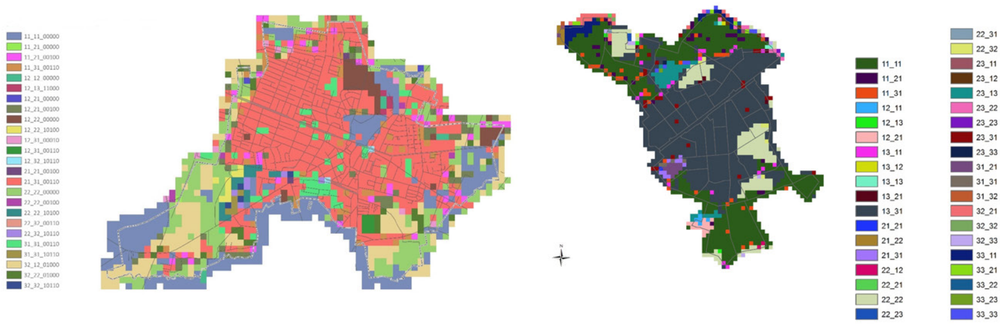
The results of climate change modelling performed separately for each of the cities do not show significant differences as regards the expected values of meteorological parameters in the perspective to the end of the 21st century (Szymalski et al. 2018; 2020). In both cases, a progressive increase in mean air temperature, a rise in minimum temperature and in the number of days with temperatures above 25°C are characteristic. Projections for the end of the 21st century indicate a pattern of minimum temperatures at 0°C, a marked warming of the cool season, and an extension of the vegetation period. In the warm season, depending on the scenario, the occurrence of temperatures above 25°C – the so-called heatwaves and the occurrence of the so-called tropical nights (thermal conditions when the daily air temperature does not fall below 20°C) – is predicted.

Table 4. Global and regional models designations composing the climate simulation bundles for the two scenarios RCP4.5 and RCP8.5 used in the study, after EURO-CORDEX

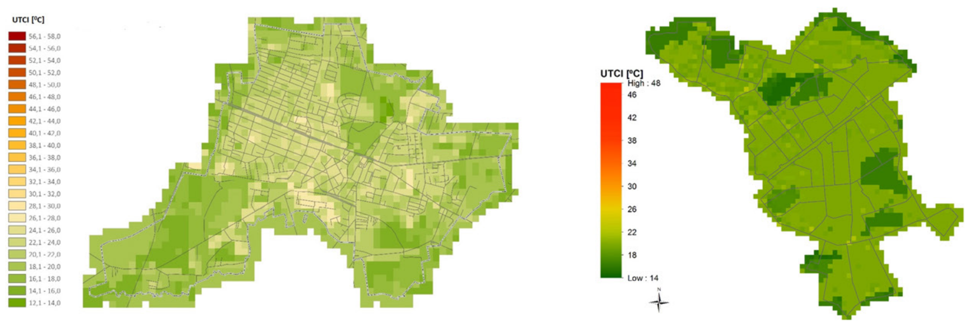
	Global Models	Regional Models
1	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17_
2	CNRM-CERFACS-CNRM-CM5	SMHI-RCA4_
3	ICHEC-EC-EARTH	CLMcom-CCLM4-8-17_
4	ICHEC-EC-EARTH	SMHI-RCA4_
5	ICHEC-EC-EARTH	KNMI-RACMO22E_
6	IPSL-IPSL-CM5A-MR	IPSL-INERIS-WRF331F_
7	IPSL-IPSL-CM5A-MR	SMHI-RCA4_
8	MOHC-HadGEM2-ES	SMHI-RCA4_
9	MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17_
10	MPI-M-MPI-ESM-LR	SMHI-RCA4_

Mińsk Mazowiecki **Wołomin**

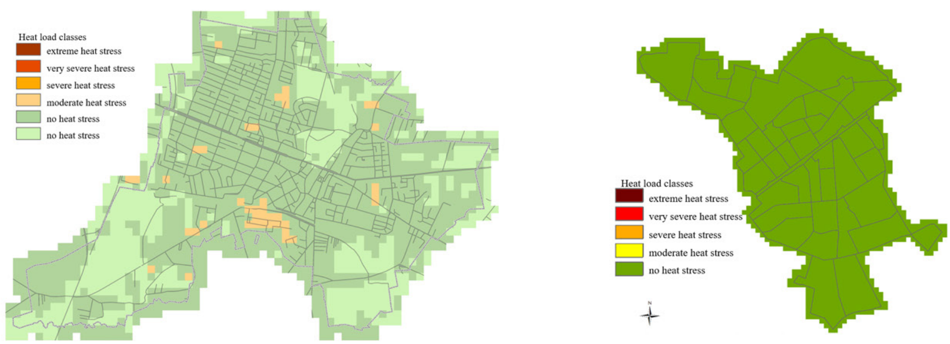
Topoclimate units (codes after tab. 1)



