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URBAN CLIMATE RESEARCH IN WARSAW: THE RESULTS OF MICROCLIMATIC NETWORK MEASUREMENTS

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Abstract

The paper presents some aspects of Warsaw's climate, in particular the urban heat island. UHI changes in different seasons and in different air mass types were analysed over the years 2011-2012. Average UHI in Warsaw is of a diamond shape which reflects the distribution of the densest built area and exceeds 2.0°C in the city centre compared to the airport station. In subtropical air mass, the intensity of UHI on the left side of the Vistula River reached 7.7°C. The basis for the analysis is the microclimatic measurement network of 28 permanent points in Warsaw and its surroundings, operated by IGSO PAS and completed by data from 7 other stations. This dense network became the IGSO PAS' input into an UHI project titled 'Development and application of mitigation and adaptation strategies and measures for counteracting the global Urban Heat Islands phenomenon (UHI)' implemented through the Central Europe Program and co-financed by the ERDF.

Keywords

city climate • network of microclimatic measurements • urban heat island • Warsaw

Introduction

Over the last 20 years Warsaw has been intensively built-over with in-fills and sky-scrapers in the city centre, closed housing estates in the outer districts and separate houses on the outskirts, on former agricultural land. At the same time, inside the city, the aeration belts transferring fresh air from surrounding forests to the city centre have disappeared and green open areas, gardens and allotments drastically diminished in size. All those processes have led to the increase of urbanization, especially intensively on the left side of Vistula River and hence increasing the urban heat island (UHI). UHI is defined as a relative increase of the temperature of the near-ground air layer inside the city in comparison to the surrounding rural areas. Urban heat island is the best-documented evidence of anthropogenic climate modification in urban areas and is often treated as one of the essential features of urban climate, though it is not a stationary phenomenon but a periodic one of varying intensity, persistence through time, spatial extent and shape (Oke 1979, 1987; Arnfield 2003; Fortuniak 2003; Peng et al. 2012).

In Warsaw the influence of urbanization on the climate was very easily seen because of dramatic destruction during the Second World War. According to the Encyclopaedia of Warsaw (1994), up to 1994, about 90% of the buildings had been destroyed and later rebuilt. However, no one investigated this phenomenon in those times. There are only some remarks, for example: in the fifties of the 20th century the mean wind speed in the centre of Warsaw reached 78% of that noted on the outskirts, while in the late seventies wind speed in the centre was reduced to 43% (Kossowska-Cezak 1999; Błażejczyk 2002).

The publications on Warsaw climate are usually based on long-term data series from few meteorological stations and consider the differences of meteorological parameters between urban and suburban areas (Kozłowska-Szczęsna et. al. 1996; Wawer 1997; Błażejczyk 2002; Lorenc & Mazur 2003; Stopa-Boryczka (ed.) 2003; Błażejczyk & Kunert 2006). Some of the studies, consisted of several measuring posts (which were arranged on chosen profiles or the chosen quarters of the town) were periodically carried on by the researchers and students of the Faculty of Geography and Regional Studies of the University of Warsaw (Stopa-Boryczka 1992).

Urban heat islands are usually defined on the basis of average long-term data from a few urban and rural meteorological stations (Szymanowski 2005; Fortuniak et al. 2006; Majewski et al. 2013). Sometimes the research is based on data from denser networks of meteorological stations, though often limited to season or days (Błażejczyk 2002; Watkins et al. 2002; Kuchcik 2003; Endlicher et al. 2008; Papanastasiou & Kittas 2012). Some of the studies rely on a vehicle equipped with meteorological instruments driving through cities (Chudzia & Ropuszyński 1998) or airplane flights providing basic data from thermal scanning (Mayer 1988). Recently, most popular studies of heat islands are based on remote sensing data of the surface temperature (Voogt & Oke 2003; Peng et al. 2012).

The area of Warsaw is about 517 km^2; the distance from the south to north edge of the city is about 25 km and from the west to east edge 20 km. Only 2 meteorological stations of the Institute of Meteorology and Water Management operate in that area (IMGW; Okęcie, Bielany) as well as a few stations belonging to universities (University of Warsaw, Warsaw University of Technology, Warsaw University of Life Sciences, the Military University of Technology in Warsaw) and research institutions: the Institute of Geography and Spatial Organization (IGSO PAS) and the Institute of Geophysics of the Polish Academy of Science.

