Vol. 145, No. 1-2 · Research article

DIE ERDE
Journal of the
Geographical Society
of Berlin

Effect of relief and land use on heat stress in Kraków, Poland

***Anita Bokwa*[1], *Danuta Limanówka*[2]**

[1] Jagiellonian University, Institute of Geography and Spatial Management, 7 Gronostajowa St., 30-387 Kraków, Poland, anita.bokwa@uj.edu.pl

[2] Institute of Meteorology and Water Management National Research Institute, Centre for Poland´s Climate Monitoring, 61 Podlesna St., 01-673 Warszawa, Poland, danuta.limanowka@imgw.pl

Manuscript submitted: 15 January 2013 / Accepted for publication: 21 November 2013 / Published online: 2 September 2014

Abstract

Heat stress in urban areas is controlled mainly by the impact of anthropogenic land use on the active surface heat balance. This paper shows the role of land form superimposed on the land-use impact, using the example of Krakow, Poland. The city is located in a concave land form, on the Wisla (Vistula) River. The automatic measurements of air temperature and humidity were realised in Kraków from April to October, in the years 2010-2012. For the day time conditions, ANOVA test and Tukey's test showed significant differences in the number of very hot days and number of heat waves, between urban areas in the valley and rural areas, both in the valley and on the slope. For the night time, significant differences were found for the number of tropical nights, not only between urban and rural areas, but also between urban areas located in various landforms and between urban areas in the valley floor and rural areas located in various landforms. Both urban and rural measurement points located in the river valley floor experienced the highest numbers of very hot days, heat waves and extreme air temperature duration. For measurement points elevated about 50 m above the valley floor, the indices' values were lower by about 50 %.

Zusammenfassung

Hitzestress in urbanen Räumen wird hauptsächlich bestimmt durch die Einwirkung der Landnutzung auf die Wärmebilanz aktiver Oberflächen. Dieser Beitrag zeigt über die Landnutzung hinaus auch die Rolle der Oberflächenformen für die Wärmebilanz, am Beispiel von Krakau (Polen). Krakau befindet sich in einer Talweitung der Weichsel. Automatische Messungen der Lufttemperatur und der Luftfeuchtigkeit wurden in Krakau von April bis Oktober in den Jahren 2010 bis 2012 durchgeführt. Bei Tage zeigten sowohl der ANOVA-Test als auch der Tukey-Test signifikante Unterschiede in der Anzahl der sehr heißen Tage und der Zahl der Hitzewellen zwischen den städtischen Bereichen im Tal und den ländlichen Bereichen (sowohl im Tal als auch an den Hängen). Nachts wurden Unterschiede in der Anzahl tropischer Nächte festgestellt, nicht nur zwischen städtischen und ländlichen Bereichen, sondern auch zwischen den verschiedenen städtischen Räumen in unterschiedlichen geomorphologischen Situationen sowie zwischen städtischen Räumen in der Talsohle und ländlichen Räumen in verschiedenen Lagen. Die Maxima an sehr heißen Tagen, an Hitzewellen sowie an der Dauer der extremen Lufttemperaturen traten sowohl im städtischen wie auch im ländlichen Raum jeweils an den Messpunkten am Talgrund auf. Die Indexwerte an Messpunkten ungefähr 50 m über dem Talgrund lagen dagegen um rund 50 % niedriger.

Keywords Hot days, Humidex, THI, effective temperature, Kraków, Poland

---

Bokwa, Anita and *Danuta Limanówka* 2014: Effect of relief and land use on heat stress in Kraków, Poland. – DIE ERDE **145** (1-2): 34-48

DOI: 10.12854/erde-145-4

1. Introduction

One of the characteristic features of urban climate is the increase of air temperature compared to surrounding rural areas. Urban heat island (UHI) is most pronounced during summer and during the night-time. The highest values of air temperature in urban areas are usually characteristic for central parts of cities, with very little share of green areas, intensive built-up and large height of the buildings (*Landsberg* 1981, *Oke* 1987). During the heat waves, the UHI effect is superimposed on the hot air masses advection. Therefore, the heat stress in urban areas is much higher than in rural areas, leading to increased mortality (e.g. *Golden* et al. 2008, *Gabriel* and *Endlicher* 2011). On the other hand, land-use types in urban areas form a mosaic, and so the microclimatic conditions are very diversified spatially, too. Therefore, the intensity of the heat stress is also spatially diversified in cities (e.g. *Cohen* et al. 2012). Studies on heat stress and its impact on urban inhabitants are realised on a regional scale (e.g. *Burkart* et al. 2011, *Pantavou* et al. 2011) or for particular cities, with respect of the microclimatic variability (e.g. *Gulyas* et al. 2006). As far as land-use impact on urban heat stress is concerned, urban green areas are studied most often (e.g. *Cohen* et al. 2012). Most studies concerning urban climate and bioclimate are realised for cities located in flat areas or areas with little height differences (*Goldreich* 1992, 2009). But many cities are located in large river valleys, and in this case, the land-use impact on micro- and mesoclimate is combined with the effect of relief (e.g. air temperature inversions, katabatic flows; e.g. *Svensson* et al. 2002). Kraków is one of such cities. The differences in relative height in Kraków seem to be rather small compared e.g. to urban areas in Alpine valleys. However, numerous studies show that air temperature inversions occur quite often in Kraków and in many cases they last over 24 hours (e.g. *Lewinska* 1984, *Walczewski* 1994). The location of Kraków in a concave land form, a foreland basin, is linked with increased variability of bioclimatic stimuli intensity in the annual course, especially during summer (*Limanówka* 1991). Additionally, climatic conditions of the western and eastern part of the city are significantly different due to the width of the valley, the geology, relief and land use (*Bokwa* and *Limanówka* 2008, *Bokwa* 2010). UHI in Kraków was studied mainly by *Lewinska* (1996). In the 1970s, she completed measurements organised only in the urban and rural areas in the river valley and estimated the mean annual value of UHI to reach 1.2K, with a maximum value of 7K. Measurements realised in the years 2009-2010 by *Bokwa* (2010) showed that the mean annual UHI value for the valley floor was 2.4K and the maximum value reached 9.9K.

The aim of the present paper is the analysis of the impact of land use and relief on the spatial distribution of heat stress. Do areas of similar land use, but located in various land forms, have different bioclimatic conditions concerning heat stress?

2. Study area

Kraków (Cracow) is located in southern Poland, on the Wisla (Vistula) River. It is a medium-size city with an area of 326.8 km^2 and 759,137 permanent registered inhabitants (data of 2011; Raport 2012). The total number is estimated to reach 1 million. The city is located in the river valley going from west to east, i.e. in a concave landform. The historical city centre is placed in the river valley bottom (at about 200 m a.s.l.), and also on a tectonic limestone horst (the Wawel Hill), emerging from the river valley. The northern part of the city belongs to the Kraków-Czestochowa Upland. The southern parts of the city belong partially to the Carpathian Foothills. The Wisla River valley is narrow in the western part of the city, with a width of about 1 km, and widens to about 10 km in the eastern part. In the western part of the valley, there are several limestone horsts, reaching about 350 m a.s.l. Therefore, the city area is surrounded by the convex land forms from the south, west and north, and it often happens that the wind speed in the valley floor is close to zero while at the nearby hill tops it reaches about 4-5 ms^{-1}. Height differences between the valley floor and the hilltops next to the city borders are about 100 m and the built-up areas do not reach those hilltops. Data on land use within the city borders show that agricultural and semi-natural areas as well as wetlands cover more than 40 % of the city area (*Bokwa* 2010). In the valley floor, the land use is most differentiated while in the convex land forms south and north of the valley, only selected land-use forms can be found. Buildings with more than four floors (districts with blocks of flats) are located mainly in the suburbs. Areas with compact built-up are found mainly in the old town. In the eastern part of the city, in the river valley, there is the district of Nowa Huta with a huge steelwork, constructed after the Second World War.