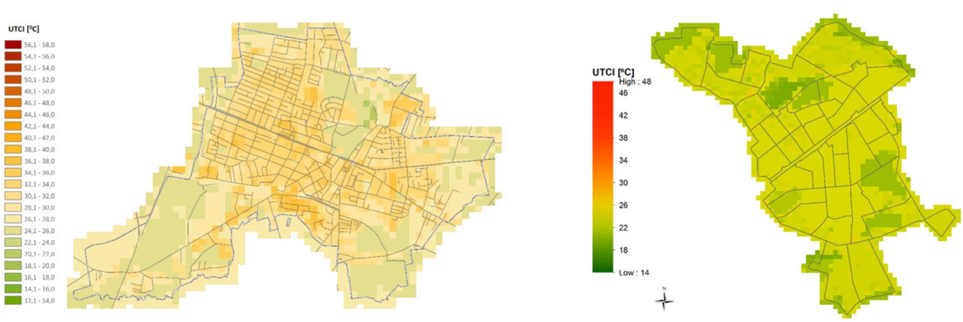
Perceptible temperature, average weather, 20°C



Heat stress, average weather, 20°C

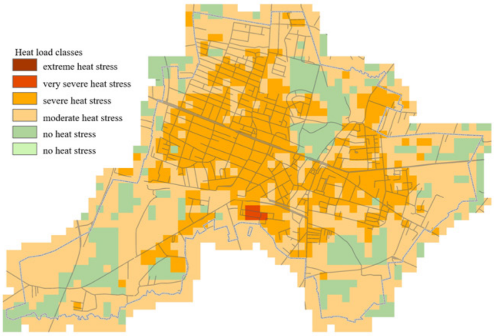


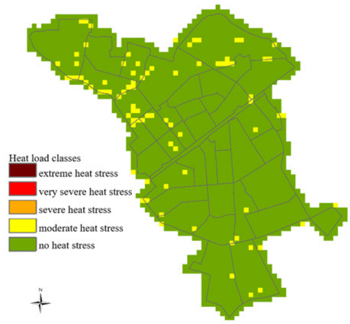
Perceptible temperature classes, warm weather, 25°C



Mińsk Mazowiecki **Wołomin**

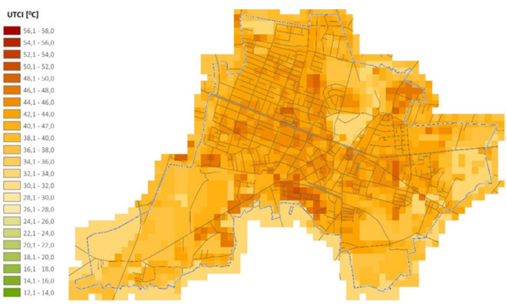
Moderete heat stress, warm weather, 25°C

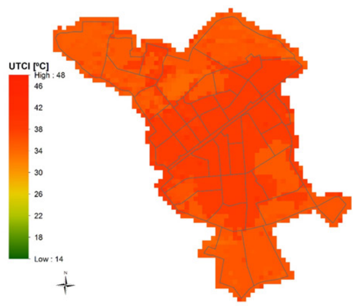




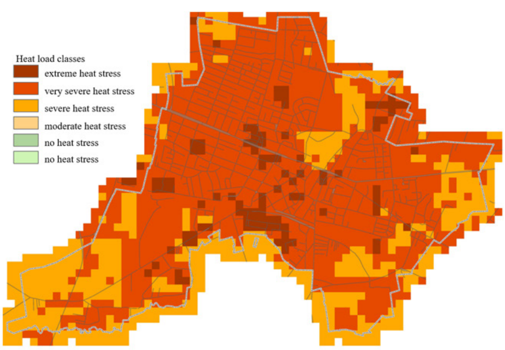
Staying in a *moderate heat stress* zone is associated with increased perspiration (above 100 g/h on average), resulting in loss of water and mineral salts (Błażejczyk et al. 2010, di Napoli et al. 2019). For conditions of elevated heat stress – such as in Mińsk Mazowiecki – it is recommended that people in areas with unfavourable biometeorological conditions periodically replenish fluids at a rate of at least 0.25 l/h, and limit both physical activity and exposure to sunlight.