In the light of fast changes in the city of Warsaw and global climate changes, this number of measurement sites is totally insufficient. Due to this, in spring 2006, climatologists from IGSO PAS began to establish a network of microclimatic measurements in Warsaw and its surroundings (Kuchcik et al. 2008). This new observational network is based on two automatic meteorological stations which have been operated by IGSO PAS since the end of 1990. They represent the downtown of Warsaw (Twarda st.) and the areas outside of the town (Borowa Góra – 35 km north from Warsaw). They are equipped with Campbell CR23X Dataloggers, Kipp&Zonen pyranometers, Young wind speed and direction monitors, Vaisala temperature, humidity and air pressure sensors.

The aim of the new network was to collect information about the influence of the complex Warsaw urban structure on the temporal and spatial variability of air temperature, air humidity and precipitation regimes. With time, the network rose in number of stations, though the station in Borowa Góra was eliminated due to technical problems. Nowadays the main results of the network refer to the spatial and temporal changes of air temperature in Warsaw, its dependence on different urban structures and land cover types (Adamczyk et al. 2008; Baranowski et al. 2008; Błażejczyk et al. 2014). The measuring points represent different urban structures, ratio of biological vital areas or arrangements of buildings.

The aim of the paper is to present a few spatial and temporal characteristics of the urban heat island in Warsaw, but also to present the Warsaw network of measurements – its development, present state and the reasons why IGSO PAS participated in the Central Europe UHI Project 'Development and application of mitigation and adaptation strategies and measures for counteracting the global Urban Heat Islands phenomenon (UHI)'.

Warsaw microclimatic network – development and present state

The first attempt of the microclimatic network in Warsaw refers to the years 2001-2002 when, within the framework of the project 'Influence of air circulation and local factors on climate and bioclimate of Warsaw', 12 HOBO Pro dataloggers were used

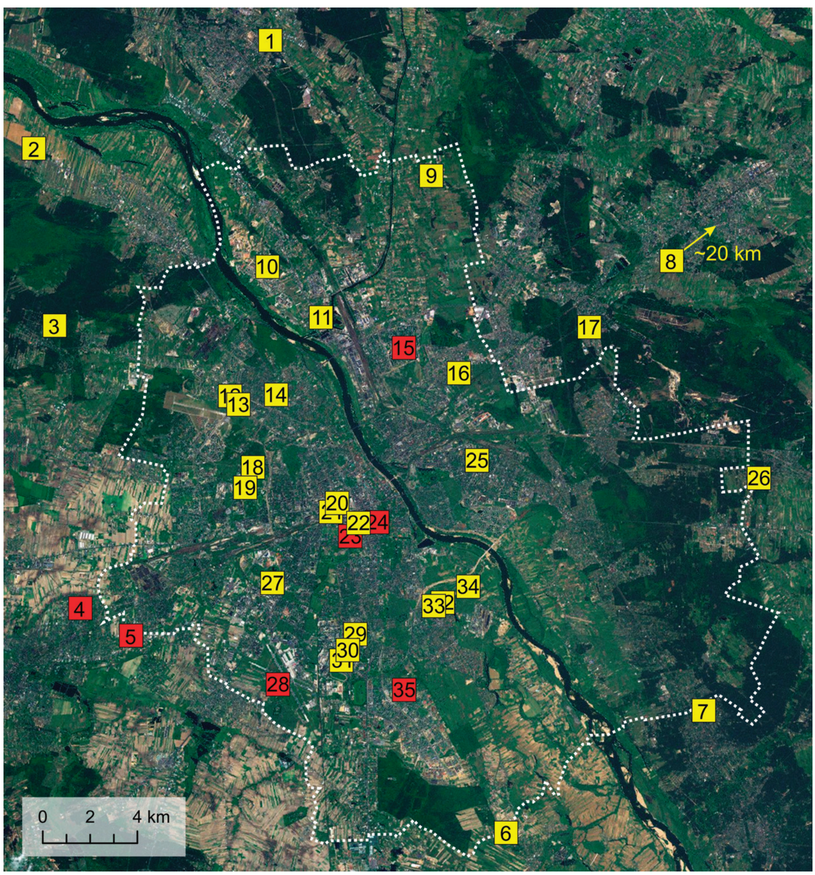

Figure 1. Location of the measuring posts in the microclimatic network (yellow – operated by IGSO PAS, red – other operators)

Source of aerial data: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, Swisstopo, and the GIS User Community.

for monitoring air temperature and humidity in selected urban structures. The network worked for 13 months and the results were applied in Błażejczyk's (2002) publication.