3. Data and methods

The data used come from permanent meteorological stations (period: 2001-2012) and temporary automatic measurement points (2010-2012). The permanent stations are located in the river valley and represent city centre and rural areas east and west of the urban area:

1. Igolomia: 50°06'N, 20°16'E, 202 m a.s.l.; the station belongs to the national meteorological network and is located 24 km east of Kraków's centre; the relief of the surrounding area is rather monotonous and agricultural land use prevails;

2. Balice: 50°05'N, 19°48'E, 237 m a.s.l.; the station belongs to the national meteorological network and is located within the area of the International Airport Kraków-Balice, about 11 km west of Kraków's centre; in the surrounding area, agricultural land use prevails;

3. Botanical Garden: 50°04'N, 19°58'E, 206 m a.s.l.; the station belongs to the Department of Climatology, Institute of Geography and Spatial Management, Jagiellonian University, but it is also included in the national meteorological network; the station is located in the city centre but within the urban green area (i.e. the Botanical Garden of the Jagiellonian University).

Data for the period 2001-2010 were used to show 10-year average values of heat stress indices, but only for the urban and rural areas in the valley floor, due to data availability. For the period 2010-2012, it was possible to obtain those indices for urban and rural areas located in various landforms. During the period 2010-2012, there were 21 automatic measurements points located in the city and its vicinities so as to represent various types of land use in three vertical zones: 1. river valley bottom, 2. areas located about 50 m above the river valley bottom (N and S from the valley floor) and 3. areas located about 100 m above

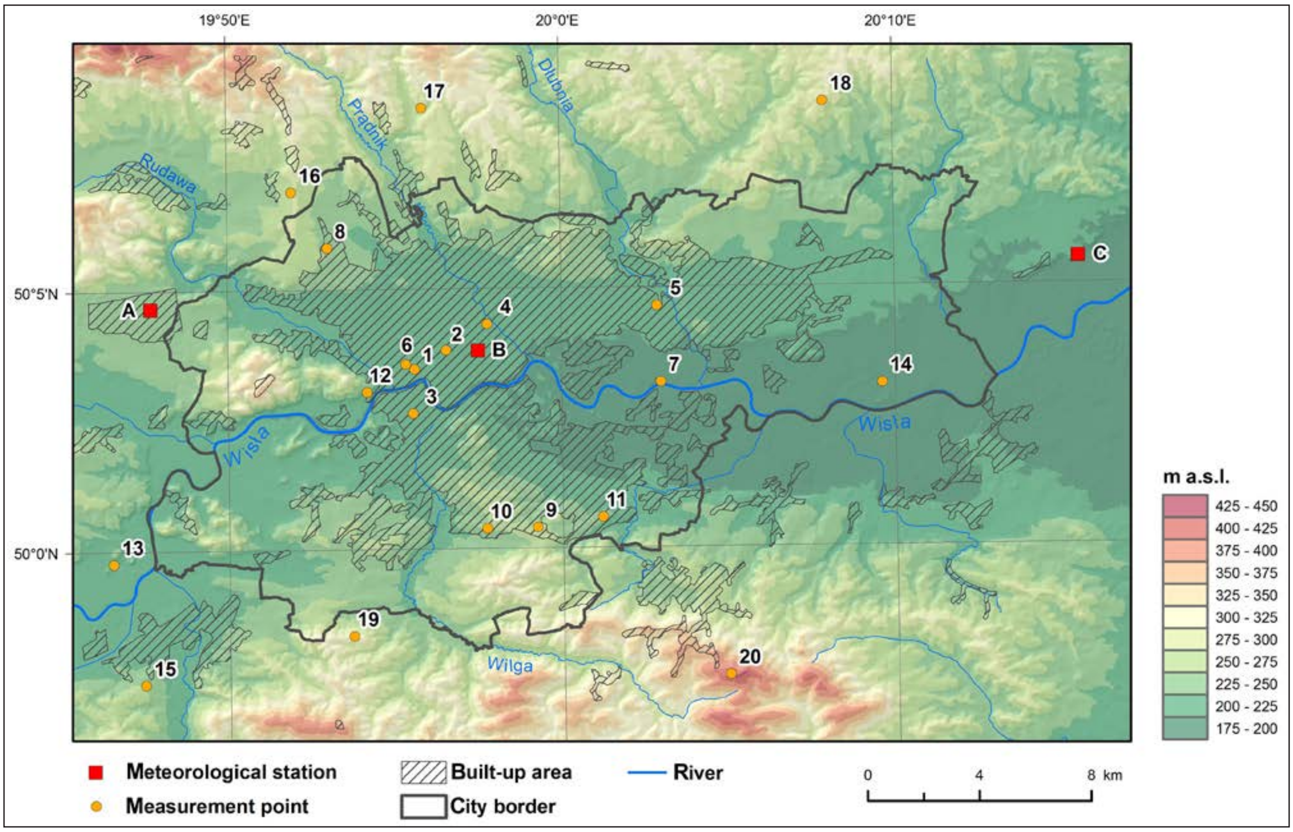

Fig. 1 Location of the stations and measurement points in Kraków. Automatic measurement points: 1: Krasinskiego St., 2: Slowacki Theatre, 3: Podwawelskie district, 4: Bema St., 5: Szkolne district, 6: Blonia meadows, 7: Wandy Bridge, 8: Ojcowska St., 9: Czajna St., 10: Bojki St., 11: Mala Gora St., 12: Malczewskiego St., 13: Jeziorzany, 14: Przylasek Rusiecki, 15: Rzozów, 16: Modlniczka, 17: Garlica Murowana, 18: Kocmyrzów, 19: Libertów, 20: Choragwica. – Permanent meteorological stations: A: Balice, B: Botanical Garden (also an automatic measurement point), C: Igolomia

Tab. 1 Automatic measurement points in Kraków and its vicinities. Explanations: Numbers 1-12 and B: urban points, numbers 13-20: rural points; λ, φ: coordinates, h: altitude (m a.s.l.); numbers of the measurement points as in Fig. 1

