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URBAN HEAT ISLAND IN KRAKÓW, POLAND: INTERACTION BETWEEN THE LAND USE AND THE LAND FORM

Bokwa A.

Institute of Geography and Spatial Management, Jagiellonian University, Kraków, Poland

Abstract
Automatic measurements of air temperature in five points in Kraków, in the period 03.2009-01.2010 were used to study urban heat island (UHI). Mean seasonal UHI intensity is the largest in the street canyon in summer (3.3K) and the lowest in urban green areas in winter (0.5K). UHI intensity >3.0K occurs in 58.4% of the night time in summer and 7.9% in winter in the street canyon. In spring and summer UHI intensity is much larger than in other Polish cities of comparable size which is the effect of the location of Kraków in the Vistula river valley and resulting cold air reservoir occurrence.
Keywords: urban heat island, Kraków, Vistula river valley, katabatic air flow, cold air reservoir

Introduction
Studies on urban heat island (UHI) are most often conducted in cities located in flat areas, so that the mesoclimatic differences in air temperature are mainly effects of the land use impact (e.g. Arya 1988, Oke 2004). However, as stated by Y. Goldreich (1984, 2009), most cities are located in areas which are not entirely flat and only in few studies the relief impact was treated as an important factor controlling urban climate. Parallel, A.J. Arnfield (2003) and C.S.B. Grimmond (2006) pointed out that the role of relief in urban climate modification is not sufficiently known and should be the subject of further studies. Most works concerning the role of relief in UHI control were realised for little mountainous towns (e.g. Nkemdirim 1980, Kuttler i in. 1996). The present study aims to show the impact of the relief on UHI in a large city located in a wide valley, in a non-mountainous area.
Kraków is a city located in Southern Poland, on the Vistula river, with the area of 326.8 km^2 and 754,624 inhabitants (data of 2009). The city and its environs are located at the junction of three large regional units. According to German (2000-2001), the northern part belongs to the southern margins of the old uplands' belt of Central Poland and is divided into the following mesoregions: Kraków Upland, Miechów Upland and Proszowice Plateau. Most of Kraków's area is placed in the Vistula river valley, which belongs to the Carpathian Foredeep. It can be divided further into the eastern part where the valley is as wide as 10 km and has many terrace levels, and into the western part where the valley is closed by the isolated hills, tectonic horsts. Southern part comprises the Wieliczka Foothills, a part of the Carpathian Foothills. The height differences between the Vistula river valley bottom, going from east to west, and the nearby hill tops, surrounding the city from the north, south and west, reach about 100 m. The urbanized areas are located in both concave and convex landforms. The location of Kraków makes it a convenient place to study the interaction between the land use and land forms in controlling UHI. The aim of the present paper is to show that issue for the part of the city placed in the bottom of the valley, where the city centre is located and where the land use is the most diversified. Apart from the areas with the dense built-up, typical for the old city centre, there are districts with blocks of flats or with residential estates. There are also numerous green areas, in some places forming green zones between the built-up districts.

Materials and methods

Within a project described in the work by Bokwa (2010), in the period 2007–2009 an automatic air temperature measurement network was established in Kraków and its vicinities. It consists of 21 points, located in various land form types and in each land form – in various land use types. The HOBO and Minikin sensors are used to record the temperature every 5 minutes. They are located 2–4 m above the ground, in the radiation shelters. In the present analysis, data from 5 points located in the valley bottom are used, from the period 03.2009-01.2010. The points are described in Table 1 and are all placed in the western part of the river valley (Fig. 1).

Table 1. Measurement points in the Vistula river valley bottom in Kraków and its vicinities

Measurement point	Land use	Height (m a.s.l.)	Sky View Factor
Jeziorzany	non-urban area	211	0.956
Krasinskiego St.	city centre, street canyon	204	0.457
Bema St.	residential estate	208	0.822
Podwawelskie district	blocks of flats	203	0.605
Botanical Garden	park area in the city centre	206	0.690