As mentioned, the creation of the contemporary network started in 2006. From 2010 the IGSO PAS network consisted of 28 permanent automatic measuring posts. 20 of them are situated in the city: in different parts of Warsaw, in residential districts of different types of building density, various age and kinds of greenery, in different building and land cover types. 8 loggers are located on the outskirts of Warsaw or in small, satellite towns (Fig. 1). In each case they are located over grasslands of different sizes, only in one case – over coniferous, creeping bushes (no. 22).

On IGSO PAS stations the air temperature and humidity HOBO Pro U23-001 and U23--002 sensors (Onset Computers Corporation) are applied. They are installed 2 m above the ground (Fig. 2). Measurements are carried out for twenty-four hours, with 10 second scanning intervals and stored as 10-minute averages. Hourly and daily air temperature values are calculated afterwards.

Figure 2. Pictures of measuring posts: Langego (up) and Włodarzewska (down)

Table 1 presents essential information of each measuring point and its surroundings: the names of the districts or cities and distance from the centre of Warsaw, which was assumed as the Marszałkowska / Aleje Jerozolimskie crossroads. The distance varies from 600 m to almost 37 km. Greenery is described by the Ratio of Biological Vital Areas (RBVA), i.e. the ratio between the areas covered by vegetation or open water (not sealed areas) to the plot size (Szulczewska et al. 2014). It changes from 4% to 85%. For the points situated on the specific housing estates, the RBVA was calculated for the whole estate of the area and varied from 5.1 ha (Włodarzewska) to 7.6 ha (Duracza). For other points the lesser areas were calculated.

The intensity of the building development is presented through Floor Area Ratio (FAR). This is calculated as the area of all building contours (Barea) multiplied by the number of floors (fn) and divided by total area of the plot (Tarea), FAR = Barea·fn/Tarea.

For each station, the built type or land cover type, corresponding to 'local climate zones' of Oke (2006), were defined. For example: – open low-rise is the open arrangement of low-rise buildings (1-3 stories), abundance of pervious land cover (low plants, scattered trees), wood, brick, stone, tile and concrete construction materials; – compact midrise means dense mix of midrise buildings (3-9 stories), few or no trees, land cover mostly paved, stone, brick, tile and concrete construction materials (Stewart & Oke 2012).

For each point the detailed inventory of the greenery, type of surfaces, the heights of buildings and horizon limitations was done. The inventory elements are presented on maps and in descriptive form. The graphical examples of the inventory of two measuring points located on the left and right side of Vistula River, situated on the very centre (Hoża) and on the north-east outskirts of Warsaw (Kobiałka) is presented in Table 2.

For the analysis of the UHI phenomenon and for the calculations of UHI maps, the database was completed by data from other measuring stations operated by the

Table 1. The list of measuring points in the network, their distances from the city centre, Ratio of Biological Vital Areas (RBVA), Floor Area Ratio (FAR), built or land cover types according to Stewart & Oke (2012) and the operators of the station

No.	Measuring point	Distance [km]	RBVA [%]	FAR	Built types/ Land cover types	Operator
1	Legionowo	20.2	85	0.05	Sparsely built	IGSO PAS
2	Dziekanów	20.5	54	0.31	Open low-rise	IGSO PAS
3	Izabelin	15.0	82	0.11	Scattered trees	IGSO PAS
4	Piastów	12.4	–	–	Open midrise	WIOŚ
5	Reguły	10.9	45	0.35	Large low-rise	LAB-EL
6	Powsin	15.1	77	0.10	Scattered trees	IGSO PAS
7	Michalin	17.0	83	0.17	Scattered trees Open low-rise	IGSO PAS
8	Tłuszcz	36.9	53	0.42	Open low-rise	IGSO PAS
9	Kobiałka	14.5	72	0.33	Sparsely built	IGSO PAS
10	Kamińskiego	10.9	45*	0.98*	Open midrise	IGSO PAS
11	Żerań	8.3	55	0.27	Open midrise	IGSO PAS
12	Conrada	7.2	60*	1.26*	Open high-rise	IGSO PAS
13	Zgr. Żmija	6.7	42*	1.02*	Open midrise	IGSO PAS
14	Duracza	5.9	52*	0.71*	Open midrise	IGSO PAS
15	Bródno	7.1	–	–	Open midrise	WIOŚ
16	Zacisze	7.2	46	0.66	Compact low-rise	IGSO PAS
17	Zielonka	12.5	45	0.40	Open low-rise	IGSO PAS
18	Koło	4.7	54*	0.80*	Open midrise	IGSO PAS
19	Olbrachta	4.8	52*	1.24*	Open high-rise	IGSO PAS
20	Pańska	8.7	18*	2.50*	Open high-rise	IGSO PAS
21	Twarda	1.1	4	2.74	Compact midrise	IGSO PAS
22	Hoża	0.6	16*	2.23*	Compact midrise	IGSO PAS
23	Niepodległości	1.2	–	–	Compact midrise	WIOŚ
24	Krucza	1.0	–	–	Compact midrise	WIOŚ
25	Kamionek	5.5	19	1.60	Compact midrise	IGSO PAS
26	Sulejówek	17.1	87	0.05	Sparsely built	IGSO PAS
27	Włodarzewska	4.7	41*	1.25*	Open midrise	IGSO PAS
28	Warszawa-Okęcie	8.1	–	–	Low plants	IMGW
29	Langego	5.3	57*	1.19*	Open high-rise	IGSO PAS
30	Orzycka	6.0	49*	0.95*	Open midrise	IGSO PAS
31	Bokserska	6.4	59*	0.56*	Open midrise	IGSO PAS
32	Bernardyńska	5.4	67*	0.72*	Open high-rise	IGSO PAS
33	Limanowskiego	5.2	65*	0.62*	Open low-rise	IGSO PAS
34	Augustówka	5.7	67	0.25	Sparsely built	IGSO PAS
35	Ursynów	7.9	–	–	Open midrise	WIOŚ