Localisation	φ, λ	h	Land use	SVF
River valley bottom				
1. Krasinskiego St.	50°03’28”N 19°55’34”E	204	Dense urban development, urban canyon, city centre	0.457
2. Slowacki Theatre	50°03’50”N 19°56’31”E	215	Old town dense urban development, city centre	0.695
3. Podwawelskie district	50°02’37”N 19°55’32”E	203	Blocks of flats	0.605
4. Bema St.	50°04’19”N 19°57’46”E	208	Residential development	0.822
5. Szkolne district	50°04’39”N 20°02’52”E	205	Blocks of flats	0.695
6. Blonia meadows	50°03’34”N 19°55’18”E	203	Urban green area, meadows, no trees, city centre	0.711
7. Wandy Bridge	50°03’11”N 20°02’57”E	197	Urban green area by the river bank	0.939
B. Botanical Garden	50°03’00 N 19°57’00 E	206	Urban green area with trees and bushes, city centre	0.690
12. Malczewskiego St.	50°03’02”N 19°54’32”E	222	Urban green area in the suburbs	0.788
13. Jeziorzany	49°59’45”N 19°46’31”E	211	Non-urban, agriculture area	0.956
14. Przylasek Rusiecki	50°03’07”N 20°09’35”E	190	Non-urban area by the fish ponds	0.690
50 m above the valley bottom N				
8. Ojcowska St.	50°05’49”N 19°52’59”E	245	Residential development	0.809
16. Modlniczka	50°06’54”N 19°51’55”E	258	Non-urban, agruculture area	0.975
50 m above the valley bottom S				
9. Czajna St.	50°00’25”N 19°59’13”E	258	Residential development	0.838
10. Bojki St.	50°00’24”N 19°57’42”E	252	Blocks of flats	0.691
11. Mala Góra St.	50°00’35”N 20°01’10”E	231	Blocks of flats	0.859
15. Rzozów	49°57’25”N 19°47’26”E	251	Non-urban, agriculture area	0.968
Hill tops				
17. Garlica Murowana	50°08’30”N 19°55’51”E	270	Non-urban, agriculture area, N of the city centre	0.975
18. Kocmyrzów	50°08’33”N 20°07’54”E	299	Non-urban, agriculture area, N of the city centre	0.968
19. Libertów	49°58’20”N 19°53’41”E	314	Non-urban area with dispersed built-up, S of the city centre	0.785
20. Choragwica	49°57’32”N 20°04’57”E	436	Non-urban, agriculture area, S of the city centre	0.940

the river valley bottom (hill tops). The urban land use types distinguished were the following: blocks of flats, residential development, dense urban development, urban green areas, water bodies. One of the automatic measurement points was located at the permanent station in Botanical Garden. Non-urban measurement points were located in the same vertical zones as urban points, so as to provide data for the estimation of the urban effect in particular zones. For each measurement point, the basic features were determined, including Sky View Factor (SVF) (*Tab. 1*). The points were established after careful analysis of various data in order to find research sites with very much the same land use but located in different land forms (*Bokwa* 2010). Still, it is not possible to avoid the impact of all factors, e.g. varying distance from the city centre within the urban area. Additionally, not all types of land use can be found in all the vertical zones considered. The location of the points in relation to the relief was based, on the one hand, on the general assumptions used in local climate studies (e.g. *Oke* 1987) but, on the other hand, on the results of multi-annual studies on local climate in Kraków (e.g. *Hess* 1974) and in the Polish part of the Carpathian Mountains (e.g. *Niedźwiedź* 1973, *Obrebska-Starklowa* 1995). The studies for rural areas in the Carpathian foreland show that in the concave land forms we can expect higher values of maximum air temperature than at the nearby hill tops; for a valley about 50 m deep the difference was established to reach about 1°C in summer, so the number of hot and very hot days can also be higher in the valley floor. The location of the stations and measurement points is shown in *Figure 1*.

For each year analysed, data for the months April-October were used. Data from the permanent meteorological stations consisted of daily maximum and minimum air temperature, and additionally for Balice and Botanical Garden: daily data of 12 UTC on air temperature, relative humidity and wind speed. The stations are equipped with automatic meteorological systems. At all automatic measurement points, air temperature was measured every 5 minutes. Seventeen points were equipped with an air temperature sensor (HOBO® PRO series Temp Data Logger, Onset Computer Corporation, Pocassette, MA, USA; operating range T: -30°C to 50°C; resolution: 0.2°C between 0°C and 40°C). The sensors were located 2-4 m above the ground, depending on the local conditions and safety demands. At four points, air temperature and relative humidity were recorded, using Minikin dataloggers (Minikin datalogger, EMS Brno, Czech Republic, operating range T: –30°C to 60°C; accuracy: 0.2°C between 0°C and 40°C; operating range RH: 0-100 %, accuracy: 2 %). For each automatic measurement point, daily values of maximum and minimum air temperature were determined as the highest or lowest 5-minute values in the period 18:00-17:55 UTC.

The data were used to calculate for each station and measurement point the number of hot days (t max 25.0-29.9°C), very hot days (t max ≥ 30.0°C) and tropical nights (t min ≥ 20.0°C) for each month and year analysed. Further, for each station and measurement point the number of heat waves was determined. A heat wave was defined as a period of at least three days with maximum air temperature ≥ 30.0°C, and additionally for each station and measurement point the number of heat waves of particular duration was presented, following the discussion and recommendations by *Aubrecht* and *Özceylan* (2013). The heat stress was further characterised for the permanent stations and selected automatic measurement points using the following bioclimatic indices:

1. Humidex:

$\text{Humidex}\ (°\text{C}) = t + 0.5555\ (e - 10)$
where: t: air temperature (°C), e: water vapour (hPa)
Values of Humidex exceeding the comfort range:
29.0-38.9°C: extreme caution
≥ 39.0°C: danger
(after *Blazejczyk* 2004, *Blazejczyk* et al. 2011)

2. THI (Thom's discomfort index):

$\text{THI}\ (°\text{C}) = t - (0.55 - 0.0055f)\ (t - 14.5)$
where: t: air temperature (°C), f: relative humidity (%)
Values of THI exceeding the comfort range:
20.0-26.4°C: hot
26.5-29.9°C: very hot
(after *Toy* et al. 2007)

3. Effective temperature:

for wind speed < 0.3 $\text{m} \cdot \text{s}^{-1}$:
$\text{TE}\ (°\text{C}) = t - 0.4 \cdot (t - 10.0) \cdot (1 - 0.01 \cdot f)$
for wind speed ≥ 0.3 $\text{m} \cdot \text{s}^{-1}$:
$\text{TE}\ (°\text{C}) = 37.0 - [[(37.0 - t)] / [(0.68 - 0.0014\, f + 1) / (1.76 + 1.40\, v^{0.75})]] - 0.29\ t \cdot (1 - 0.01 f)$
where: t: air temperature (° C), f: relative humidity (%), v: wind speed ($\text{m} \cdot \text{s}^{-1}$)
(after *Blazejczyk* 2004, *Blazejczyk* et al. 2011)

The values were interpreted using the scale of *Baranowska* and *Gabryl* (1981), adjusted to Polish conditions. Values of TE exceeding the comfort range belonged to categories warm and hot, as defined in *Table 2*.