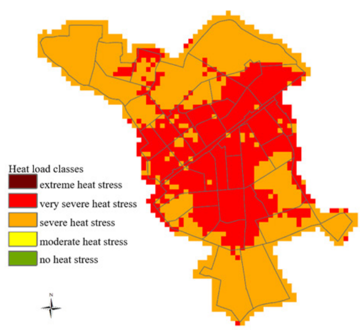
Perceptible temperature classes, hot weather, 30°C





Very high heat stress, hot weather, 30°C

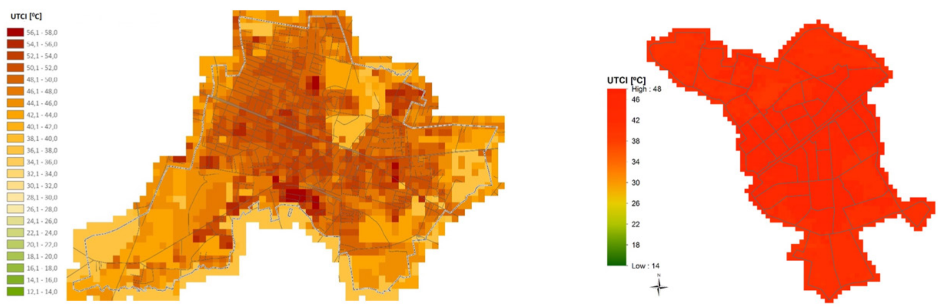




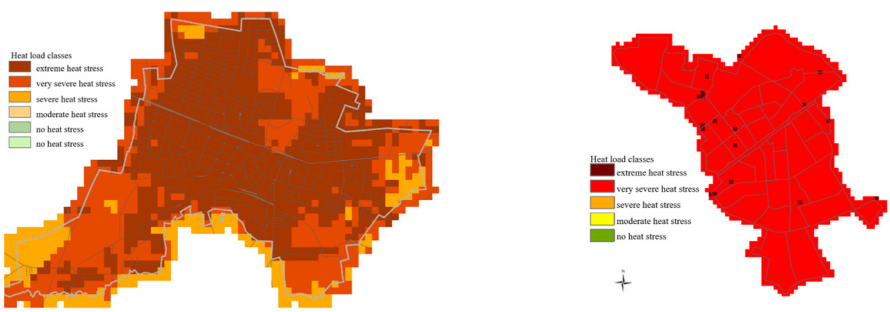
Mińsk Mazowiecki **Wołomin**

In the *very high heat stress* zone, an increase in internal body temperature occurs after about two hours of exposure, and prolonged exposure to such conditions is associated with a high risk of dehydration and even heat stroke. UTCI values mean that sweat secretion can be increased up to 200 g/h under hot weather conditions, with a significant risk of water loss and electrolyte imbalance of the body with prolonged exposure (Błażejczyk et al. 2010, di Napoli et al. 2019). It is essential to keep the body adequately hydrated and to take measures to minimise the duration of exposure to high temperatures, particularly for the elderly or people who are unwell. Under such conditions, it is essential to periodically cool the body and replenish fluids at a rate of at least 0.5 litres/hour. High physical exertion should also be avoided, and people with inefficient thermoregulatory systems should not stay in these areas. In areas of *very high heat stress*, additional use of air-conditioned rooms is necessary. The elderly and children should avoid such areas. A relief from heat stress conditions can be found in well-ventilated, exposed areas on the periphery of cities and in park areas. Staying in garden lots is also beneficial. Reduced wind speeds and poorer ventilation mean that forest areas do not alleviate heat stress as effectively as exposed areas in their surroundings. Some relief for the organism can be found in shaded areas with high vegetation (forests, parks, areas near water), however, the modelling carried out indicates that in the considered weather conditions, avoiding heat stress by staying outside is very difficult in the case of Mińsk Mazowiecki, definitely more favourable conditions occur in the area of Wołomin.