* RBVA and FAR calculated for the whole housing estate of the area from 5.1 ha to 7.6 ha

WIOŚ – Voivodship Inspectorate for Environmental Protection, LAB-EL – Laboratory Electronics, IMGW – Institute of Meteorology and Water Management

Voivodship Inspectorate for Environmental Protection (WIOŚ, points 4, 15, 23, 24 and 35 on Fig. 1), the Institute of Meteorology and Water Management (IMGW, point 28 on Fig. 1) and Laboratory Electronic (LAB-EL, point 5 on Fig. 1).

UHI project

The experience of the IGSO PAS climate research group in urban climate studies, as well of this dense network of permanent microclimatic measures became the Institute

Table 2. The example of the inventory of two measuring points: land cover, topographic maps, horizon limitations of obstacles and the pictures

<table>
<tr><th>Hoża (no. 22) – city centre, compact midrise</th><th>Kobiałka (no. 9) – outskirts, sparsely built</th></tr>
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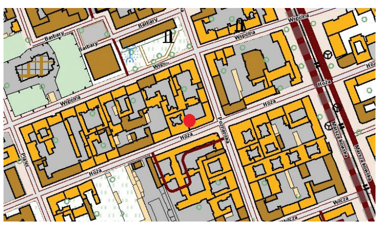
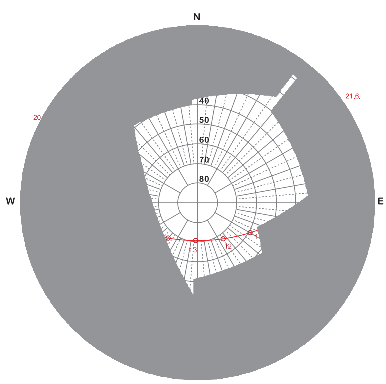
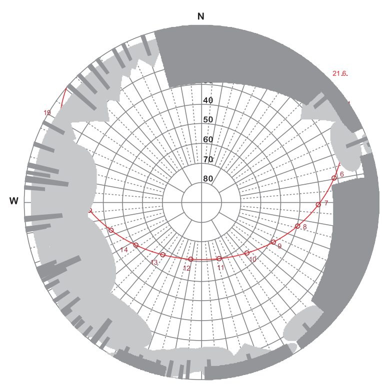
<tr><td></td><td></td></tr>
<tr><td>
</td><td>
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input into a UHI project entitled 'Development and application of mitigation and adaptation strategies and measures for counteracting the global Urban Heat Islands phenomenon (UHI)' implemented through the Central Europe Program and co-financed by the ERDF. The project was conducted from 1.05.2011 to 31.07.2014. The UHI Project encompasses 8 of the most relevant metropolitan areas and MEGAs (Mega Urban Regions) of Central Europe: Bologna-Modena, Venice-Padua, Wien, Stuttgart, Warsaw-Łódź, Ljubljana, Budapest and Prague. Besides the inventory of heat islands in these regions (Błażejczyk et al. 2013; Fallmann et al. 2013; Busato et al. 2014), several scenarios of heat islands after the implementation of lesser or bigger possible changes (removing buildings, planting trees, green roofs, water bodies) were calculated (Ketterer & Matzarakis 2014). The project also boosted transnational discussion among policy makers, local authorities and professionals that develop policies and actions for preventing, adapting and mitigating the natural and man-made risks arising from the UHI phenomenon (http://eu-uhi.eu/). As a result of these communications various important documents were issued, among them the Gold Standard for UHI evaluation (http://eu-uhi.eu/download/publications/wp4/WP4.2.3_Gold_Standard.pdf).