Due to data availability, effective temperature was calculated only for the stations at Balice and Botanical Garden, Humidex and THI for the stations at Bal-

Tab. 2 Values of effective temperature (°C) assigned to the categories "warm" and "hot", in particular months from April to October, according to the scale of Baranowska and Gabryl (1981)

Month	Warm	Hot
April	13-17	> 17
May	15-20	> 20
June	18-21	> 21
July	19-24	> 24
August	18-23	> 23
September	17-21	> 21
October	14-19	> 19

ice and Botanical Garden, and for the measurement points at Slowacki Theatre, Blonia meadows, Szkolne district and Libertów; other indices were calculated for all stations and measurement points.

The automatic air temperature measurements of high temporal resolution were used to calculate an additional indicator of the heat stress: the duration (in hours) of the air temperature ≥ 30°C at particular measurement points during the heat waves. *Smoyer-Tomic* et al. (2003) recommend this as one of several univariate heat stress measures. As measurements were taken every 5 minutes, each air temperature value exceeding 30°C was assigned to the 5 minutes preceding the measurement. Then the number of minutes was summed and turned into the number of hours.

In order to verify the hypothesis that heat stress conditions differ significantly in certain land use types combined with landforms, the ANOVA test was used. For the period 2001-2010, only rural and urban areas in the valley floor were compared, while for 2010-2012, data were grouped in three ways:

1. Two landforms (valley floor (f) and slope (s)) and three land-use types (urban dense (ud), urban (u), rural (r)) with two points in each combined category (symbols of points in each category, according to *Fig. 1*: fud: 1, 3; fu: 2, 4; fr: A, C; sud: 10, 11; su: 8, 9; sr: 15, 17);
2. Two landforms (valley floor and slope) and two land-use types (urban and rural) with three points in each combined category (fu: 1, 3, 4; fr: 7, A, C; su: 8, 10, 11; sr: 15, 16, 17);
3. Three landforms (valley floor, slope and hill top) and only points with rural land use, with three stations in each landform (f: 13, A, C; s: 15, 16, 17; ht: 18, 19, 20).

The significance of differences was analysed at $p < 0.05$ and Tukey's test was employed.

4. Mean frequency of the heat stress conditions in Kraków and its surroundings in the period 2001-2010

Data presented in *Table 3* show that the heat stress, expressed by the average annual number of hot days and very hot days, is almost the same in the city centre and in the rural part of the river valley. The one-way ANOVA test showed no statistically significant differences between the mean values for the three stations. On average, hot days occur in Kraków and its vicinities during 21 % of days in the period April-October, while very hot days during 6 %.

Figure 2 shows the average distribution of hot and very hot days in particular months from April to October. The largest frequency of hot days is observed at all stations in August (about 50 % of all days in this month), while for very hot days it is in July (22 %). Very hot days occur only from May to September. In case of hot days, the differences between the stations are negligible in all months, while the average number of very hot days in August differs from 2.4 in Balice to 4.9 in Botanical Garden and in September no very hot days were observed in Balice in the study period. Tropical nights are very rare in Kraków and its sur-

Tab. 3 Mean annual numbers of hot days (t max 25.0-29.9°C) and very hot days (t max ≥ 30.0°C) at the stations in Igolomia, Balice and Botanical Garden, in the period 2001-2010, together with the lowest and the highest values and the years of their occurrence

Index	Igolomia	Balice	Botanical Garden
Hot days (t max 25.0 - 29.9°C)			
Mean	47.3	44.1	46.0
Lowest	31 (2004)	28 (2004)	30 (2004)
Highest	61 (2002, 2008)	64 (2002)	65 (2002)
Very hot days (t max ≥ 30.0°C)			
Mean	13.3	9.7	14.9
Lowest	5 (2004)	5 (2004)	9 (2004, 2005)
Highest	30 (2006)	22 (2006)	24 (2006)

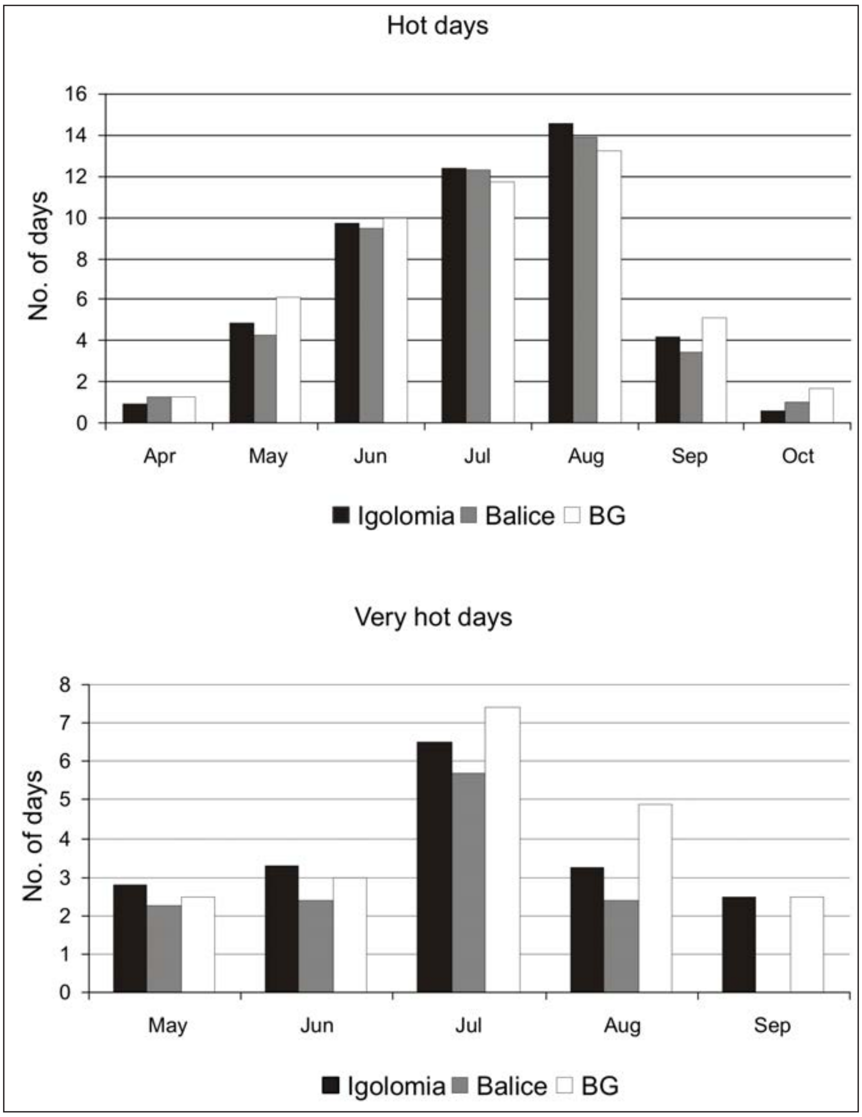

Fig. 2 *Mean monthly numbers of hot days (t max 25.0-29.9°C) and very hot days (t max ≥30.0°C) at the stations in Igolomia, Balice and Botanical Garden (BG), in the period 2001-2010*

roundings. In the period 2001-2010, five such nights occurred in Igolomia, three in Balice and twelve in Botanical Garden (five of them in 2010).