Perceptible temperature, extremely hot weather, 35°C



Extreme heat load, extremely hot weather, 35°C



Extreme heat stress is the highest classification found in the UTCI and signifies very intense heat stress. In the city area, it occurs in topoclimates of classes 13_31 and 23_31, i.e., warm and quiet, although its extent is mostly limited to a small area. It should be emphasised that even though there is a very high thermal load in conditions of extremely hot weather in Wołomin, the conditions of perceptible air temperature are significantly better than in the case of Mińsk Mazowiecki. Conditions in the zone of *extreme heat stress* are very unfavourable for outdoor occupants. Sweat secretion can exceed 650 g/h, which can lead to rapid dehydration and electrolyte imbalance of the body (Blazejczyk et al. 2010, di Napoli et al. 2019). If the air temperature, and hence the UTCI value, increases further, loss of thermoregulatory capacity may occur, posing an immediate health risk. It is advisable to strictly limit staying in areas subject to *extreme heat stress* and to frequently replenish fluids and take electrolytes to compensate for the loss of mineral salts through sweat secretion. People susceptible to environmental factors should not expose themselves to extreme heat stress.

Figure 1. Topoclimate units and spatial distribution of thermal stress (as the UTCI index) for 4 weather conditions, after tab. 5

Nearly 80% of the area of Wołomin is covered by topoclimates from two groups: 13 (46.3%) and 11 (32.8%). The topoclimates of group 13 are found in the city centre and in the area of high-density housing; they are topoclimates with reduced solar radiation inflow and increased reflected radiation values. These features result directly from the form of land use. In urban development conditions, the inflow of solar radiation to the active area is difficult, due to, among other things, mutual shading of buildings and the presence of the so-called street canyons – existing in local scale in both cities. At the same time, bright facades and the presence of glass surfaces (e.g., windows, shop windows) contribute to the increase of albedo, and thus the values of reflected radiation achieved are higher than on the standard surface. Topoclimates of group 11, in which the reflected radiation values are reduced in relation to the standard area, occur mainly in wooded and agriculturally used areas, located close to the northern and southern administrative borders of the city (Fig. 1).

In the case of Mińsk Mazowiecki, the largest surface area (38% of the study area) is occupied by a topoclimate classified as group 21, with reduced inflow of solar radiation to the active surface and average values of reflected radiation (Fig. 1). The majority of areas included in this group are characterised by warm and cool conditions (type 21_31, Fig. 1) – this group is typical for urban areas and includes the most urbanised parts of the Mińsk city. The second most frequent occurrence – 18% of the area, is the topoclimate of group 11. It is characterised by reduced solar radiation input to the active surface and reduced values of reflected radiation, type 11_11 – cool and quiet (Tab. 1). This type characterises urban areas with high vegetation (forests, parks), and in the analysed area it occurs mainly on the southern periphery of the city and in Dernalovich Park. The third significant type is the topoclimate of group 22 (14.4 % of the city's area), with average inflow of solar radiation to the active area and average values of reflected radiation, moderately warm and moderately windy type (22_22). This topoclimate type is characterised by standard conditions, typical of a meteorological station. Topoclimates from group 32 – with average values of total radiation and increased values of reflected radiation, classified as type 32_12 with cool and moderately windy conditions occupy 10% of the analysed area. Types 22 and 32 are typical of the city's exposed areas, with low urbanisation and predominantly agricultural character with scattered buildings (Fig. 1).

The biothermal conditions of summer weather, according to the classification in Table 2, are similar for both cities for average weather, but they vary quite rapidly with increasing air temperature (Table 6). In the case of Wołomin, the UTCI heat load index during average weather ranges from 15.0 to 22.5°C (average 19.1°C), the entire city is then in the comfort zone and there are no thermal loads in its area, the perceptible air temperature is close to the actual temperature. In the case of Mińsk Mazowiecki, the average UTCI (perceptible climatic conditions) remains in the analysed area in the class of full thermal neutrality, at 19.2°C. The great majority of the city's area – almost 70% of the area – is in this class, with almost the entire area of the city being heat-neutral. Extreme values range from 12.1°C to 27.7°C (Fig. 1). The maximum modelled UTCI value indicates that heat stress conditions may occur in the southern part of the city, i.e., in the industrial part of the area (total 2% of the city area).