Urban climate of Warsaw

The microclimatic measurements network in Warsaw is applied in the analysis of spatial and temporal characteristics of urban climate. Dense network and detailed time resolution of data allow for the analysis of several aspects of city climate e.g. microclimatic differences between different urban structures, patterns of air temperature in various weather types or air masses in different parts of Warsaw, episodes of extreme weather events etc.

The intensity of the urban heat island is determined in each of the measuring points as the difference of the minimum daily temperature between the considered site to the value of the minimum daily temperature for the Warszawa-Okęcie airport station (no. 28) – hereinafter referred to as the UHI-index.

The data from the network also allows the creation of heat island maps. Maps of urban heat island intensity were prepared with the use of Esri ArcGIS software, version 10.1. For interpolation of measured data the Geostatistical Analyst extension was used from which the kriging model was applied. The values predicted by kriging are estimated based on the weighted arithmetic mean of surrounding samples. This group of methods selects the most probable value and gives very good results when data have normal distribution, are stationary, without trends, and the number of samples is sufficient (Krivoruchko 2011). From among the group of kriging models, linear ordinary kriging was chosen.

Figure 3 presents the comparison of UHI measurement network in 2001 and 2011-2012 and the area of interpolation and extrapolation of data. In 2001, almost half of the area of Warsaw was outside the network consisting of 12 measuring points, especially the western and south-eastern parts of the city. In 2011, new stations located in the outskirts of Warsaw improved this situation. Nowadays, most of the city is within the interpolation area and only small, suburban parts are outside.

The most visible and clear result of the denser and wider microclimatic measurement network are detailed maps of the UHI--index (Fig. 4). In 2001, the average annual UHI-index reached 1.0°C in two separate 'islands', one in the city centre and a second in the vicinity of the Żerań heat and power plant. However, according to the analysis of UHI in Warsaw over the years 1981-2011, the year 2001 turns out to be the least intensive; the average annual UHI intensity was ca. 2°C, whereas in 2001 it was only 1°C.

The mean picture of urban heat island in Warsaw in the years 2011-2012 is entirely different. UHI covers most of the Warsaw area and is over 2.0°C in the very city centre. UHI from the years 2011-2012 has a diamond shape which reflects the distribution

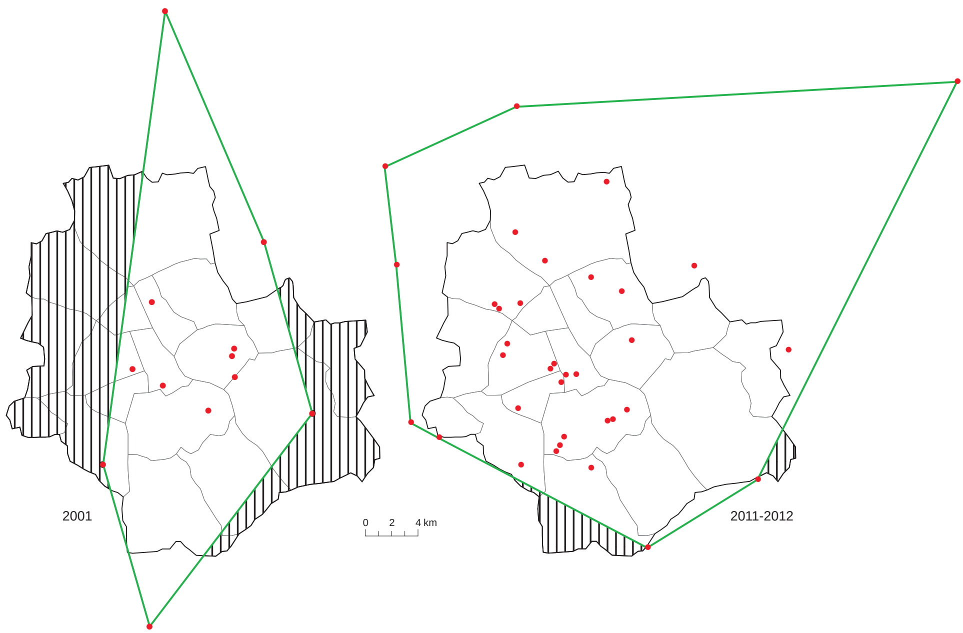

Figure 3. Area of interpolation (green polygon) and extrapolation (hatched area) of measurement data in 2001 and 2011-2012