Heat waves do not occur every year, most often they last for 3-4 days and the longest heat waves of 11-12 days were observed at all stations in July 2006, when long-term heat waves were also observed in many parts of Europe (e.g. *Gabriel* and *Endlicher* 2011) (*Tab. 4*). The one-way ANOVA test showed no statistically significant differences between the mean values for the three stations. The results on heat waves presented above can be related to the data for the whole Poland. *Wibig* et al. (2009) studied data from seven stations located in various regions of Poland (Kraków was not included), from the period 1951-2006. Mean annual number of days with t max ≥ 25°C varied from 10 to 40, and the number of days with t max ≥ 30°C from 0.5 to 9. Tropical nights were very rare and did not occur every year. Their occurrence is connected with the advection of tropical air masses from North Africa and the Mediterranean region. The average data for Kraków for the period 2001-2010 show a large similarity to the values for large cities, presented in the work mentioned above.

Table 5 shows the average annual number of days with heat stress of varying intensity, according to three different bioclimatic indices. Almost in all cases, more such days are observed in the city centre (Botanical Garden) than in the rural areas (Balice). Days with increased heat stress, i.e. days with the

Tab. 4 Number of heat waves of varying duration at the stations in Igolomia, Balice and Botanical Garden, in the period 2001-2010

Duration (days)	Igolomia	Balice	Botanical Garden
3	6	5	8
4	2	2	4
5			1
6	1	2	
7	1		1
8	1		2
9			
10			
11		1	1
12	1		
Total	**12**	**10**	**17**

Tab. 5 Mean annual number of days with increased heat stress, according to the values of Humidex, THI and effective temperature (°C) in Balice and Botanical Garden in the years 2001-2010

Index	Balice	Botanical Garden
Humidex		
Extreme caution	29.4	35.4
Danger	1.5	1.5
THI		
Hot	66.9	75.9
Very hot	1.8	2.6
Effective temperature		
Warm	41.7	56.1
Hot	8.8	17.4

conditions “extreme caution” (Humidex), “hot” (THI) and “warm” (Effective Temperature), occur at both stations during about 14 %, 33 % and 23 % days in the period April-October, respectively. Days with extreme heat stress (“danger” – Humidex, “very hot” – THI, “hot” – Effective temperature) are very rare and in case of Humidex and THI do not exceed 3 days per year on average. With regard to effective temperature it is about 9 days in Balice and 17 in Botanical Garden (4 % and 7 % of days in the period April-October, respectively). The values of effective temperature show the bioclimatic conditions in a most complex way, due to the combination of three factors (air temperature, humidity and wind speed) and the adjustment of the scale to Polish conditions. In the city centre, 26 % of days in the period April-October can be characterised as warm (i.e. increased heat stress), while in the case of the rural station it is about 20 %. The one-way ANOVA test showed no statistically significant differences between the mean values of Humidex and THI while for effective temperature the differences turned out to be significant. Effective temperature has already been used in previous works concerning bioclimatic conditions of Kraków. For example analyses completed by *Niedźwiedź* et al. (1996) for the period 1971-1980, which were based on data from three points (Balice, Botanical Garden and a suburban point located in-between), showed that the horizontal lapse rate of effective temperature was highest between the city centre and the suburbs and much lower between the suburbs and the airport station. The results obtained by *Limanówka* (1992) showed that the largest daily variability of effective temperature was noted during non-advective synoptic situations (when a central anticyclonic situation or anticyclonic wedge occurred over southern Poland) or during anticyclonic synoptic situations with air advection from the south or south-west; the lowest daily variability of effective temperature was noted during cyclonic synoptic situations with air advection from the north or north-east.

5. Heat stress conditions in the years 2010-2012

The automatic network measurements from the years 2010-2012 allow to analyse the impact of various land uses and landforms on heat stress in the urban area of Kraków and its rural vicinities. Additionally, it is possible to verify the representativeness of the permanent stations in terms of heat stress indication and revise the background data presented in the previous section.

Figure 3 presents mean annual numbers of hot and very hot days at particular regular stations and automatic measurement points. The comparison of *Table 3* and *Figure 3* shows that mean annual numbers of hot and very hot days at the three regular stations were rather similar in the periods 2001-2010 and 2010-2012. In the period 2010-2012, the average number of hot days was little diversified spatially and reached 40-45 days at most points. However, the numbers of very hot days varied from 10 to 43 days and showed much larger spatial differences.

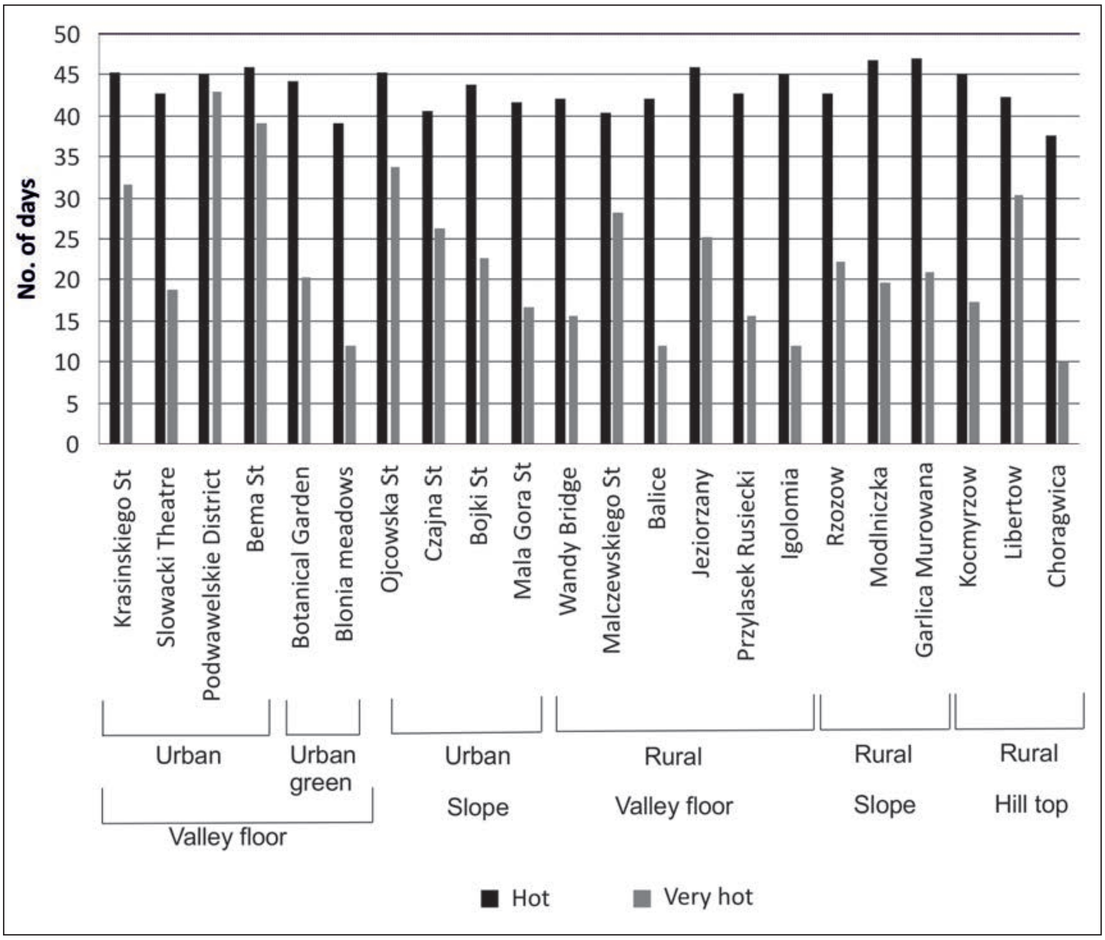

Fig. 3 *Mean annual numbers of hot days (t max 25.0-29.9°C) and very hot days (t max ≥30.0°C) at the permanent stations and automatic measurement points in Kraków and its vicinities in the period 2010-2012*