For both cities, average weather gives the most favourable conditions possible in terms of thermal comfort for inhabitants. In average weather temperatures, biometeorological conditions do not require any special precautions to be taken during outdoor activities (Fig. 1). With a change in the weather type – an increase in average daily air temperature, the biothermal conditions of the two cities start to differ drastically, to the disadvantage of Mińsk Mazowiecki (Tab. 5).

In the case of Mińsk Mazowiecki, the increasing air temperature and decreasing

Table 5. Percentage contribution of zones corresponding to heat load classes according to UTCI in the area of Mińsk Mazowiecki and Wołomin in particular weather types

Weather type	No heat stress		Moderate heat stress		Severe heat stress		Very severe heat stress		Extreme heat stress	
	MM	W	MM	W	MM	W	MM	W	MM	W
Average (20°C)	98.0	100.0	2.0	0.0	2.4	0.0	0.0	0.0	0.0	0.0
Warm (25°C)	0.0	95.9	17.3	4.1	55.2	0.0	27.3	0.0	0.3	0.0
Hot (30°C)	0.0	0.0	0.0	0.0	29.6	57.0	64.4	43.0	6.0	0.0
Extremely hot (35°C)	0.0	0.0	0.0	0.0	13.1	0.0	33.0	99.1	54.0	0.9

MM – Mińsk Mazowiecki, W – Wołomin

cloud cover influence the differentiation of biometeorological heat stress conditions. As indicated in Table 6, the area is already covered by three classes of heat stress, indicating a dynamic increase in heat loads with a relatively small increase in temperature. The variability of possible heat loads in this weather type is the greatest (Fig. 1). The mean UTCI value is 28.8°C and characterises the *moderate heat stress class*, in which half of the analysed area is located. The extremes range from 20.1°C (thermoneutral conditions) to 38.2°C (*very severe heat stress*) (Fig. 1).

In the area of Wołomin in warm weather, the modelled value of the UTCI ranges from 20.3°C to 28.7°C (average 24.8°C) (Fig. 1). The vast majority of the city (95.9%) is then still in the thermal comfort zone (Tab. 5), but the index values are approaching the upper limit of this range. There are also isolated areas characterised by *moderate heat stress* (4.1%). Sites of *moderate heat stress* are particularly abundant in the northern and western parts of the city, and their occurrence largely coincides with the extent of topoclimates of classes xx_31, i.e., warm and sheltered. Reduced wind speeds combined with increased air temperatures in these topoclimates can exacerbate feelings of thermal discomfort compared to the rest of the city.

Under hot weather conditions in Mińsk Mazowiecki, the mean UTCI is 40.1°C (*very severe heat stress*) (Fig. 1). Heat stresses range from *severe heat stress* (UTCImin = 32.6°C, 30% of the area) to *extreme heat stress* (UTCImax = 50.3°C, 6% of the area) (Tab. 5). *Extreme heat stress* conditions are again characterised by areas with compact buildings or a high proportion of impermeable surfaces, dense dwellings, industrial/warehouse areas and other smaller areas with high ground impermeabillity.

Hot weather in Wołomin does not have as strong a negative impact as in the case of Mińsk Mazowiecki. The modelled UTCI value for the city area ranges from 33.7 to 40.0°C (average 36.8°C) (Fig. 1). This means that the entire city is subject to *strong* or *very strong heat stress* (Tab. 5). *Very strong heat stress* is characteristic of areas with the highest density of housing, particularly in the strict city centre – the area with the highest concentration of commercial facilities and public utilities (43%) (Fig. 1). Areas of *very high heat stress* are also found along the main traffic arteries constituting the inlet and outlet routes from Wołomin (Fig. 1). The remaining part of the city (57%) is characterized by *strong heat stress*. The concentration of *strong* and *very strong heat stress* in areas of high residential activity means that a significant proportion of the population residing in Wołomin may be subject to very strong heat stress.