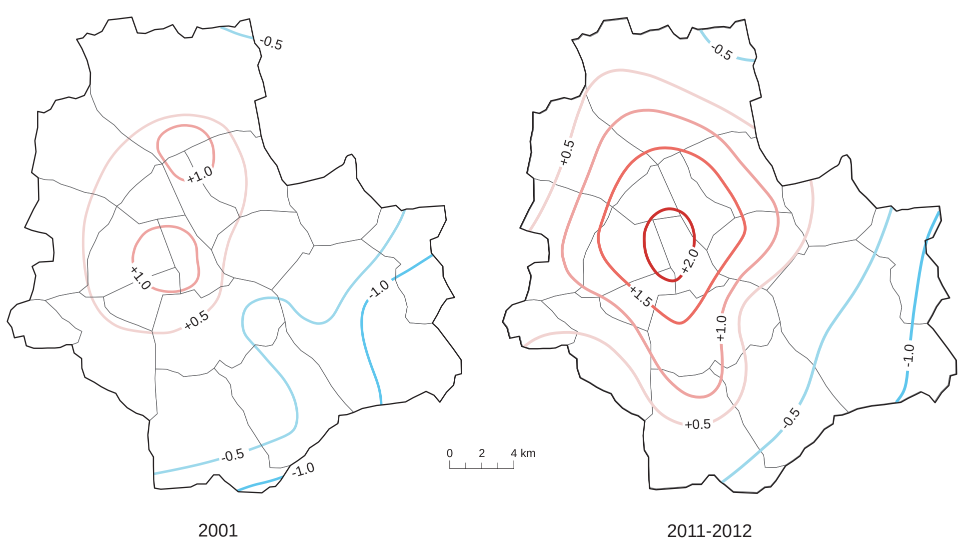

Figure 4. Spatial distribution of UHI-index in Warsaw in 2001 and 2011-2012

of the densest built area. The south-east part of Warsaw which is the forest area of Mazowiecki Landscape Park is 1.0°C colder than the Warszawa-Okęcie airport station (Fig. 4).

Diurnal changes of UHI or the episodes of the most intensive UHI cases are the next ways of presenting and analysing urban climate. For this study, the courses of hourly air temperature data from 6 stations distributed on two profiles from the city centre to the south outskirts, on the left and right sides of Vistula River were chosen. 5-day periods from various seasons of 2011 and various air masses were selected.

The left side (west) profile consists of the stations: Hoża (no. 22) – from the exact city centre, the point is situated in a small courtyard surrounded by 6-8 floor buildings; Orzycka (no. 30) – a housing estate halfway from the outskirts to the city centre and Powsin (no. 6) – situated in a clearing in a botanical garden. The right side (east) profile runs from Żerań (no. 11) – situated in the vicinity of the heat and power generation plant, through Kamionek (no. 25) – a housing estate located in the most densely built area of the Praga Południe district to Michalin (no. 7) – situated in an open low-rise built type, on the higher terrace of the valley of the Vistula river, surrounded by forest. Stations Powsin and Michalin are located near the city border.

5-day periods represent not only four seasons but also different air masses: arctic air mass in winter, maritime fresh air in spring, subtropical in summer and polar continental in autumn. In Warsaw, over the years 1991-2001, the yearly average frequency of those masses was 21% for arctic, 36% for maritime fresh air mass, 6% for subtropical and 11% for continental (Kuchcik & Ożga 2002). In 2011, the frequencies were respectively: 13%, 43%, 6% and 8%. Therefore, the large changes concerned the less frequent occurrence of arctic air masses and the greater frequency of maritime fresh air (Więcław 2012).

In February 2011, in arctic air mass, with daily maximum air temperatures below zero, the east profile was on average 0.5°C colder than the west one. UHI intensity, considered as the difference of air temperature between Michalin and Kamionek on the east side, reached 6.4°C while between Powsin and Hoża it was 4.9°C (Fig. 5a, 5b). Mean differences between those stations for the whole 5-day period are: 1.0°C and 0.6°C. On the east side, the clear UHI was seen at night on 14-15 February. During the day, about noon, a distinct negative UHI, up to 3.6°C was observed (outskirts warmer than the city).