The two-way ANOVA test was used for the combination of two land forms and three land use types, but for both hot and very hot days the differences turned out to statistically insignificant. In case of the combination of two land forms and two land use types, significant differences were found only for very hot days. Land use and the combination of landform and land use turned out to be the factors controlling the differences. Tukey's test showed that significant differences occurred between urban areas in the valley and rural areas, both in the valley and on the slope.

The number of heat waves which occurred at particular points in the period 2010-2012 (*Tab. 6*) shows a pattern which resembles to a large extent that for the average numbers of very hot days. The longest heat wave lasted 13 days (29.06-11.07.2012). On 6.07.2012 at Podwawelskie district, the highest value of maximum air temperature in the whole period 2001-2012 and the whole study area was noted: 40.3°C. The most severe heat waves of a duration ≥ 10 days were noted only at the points: Krasinskiego St. (point No. 1 in *Fig. 1*), Podwawelskie district (No. 3), Bema St. (No. 4), Ojcowska St. (No. 8) and Malczewskiego St. (No. 12). The total number of heat waves, regardless duration, was highest and exceeded 15 at Podwawelskie district (No. 3), Bema St. (No. 4) and Ojcowska St. (No. 8). In the urban area of Krakow, the lowest number of heat waves (3) was noted at Blonia meadows (No. 6), and in the rural areas the values varied from 2 at Choragwica (No. 20) to 13 in Libertów (No. 19), following the spatial pattern already described for very hot days. The two-way ANOVA test was used for the combination of two landforms and three land-use types but the differences turned out to be statistically insignificant. In case of the combination of two landforms and two land-use types, significant differences were found. Land use turned out to be the factor controlling the differences and Tukey's test showed that significant differences occurred between urban areas in the valley and rural areas, both in the valley and on the slope, like in the case of very hot days.

Numbers of days with increased heat stress, according to the values of Humidex and THI, are presented in *Table 7*. Days with increased heat stress, i.e. days with the conditions "extreme caution" (Humidex) and "hot" (THI) occur at all the points analysed on about 30 days and 60 days per year, respectively. Days with extreme heat stress ("danger" – Humidex, "very hot" – THI) are very rare and do not exceed 3 days per year on average. The only exception is Libertów where such days occur more often (up to 10 days per year) and this is connected with a relatively high number of very hot days (*Fig. 3*). These values show a similar pattern as the values for the period 2001-2010 (*Tab. 5*).

Another index which allows to estimate the heat stress at particular points is the number of hours when air temperature was 25.0-29.9°C or ≥ 30°C during the selected four heat waves. Maximum air temperature, used to determine the number of hot and very hot days, gives no information about the duration of extreme air temperature during a day which is also an important element of the heat stress conditions. Four heat waves were analysed: 9-18.07.2010, 22-27.08.2011, 16-21.06.2012 and 3-11.07.2012. *Figure 4* shows the data for 9-18.07.2010 when the highest values for particular points were achieved. During all heat waves analysed, at Krasinskiego St. (No. 1 in *Fig. 1*), Podwawelskie district (No. 3), Bema St. (No. 4) and Ojcowska St. (No. 8) the air temperature ≥ 30°C lasted for the longest periods, about 20-30 % of the heat wave duration. In case of rural areas, the highest number of hours with air temperature ≥ 30°C was observed in all heat waves at the point in Jeziorzany (No. 13). Those results are in accordance with the findings presented in former sections (*Fig. 3, Tab. 6*). The two-way ANOVA test, designed in the same way as for the number of heat waves, showed the differences between the land-use types and landforms to be insignificant in that case.

Figure 5 shows the number of tropical nights at the stations and automatic measurement points in Kraków and its vicinities in the period 2010-2012. The highest value (21) was noted for Krasinskiego St. (No. 1 in *Fig. 1*), the lowest value (0) was noted for Balice (A in *Fig. 1*). In the period 2010-2012, tropical nights occurred very rarely in the study area, like in the years 2001-2010. Urban areas in the valley floor experienced such conditions most often which is in accordance with the heat stress data for the daytime. However, air temperature during the night time

Tab. 6 Number of heat waves of various duration at the stations and automatic measurement points in Kraków and its vicinities in the period 2010-2012

No.	**Station/ measurement point**	**Duration (days)**											
		3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**∑**
1	Krasinskiego St.	3	3	1	3				1			1	**12**
2	Slowacki Theatre	3	3				1						**7**
3	Podwawelskie District	5	1	2	5	1			1	1		1	**17**
4	Bema St.	5	2	3	4				1			1	**16**
B	Botanical Garden	5			1		1						**7**
6	Blonia meadows	1	1				1						**3**
7	Wandy Bridge	4	1			1							**6**
8	Ojcowska St.	6	3	2	3	1			1				**16**
9	Czajna St.	4	3	1	2		1						**11**
10	Bojki St.	3	2	2	1		1						**9**
11	Mala Gora St.	5	2	1									**8**
12	Malczewskiego St.	4	2	1	1		1					1	**10**
A	Balice	3			1								**4**
13	Jeziorzany	4	4		2		1						**11**
14	Przylasek Rusiecki	4					1						**5**
C	Igolomia	1				1							**2**
15	Rzozów	3	2		1		1						**7**
16	Modlniczka	3	1		1		1						**6**
17	Garlica Murowana	5	3				1						**9**
18	Kocmyrzów	3	1				1						**5**
19	Libertów	4	5	2	1			1					**13**
20	Choragwica	1		1									**2**

Tab. 7 Number of days with increased heat stress, according to the values of Humidex and THI, at selected stations and measurement points in Kraków and its vicinities in the period 2010-2012. Explanations: Humidex: EC – extreme caution, D – danger; x – no data available