During extremely hot weather, with air temperatures of 35°C and light winds, the proportion of areas under *extreme heat stress* increases significantly in Mińsk Mazowiecki (Tab. 5). Under these weather conditions, they include all types of buildings located within the city – more than half of the analysed area (Tab. 5). The mildest conditions for this weather situation are observed in forested areas on the periphery of the city and represent the *severe heat stress* class (Tab. 5). The mean UTCI during extreme heat stress weather is 45.8°C (UTCI min = 37.3°C, UTCI max = 57.7°C) (Fig. 1). Of great importance in these weather conditions is the high density of vegetation of the park and forest type. These areas on the map of the city are the "chill points", the relative chill being when the temperature difference between the area of high-density housing and the area of high and dense vegetation can reach up to 40°C (Fig. 1).

The results of the modelling of the spatial distribution of the UTCI for Mińsk Mazowiecki indicate that areas of dense high-growth greenery and easily ventilated undeveloped areas play a particular role in mitigating heat load during weather conditions.

In the case of Wołomin, the extreme heat weather conditions as modelled values of the UTCI are in the range from 39.2°C to 46.4°C (average 42.6°C) (Fig. 1). This means that almost the whole of Wołomin is in the zone of *very strong heat stress* (99.1%), and individual isolated areas are in the zone of *extreme heat stress* (0.9%).

3. Discussion

From the point of view of urban thermal comfort, under climate conditions typical of central Europe, the occurrence of a heatwave is one of the most difficult phenomena to monitor and manage, resulting in life and health risks for urban populations (Campbell et al. 2018). By far, most analyses and publications focusing on the impact of heatwave on the public health provide data based on the country scale monitoring systems or concentrate on big cities (e.g., di Napoli et al. 2019, AdapCity). However, the above-presented results regarding heat load related to urban fabric show that the size of the city does not matter. Medium-sized and small cities are facing the same problems with the consequences of heatwave on thermal comfort as the biggest ones.

The results of spatial differentiation of topoclimatic conditions are strongly correlated with biothermal conditions (perceptible temperature, UTCI index, Błażejczyk et al. 2010, Bröde et al. 2012) even in medium-sized cities (40-50 thousand inhabitants) and relatively small, urbanised areas (areas of cities respectively: Wołomin approx. 40 km^2, Mińsk Mazowiecki approx. 13 km^2). Significant differences between the cities are revealed in the characteristics of the topoclimate and in the bioclimatic conditions under the same regional weather patterns. The analysis of topoclimatic units (Fig. 1) indicates their greater diversity in the case of Wołomin (a total of 69 topoclimatic types), while in the Mińsk Mazowiecki's it is only 25 topoclimatic types.

The differences in adaptation to meteorological conditions shown in the modelling results between the analysed cities are due to the different topoclimatic conditions and their spatial distribution in the urban fabric. It was shown that, depending on the character of land use – the response of the urban fabric to the pattern of biometeorological conditions is fundamentally different. In terms of the perceptible temperature, relatively small-surface urbanised areas showed exactly the same pattern of the thermal comfort of the inhabitants as in large urban centres (AdaptCity 2019). It follows that, irrespective of the size of the urban complex, the presence or not of the so-called urban heat island effect – biothermal conditions are de facto regulated by strictly local characteristics of the urbanised space.

Analysing the results of the spatial variation of thermal stress by weather type for the two cities, it is clear that the differences are due to the characteristics of land use as an effect of the functioning of local communities. In spite of the similarities in the mean UTCI between the cities, the unfavourable biometeorological conditions in the area of Mińsk Mazowiecki are determined by the topoclimatic conditions occurring there (Fig. 1), patterned by the energy balance of the surface area. The physiological consequences of urban community functioning under thermal stress, indicated in the previous paragraph, occur under specific topoclimatic conditions. The topoclimate is the component in urban space which can and should be patterned to improve the conditions of perceptible temperature in cities – regardless of their size as it is shown here. This will enable effective mitigation of stressful thermal conditions.

The most straightforward efforts in this respect include introduction of those elements of urban infrastructure that improve rainwater circulation and aerosanitary conditions or reduce the amount of accumulated solar energy. These effects can be achieved, for example, by introducing green-blue infrastructure in the form of parks and street planting, streams, fountains, water curtains, which provide natural shade for pedestrian thoroughfares and increase air humidity. The proportion of green space can also be increased by planting trees on uncultivated land. Green shading of city squares, plazas and playgrounds allows for a local reduction in temperature in the neighbourhood of buildings and enables the heat-overloaded organisms of city residents to regenerate (Gal et al. 2021). The use of zero-energy solutions in construction and the introduction of passive buildings are also part of this group of measures, including the design of roof coverings in colours and with materials with suitable thermal storage and conductivity characteristics. The preservation of unbuilt surfaces is necessary to mitigate the heating processes of urban space and, through facilitated air movement, allows it to cool down more quickly (Kuchcik et al. 2013). Green space determines multifunctionality as well. Green infrastructure improves environmental health in the cities, benefits human health and provides habitat for wildlife, which is in line with the One Health principles (Felappi at al. 2020).