Minimum air temperature during the analysed 5-day period was -17.9°C in Michalin and -14.0°C in Powsin, while only -12,4°C in Hoża. Despite Michalin and Powsin being the same distance from the Vistula river, the difference between them was distinct. Point Michalin is situated at 95 m a.s.l., on the higher terrace of the Vistula valley, in the forest's clearing, in the open low-rise built type and is characterised by a great range of air temperature, especially its great falls. Point Powsin is located on the edge of the moraine plain, at 103 m a.s.l., in the clearing in the botanical garden.

In May 2011, in maritime fresh air, in warm and sunny weather, the difference between the west and east side of Warsaw diminished. On both sides, the temperatures were almost the same and the warmest were the stations situated in the densest built-up areas (Hoża, Kamionek). However, heat island intensity reached 7.1°C on the west side, where the degree of urbanization is higher and 6.4°C on the east, less urbanised side. During the day, the outskirts exposed to solar radiation became warmer than the shadowed city centre by 2.8°C on the east profile and 2.3°C on the west one. Daily air temperature amplitude reached 25.3°C on the east side and 21.1°C on the west profile. These chosen days give a good example of the reduced night cooling of the city centre and decreased daily air temperature amplitude in accordance to the decrease of the ratio of biological vital areas (RBVA) and increase of Floor Area Ratio (FAR). The minimum air temperatures were 4.3°C on the outskirts where RBVA are 77-83%, and 7.8-8.5°C in the city centre where RBVA are only 16-19%. During the day, the city centre, with many shadowed areas, was slightly cooler than the outskirts exposed to the sun. These two processes resulted in lower daily air temperature amplitudes by 4.7°C (east side) to 5.7°C (west side) in the city centre as compared to the rural sites (Fig. 5c, 5d).