Period	Apr-Oct 2010		May-Aug 2011		Apr-Aug 2012	
Humidex						
Station	**EC**	**D**	**EC**	**D**	**EC**	**D**
Slowacki Theatre	36	0	29	1	32	2
Szkolne district	35	0	x	x	x	x
Blonia meadows	33	1	29	1	x	x
Botanical Garden	35	0	30	1	35	1
Balice	32	0	28	1	26	
Libertów	x	x	40	4	35	10
THI						
Station	**Hot**	**Very hot**	**Hot**	**Very hot**	**Hot**	**Very hot**
Slowacki Theatre	62	2	63	1	62	2
Szkolne district	59	0	x	x	x	x
Blonia meadows	61	3	62	1	x	x
Botanical Garden	61	5	63	2	59	3
Balice	52	1	63	1	55	1
Libertów	x	x	63	6	52	13

is controlled mainly by the heat balance of the active surface, depending on the land use; turbulence is very limited due to absence of solar radiation. In rural areas, tropical nights are noted most often at the points on the hill tops which is connected with frequent air temperature inversions in the study area and with the asymmetry of nighttime thermal conditions between northern and southern slopes, and western and eastern parts of the valley (*Bokwa* 2010). The two-way ANOVA test for the combination of two landforms and three land-use types showed both factors to have a significant impact on the mean values' differences, but not their combination. Tukey's test showed that significant differences occurred between dense urban areas in the valley and urban areas on the slope, and also between dense urban areas in the valley floor and rural areas, both in the valley floor and on the slope. Urban areas in the valley floor also turned out to have a number of tropical nights significantly different from rural areas, both in the valley and on the slope. With regard to the combination of two landforms and two land-use

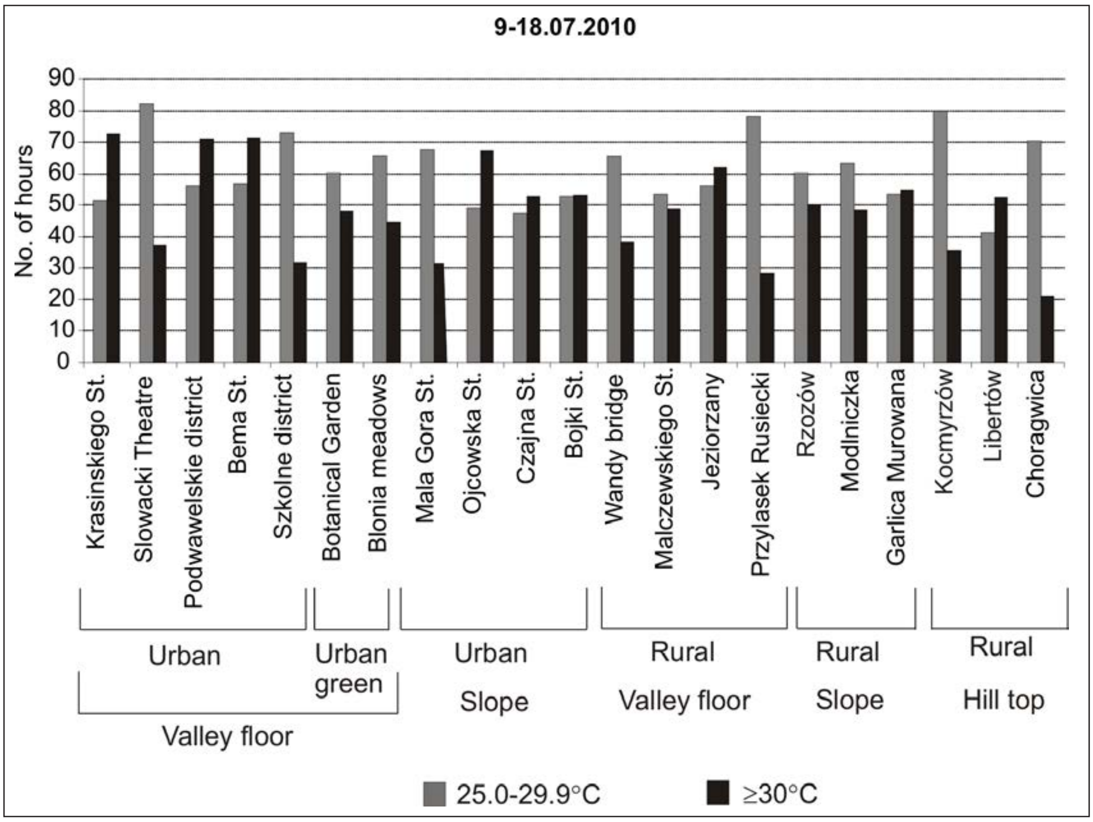

Fig. 4 Number of hours when air temperature was 25.0-29.9°C or ≥ 30°C at the automatic measurement points during the heat wave 9.-18.07.2010

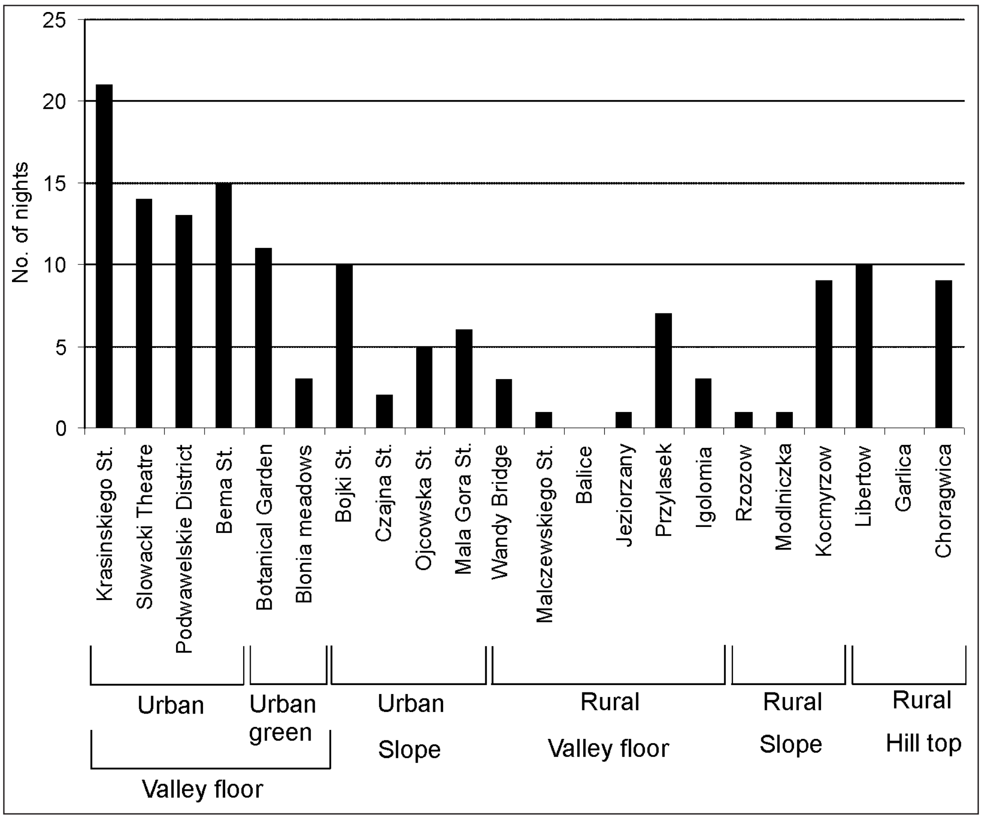

Fig. 5 Number of tropical nights at the measurement points and stations in Kraków and its vicinities in the period 2010-2012

types, the differences were found to be statistically significant for urban areas and all other categories.