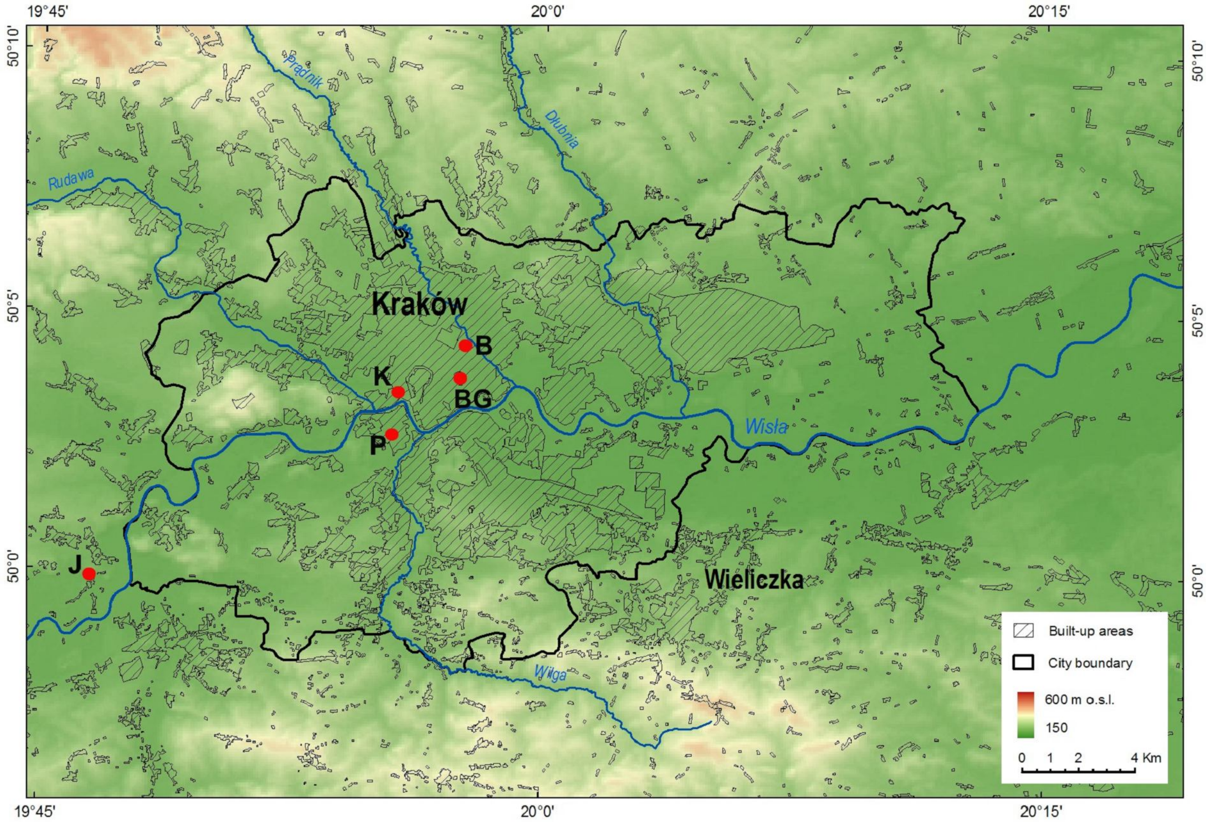

Fig. 1. Location of the measurement points

Explanations: K – Krasinskiego St., B – Bema St., P – Podwawelskie district, BG – Botanical Garden, J - Jeziorzany

Figure by P. Chrustek and A. Bokwa

The data available were divided into sub-periods so as to represent particular seasons. Synchronous measurements from all the points were available for the following sub-periods:

1. Spring: 24.03-16.05.2009;
2. Summer: 16.07-29.08.2009;
3. Autumn: 1.09-30.11.2009;
4. Winter: 1.12.2009-28.01.2010.

The period 03.2009-01.2010 was compared to 1901-2000 in terms of its representativeness and no major anomalies were found, only April 2009 was exceptionally dry, with the sum of precipitation as low as 0.5 mm. The number of so-called clear nights, with cloudiness ≤2/8 and wind speed ≤2 $m \cdot s^{-1}$, when the mesoclimatic differences are best visible, was also similar in the resrearch period as in the years 1971-2005 (Bokwa 2010).

The intensity of UHI was defined in a classical way, as the air temperature difference between particular urban stations and the non-urban station (Jeziorzany). As UHI is best developped in the night-time, only the measurements recorded from the sunset to the sunrise were taken for further analysis.

The results presented below are of preliminary character, as the measurements are still continued.