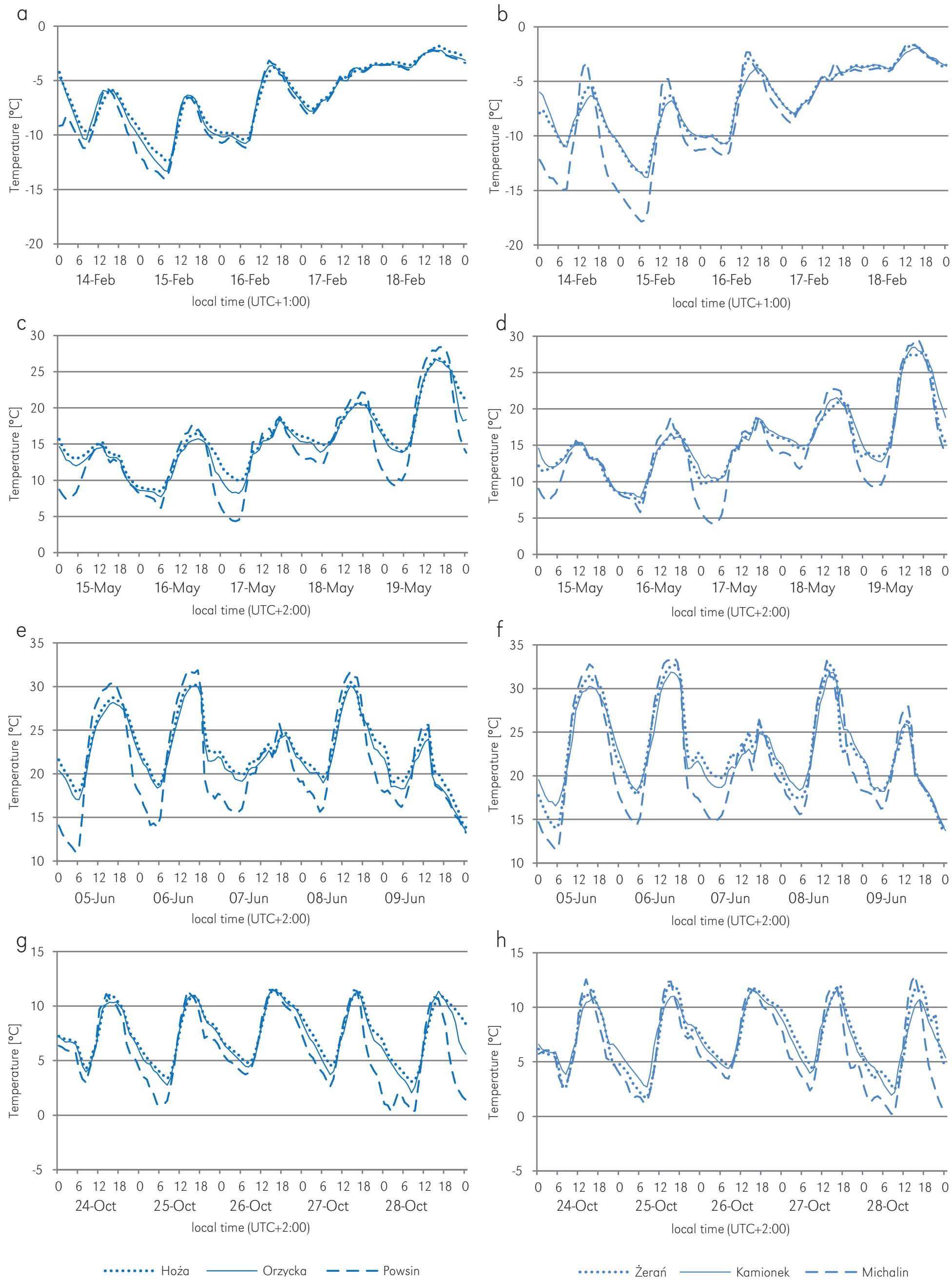

Figure 5. The air temperature courses on the profiles present the west (graphs on the left) and the east (graphs on the right) side of Warsaw in different air mass types and seasons: arctic air mass in winter (a, b), maritime fresh air mass in spring (c, d), subtropical air mass in summer (e, f) and polar continental air mass in autumn (g, h)

Subtropical air brought few hot days in June 2011. The maximum air temperatures were higher on the east profile and reached 33.5°C, while in the west it was 31.9°C. In June, as in May, UHI intensity was significantly higher in the west, more urbanized, side and reached 7.7°C (the difference between Powsin and Hoża) and 5.0°C on the east side. The minimum air temperatures were 11.0-11.5°C on the outskirts and 13.7-13.8°C in the city centre. During the day, the city centre was 1.5°C cooler than the outskirts and daily air temperature amplitudes were lower by 4°C (Fig. 5e, 5f).

In October, in polar continental air mass, the difference between both sides of the river as well as among each of the profiles became smaller. The intensity of UHI on the west profile stayed at the level of 7.2°C but on the east profile it grew up to 6.9°C. Maximum air temperatures were very similar on all points and only minimum temperatures differed significantly and favoured the warm city centre. Daily air temperature amplitudes were less than half of the value from spring and reached only 12.7°C on the east profile and 11.2°C on the west one (Fig. 5g, 5h).

Summarizing, despite the yearly average, the UHI-index over 2011-2012 is little more than 2.0°C and its maximum values exceeded 8.0°C. When comparing the air temperature courses from the rural stations and those situated in the city centre in different air masses – the intensity of UHI reached 7.7°C. It occurred on the west profile, in subtropical air mass, when the maximum air temperature exceeded 30°C and the minimum air temperature in the city centre was about 20°C. On the contrary, the negative UHI (sometimes called 'cold lake'), which means that the sunny outskirts are warmer than shadowed compact city structures, were 1-2°C higher on the east profile compared to the west one.

These are only few examples of using the data from the microclimatic network in analysing the climate of Warsaw, but they show the potential for future analysis.

Conclusions

The research based on the network of automatic microclimatic stations of air temperature monitoring organised by the climate research group from the Institute of Geography and Spatial Organization of the Polish Academy of Sciences (IGSO PAS) has brought much valuable data which allow the deepening of the knowledge of the Warsaw UHI. This dense network of 35 measuring stations represents various land use units and different distances from the city centre. The results will also allow for different analyses of the climate of Warsaw, from different viewpoints and for various purposes.

While the UHI phenomenon is well known as a specific feature of the Warsaw urban climate, the present study brings new valuable information regarding its temporal and spatial variability. The comparison of six stations: two situated on the very city centre, two on the outskirts and two in the mid distance, with different land cover types and city structures shows the distinct influence of biologically vital surfaces on thermal regimes.

The differences of air temperature between Michalin and Powsin, situated at the same distance from the Vistula River, though on opposite sides and in different morphological units, reflects at least the climatic difference between the low terrace on the right bank of the Vistula river and the high moraine plain on the left bank. In a wider perspective, these differences could assign the Vistula valley as some stable and clear climatic border between west and east part of Mazovian Lowland or an even bigger geographical region. This suspicion is planned to be studied in detail in the future.

In relation to the issue mentioned above, in the succeeding months, some measuring sites situated in the west part of Warsaw, which are close to each other, are planned to be moved closer to the Vistula River and to its right side. This reorganized network will provide information which can be used for better representation of the city structure and for verification of the hypothesis of the importance of the Vistula River as the climatic border on the local and regional scale.

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Editors' note:
Unless otherwise stated, the sources of tables and figures are the author(s), on the basis of their own research.

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