The results also indicate a significant potential burden on the human organism in urban space in zones that have already been diagnosed as thermal stress areas in warm and very warm weather conditions (Tab. 5). Modelling of future climatic conditions carried out for Wołomin and Mińsk Mazowiecki indicate that already in the middle of the 21st century the number of days with maximum temperature above 25°C should be expected to increase – the expected number of days in the range between 40-50 days per year (10-14% of days per year, up to 40% of the length of the summer period). By the end of the century, the expected number of days with a maximum temperature above 25°C will be in the range of 55-75 days, giving between 46 and 62% of the summer period under unfavourable biometeorological conditions of thermal stress, also predicted at KLIMADA2.0 project. In the case of Mińsk Mazowiecki, warm weather already causes severe thermal stress for 55.2% of the city area (Tab. 5). This means that without adaptive interventions to improve the topoclimatic conditions in the urban space, unfavourable biothermal conditions for the inhabitants will increase very quickly. The situation of Wołomin is more favourable here, but not fully comfortable, in particular in the city centre with its service and administrative functions for the urban community.

The location of the two analysed cities in the immediate neighbourhood of Warsaw, with good transport links, is favourable to rapid demographic and housing volume development as a consequence of the arrival of new residents (Cieciora, Muraska 2020). The obtained results of the differentiation of the cities' current thermal comfort and the direct relationship between biometeorological conditions and the topoclimate suggest the necessity of taking these two components into account in planning the development of the urban fabric and in the spatial development plan.

Modelling the topoclimatic conditions and thermal comfort of cities also appears to be a good diagnostic tool for adaptation to future climatic conditions. This is particularly important in ensuring good living and health conditions for communities in medium-sized cities.

As regards public health, the problem of excess morbidity and mortality related to extremely hot weather and poor air quality already exists and is going to exacerbate in the nearest future (Harlan, Ruddell 2011). As research indicates, the human body's ability to adapt to conditions of heat stress resulting from sustained high air temperature is difficult – regular hydration, limiting physical activity, taking care to cover the body from direct long-term exposure to sunlight, among other factors, are essential. These measures are particularly recommended for children and the elderly (Kenny et al. 2010, Xu et al. 2014). Taking into account the prediction of future climate trends, the possible adaptation to thermal stress conditions by managing the quality of the urban fabric seems to be a favourable policy direction.

Conclusions

The results of modelling spatial diversity of thermal comfort are presented based on the identification of spatial diversity of topoclimates occurring in two Polish medium-sized cities – Mińsk Mazowiecki and Wołomin, located in the vicinity of Warsaw. The modelling results were analysed for current conditions and indicated future potential thermal comfort conditions of the urban space in the cities under study. Despite the similarity in terms of geographical location and standard meteorological and climatic conditions, significant differences were found in the pattern of biothermal conditions in the two cities depending on the weather during the summer season.

Mińsk Mazowiecki, despite its smaller area and lower population, is a city with significantly poorer biothermal parameters. At least 55% of the city's area is within the range of thermal stress of its inhabitants under conditions of air temperatures of 25°C and above. In the case of Wołomin, the present, more favourable biothermal conditions result from the topoclimatic characteristics, which are significantly different from those of Mińsk Mazowiecki.

In the case of both cities, future thermal conditions will be a major challenge, where it is predicted that by the end of the century more than half of the summer period could be at least warm weather, with temperatures of 25°C and above. This implies a significant degradation of biothermal conditions in both cities in a relatively short period of time.

City thermal comfort is one of the most important factors for social activity and urban vitality. Given the demonstrated benefits of taking into account the contemporary topoclimatic diversity of cities and modelling their spatial thermal comfort, it seems expedient to use these tools in spatial planning and adaptation of the urban structure to future climate conditions.

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