Results and discussion

Mean seasonal UHI intensity in the period 03.2009–01.2010 is presented in Table 2. The highest values in all seasons are observed for the street canyon (Krasinskiego St.), while all other kinds of land use show similar air temperature conditions. The lowest values are characteristic in all seasons for the botanical Garden, and the difference between Krasinskiego St. and Botanical Garden varies from 0.8K in summer to 0.6K in autumn. In spring and summer the UHI intensity is much larger at all points than in autumn and winter. The difference between the highest and lowest seasonal values (i.e. summer and winter) varies from 1.9 to 2.1K in particular points. Previous studies on UHI in Kraków, performed by J. Lewinska et al. (1982), estimated its intensity to be 1.9K in the cold half-year and 2.0 in the warm one in the city centre, while for green urban areas it was 0.9 and 0.8K, respectively. Those values are much lower than those presented in Table 2 but the authors compared the air temperature in the city centre with a mean air temperature for a few non-urban stations, while in the present work only one non-urban station is used, so that may be the reason for that difference. The UHI intensity in Kraków may be compared with the one in other Polish cities of similar size, i.e. cities located in comparable climatic conditions but in flat areas. In Wroclaw (Szymanowski 2004) mean UHI intensity for the night time in the city centre was 2.0K in spring, 2.3K in summer, 1.3K in autumn and 1.1K in winter, while for the areas with blocks of flats it was 1.5K, 1.6K, 1.0K and 0.6K, respectively. In Lodz (Fortuniak 2003) mean monthly UHI intensity for the night time in the city centre does not exceed 2.0K in summer and in winter it decreases to about 0.5K. It means that the UHI intensity in Kraków's centre but also in the areas with blocks of flats is much larger than in Wroclaw or Lodz, especially in spring and summer. The analysis of the thermal conditions in the non-urban areas around Kraków (Bokwa 2010) proves significant impact of relief on local climate, expressed with the occurrence of temperature inversions, katabatic flows and cold air reservoirs in the valley bottom. So the high values of UHI intensity are a result of the much cooler thermal conditions in the rural areas at night than in case of cities located in flat areas.

Table 2. Mean seasonal UHI intensity (K) during the night time in different types of land use in the period 03.2009–01.2010.

Season	**K-J**	**B-J**	**P-J**	**BG-J**
Spring	2.9	2.5	2.4	2.3
Summer	3.3	2.8	2.6	2.5
Autumn	2.0	1.4	1.4	1.4
Winter	1.2	0.7	0.7	0.5

Explanations: K – Krasinskiego St., B – Bema St., P – Podwawelskie district, BG – Botanical Garden, J - Jeziorzany

Table. 3. Seasonal frequency (%) of UHI various intensity (K) during the night time in the western part of the studied area, in different types of land use in the period 03.2009–01.2010

UHI	**K-J**	**P-J**	**B-J**	**BG-J**
spring				
0.1-1.0	10.2	18.9	18.6	23.3
1.1-2.0	22.3	21.8	21.5	19.5
2.1-3.0	17.2	19.5	17.1	15.7
3.1-4.0	18.6	17.3	18.6	18.9
4.1-5.0	15.6	12.8	12.1	12.7
5.1-6.0	9.6	4.7	5.9	4.4
6.1-7.0	3.9	1.6	2.5	1.2
>7.0	0.4	0.1	0.3	0.1
Σ	**97.8**	**96.7**	**96.5**	**95.7**
summer				
0.1-1.0	3.9	7.8	5.0	9.8
1.1-2.0	14.1	23.1	20.9	24.2
2.1-3.0	23.4	32.0	29.5	27.1
3.1-4.0	27.5	24.8	29.5	29.0
4.1-5.0	21.9	10.3	13.0	9.2
5.1-6.0	7.4	1.9	1.9	0.6
6.1-7.0	1.5	0.0	0.0	0.0
>7.0	0.1	0.0	0.0	0.0
Σ	**99.9**	**99.9**	**99.8**	**99.9**
autumn				
0.1-1.0	24.2	42.0	38.9	39.3
1.1-2.0	29.5	23.7	21.9	20.8
2.1-3.0	18.0	16.4	17.2	14.8
3.1-4.0	13.3	9.5	10.5	11.6
4.1-5.0	9.4	2.4	3.2	5.1
5.1-6.0	2.8	0.2	0.6	0.7
6.1-7.0	0.4	0.0	0.0	0.0
>7.0	0.0	0.0	0.0	0.0
Σ	**97.4**	**94.3**	**92.4**	**92.3**
winter				
0.1-1.0	48.1	70.0	58.9	53.0
1.1-2.0	31.7	16.1	16.1	9.9
2.1-3.0	9.4	4.4	5.7	5.3
3.1-4.0	4.6	1.7	2.5	2.7
4.1-5.0	1.6	1.0	0.9	1.3
5.1-6.0	1.3	0.4	0.9	0.4
6.1-7.0	0.4	0.0	0.4	0.1
>7.0	0.0	0.0	0.0	0.0
Σ	**97.0**	**93.6**	**85.4**	**72.6**

The mean seasonal values of UHI intensity give only a very general image of the phenomenon. Therefore, seasonal frequency of various UHI intensity was calculated (Table 3). In all seasons and at all measurement points UHI situations occur in more than 90% of the night time, with the exception of winter at Bema St. and Botanical Garden. Then at those two points an increase in non-UHI situations (i.e. cold lake situations) may be observed. Large UHI intensity values, i.e. >3.0K, occur most often in all seasons in the street canyon (from 58.4% in summer to 7.9% in winter) and least often in the areas with blocks of flats (37.0% and 3.1%, respectively). The comparison with Wroclaw and Lodz shows differences again. In Wroclaw (Szymanowski 2004) UHI intensity >3.0K in the city centre makes 29.2% in summer and 5.9% in winter, while in Lodz (Fortuniak 2003) at 2 a.m. its frequency reaches in the city centre 15% in summer and 3% in winter. The much higher share of large UHI intensity in Kraków than in Wroclaw or Lódz is due to the occurrence of the cold air reservoirs in rural areas around Kraków, not due to extremely high air temperatures in the city.

The non-UHI situations, so-called cold lake situations, have the frequency comparable to those for Wroclaw and Lódz (Szymanowski 2004), i.e. about 3% for the city centre.
The UHI intensity described for Kraków may be compared to the one measured in other cities or towns located in the river valleys. The maximum UHI intensity in Kraków in the study period, taking under consideration the data from the measurement points in Krasinskiego St. and in Jeziorzany, was 7.7K and occurred during the night 20/21.04.2009. An even larger value, 9.9K was noted during the night 29/30.04.2009, but it was the air temperature difference between the measurement point by the Slowacki Theatre in the old town and Jeziorzany (Bokwa 2010). In Calgary (Nkemdirim 1980) the katabatic cold air flows decreased UHI intensity by about 40%. For Stolberg (Kuttler et al. 1996) maximum UHI intensity was similar as in Calgary: about 4K and it was also lower than the expected one. In both towns the katabatic flows were able to enter into the urban areas which is not the case in larger cities, like Kraków. In Swiss Freiburg the maximum UHI intensity was 5K in all seasons (Roten et al. 1984, Fallot et al. 1986), in Trier 2.6K in winter (Junk et al. 2003), in Graz 4K in winter (Lazar, Podesser 1999) and in Lisbon 3.5K in winter. Most of those towns are smaller than Kraków and UHI intensity depends on the city size and number of inhabitants (Oke 1973, 1987). However, in case of cities located in the valleys, also other factors play significant role. The UHI intensity in Kraków is much larger than in the cities recalled above not only because Kraków is a larger city but also because the katabatic flows do not enter the city interior, in the rural areas the cold air reservoirs are formed and additionally the sensible heat flux is significantly limited there due to the evaporation of the river waters.

Conclusion

The phenomenon of UHI is well known, but the role of particular factors controlling it is still the subject of discussion. The results obtained for Kraków show the role of relief and location of a city in a wide river valley. The impact of relief is expressed in much higher UHI intensity than in cities of comparable size but located in flat areas. It means that various models describing relations between the UHI intensity and e.g. number of inhabitants have to be used carefully in the studies of urban climate in such places or they may simply turn out to be useless. Additionally, just the location in a valley is not a sufficient and uniform criterion, as the size of both the valley and the city/town matters in terms how, for example, the katabatic air flows interact with urban structures. Further studies are needed to find out e.g. how UHI intensity in cities located in valleys depends on atmospheric circulation.

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Contact address of the first author:
Dr. Anita Bokwa
Jagiellonian University
Institute of Geography and Spatial Management

7 Gronostajowa St.
30-387 Kraków
Poland
email: anita.bokwa@uj.edu.pl