The one-way ANOVA test was additionally conducted for data from only rural measurement points, located in the three vertical zones (valley floor, slope, hill top). The inhabitants usually try to leave urban areas during extreme hot periods, looking for more favourable conditions in rural areas. Therefore, the recognition of the heat stress there is of high importance. For the number of heat waves and the numbers of hot days and very hot days, no significant differences were found, unlike for the number of tropical nights. Tukey's test showed that the number of tropical nights in the valley floor and at the slopes were significantly different from the respective number for the hill tops.

6. Discussion

The data and analyses presented above show the heat stress conditions mainly during daytime; nighttime conditions are described only with regard to the number of tropical nights. For the period 2001-2010, when only data from a very limited number of stations were available, the results of ANOVA test and Tukey's test for daytime conditions showed no significant differences in heat stress between rural and urban areas in the valley floor, except for effective temperature. The same tests, but applied for data of 2010-2012 from the measurement network, revealed significant differences only in the number of very hot days and number of heat waves, between urban areas in the valley and rural areas, both in the valley and on the slope. It can be concluded then that for the daytime, the tests' results only confirm the well-known feature of the urban climate, i.e. that the heat stress is higher in urban areas than in rural ones. On the other hand, it is worth noting that for measurement points representing urban areas located in the valley bottom, the numbers of very hot days are much larger than at points with similar land use, located 50 m higher. In Podwawelskie district (blocks of flats in the valley bottom), the value reaches 43 days and is about 50 % higher than in Bojki St. (blocks of flats, 50 m higher, western part of the valley, south of the city centre) and about 60 % higher than in Mala Gora St. (blocks of flats, 50 m higher, eastern part of the valley, south of the city centre). In Bema St. (residential development in the valley bottom), the value reaches 39 days and it is about 65 % higher than in Czajna St. (residential development, 50 m higher, western part of the valley, south of the city centre) and about 15 % higher than in Ojcowska St. (residential development, 50 m higher, western part of the valley, north of the city centre).

Another interesting feature is connected with large differences in the indices values between points representing urban land use and located in the valley floor. Krasinskiego St. is a street canyon, going almost N-S, with mostly 4-floor buildings on both sides, not far from the Blonia meadows (a large green area). The point near the Slowacki Theatre is in the old town core area, between the built-up area and the Planty green belt going around the old town (delineating the former city walls). At both these points the average number of very hot days is much lower than at Podwawelskie district and Bema St., even though these points are in the same land form and in the area with dense urban built-up. Most probably there are two factors contributing to this: In both cases, there are quite large green areas located nearby the measurement points (at a distance of about 100 m) and additionally the spatial arrangement of the buildings is responsible for shading the measurement points during a part of the daytime. These two factors were found to have a great importance in controlling the bioclimatic conditions in urban areas (e.g. *Deb* and *Ramachandraiah* 2011). However, green areas can often be found in built-up areas in Kraków, as about 40 % of the city area is covered by vegetation. Green areas can also be found in the vicinity of the points in Podwawelskie district and Bema St., but they cover much smaller areas than Blonia meadows (48 ha), located near Krasinskiego St., or Planty green belt (21 ha), near the Slowacki Theatre.

For the nighttime conditions, represented by the number of tropical nights, the ANOVA test and Tukey's test could be conducted only for the data of 2010-2012, as in the period 2001-2010, the phenomenon occurred very rarely. The results showed significant differences in heat stress not only between urban and rural areas, like during the daytime, but also between urban areas located in various landforms (however, belonging to two categories) and between urban areas in the valley floor and rural areas located in various landforms. As already mentioned, air temperature during the nighttime is controlled by different factors than during the daytime. Additionally, air temperature inversions occur often in Kraków (e.g. *Lewinska* 1984, *Walczewski* 1994) and a cold air reservoir is often formed in rural areas in the valley floor (*Bokwa* 2010). It can be concluded then that heat stress conditions in Kraków are more diversified spatially during the nighttime than during the daytime and both sub-periods should be analysed separately.

The analyses conducted should contribute to the construction of a model which would allow to recognise the spatial pattern of the heat stress in the whole study area. However, the considerations presented above show that many specific local features must be included during the model construction. As stated by *Gulyás* et al. (2006: 1721), "complex urban environments can result in very different and often extreme comfort sensations even within short distances". The methods developed for cities located in flat areas (e.g. *Szymanowski* and *Kryza* 2011) cannot be used directly in the case of Kraków. Mobile measurements realised so far for the nighttime in selected weather conditions (*Bokwa* et al. 2008, *Bokwa* 2010) showed very sharp air temperature differences in a N-S profile, but much more extensive mobile measurements are needed to obtain data sufficient for the construction of the model of the nighttime heat stress spatial pattern. Additionally, as shown above, land-use data of a resolution higher than usually available are needed. During the daytime, especially during heat waves, well-developed turbulence is responsible for intensive mixing of the air, so the microclimatic differences are supposed to be smaller than during the nighttime. However, local differences in land use seem to be well pronounced, particularly in the valley floor where the natural ventilation conditions are much worse than in the higher parts of the study area.

Measurements from the years 2010-2012 may additionally be used to verify the representativeness of the permanent stations, concerning the analysis of the data from the period 2001-2010. For the period 2001-2010, the urban areas were represented by the station in Botanical Garden. Data from the years 2010-2012 show that the station is representative for large green urban areas and in such areas the heat stress, defined by the number of very hot days, is about 50 % less than in densely built-up areas, located in the valley floor. The number of very hot days for Botanical Garden is comparable with the value for Slowacki Theatre, which shows that at both points there is an interaction between natural and anthropogenic factors; in Botanical Garden the prevailing impact of vegetation is influenced by the impact of densely built-up areas surrounding the garden, while at Slowacki Theatre the dense built-up area impact is mitigated by the influence of the nearby large green area (Planty park).

7. Conclusions

The results of measurements and analyses presented allow to state that both land use and relief have a significant impact on the heat stress spatial variability in Kraków in the months April-October. The indices for which significant differences were found comprise the number of very hot days, the number of heat waves and the number of tropical nights. The relief and land-use impacts should be studied separately for daytime and nighttime. During the daytime, land use is the main factor controlling the spatial distribution of heat stress. There are no significant differences between urban areas located in various landforms, or between rural areas located in various landforms, but a clear difference occurs between the hottest urban areas in the valley floor and all rural areas. During the nighttime, the pattern gets more complicated. Significant differences occur between rural areas located in various landforms and between urban areas located in the valley floor (dense urban land use) and on the slope (urban land use). At measurement points representing urban areas of the same land use but located 50 m above the valley floor, the indices mentioned show values lower by even 50 %. In the case of rural areas, it was found that the strongest heat stress is characteristic for areas located in the valley floor. The results obtained suggest that in cities located in concave land forms, relief is at least equally important as land use in controlling the spatial pattern of heat stress. During the daytime, the impact of relief is mainly linked to modifications of local air flows, while during the nighttime, the relief decides about katabatic flows and the development of air temperature inversions.

Further studies would need a modeling approach. However, it has to be based on extensive field measurements and include the landforms impact, as the local air circulation within the urbanised valley where Kraków is located is poorly recognised so far. The results presented can be used in the spatial planning and the main recommendation is to plan new built-up areas in higher locations.

Acknowledgements

The automatic measurements of air temperature and humidity used in the present study were realised thanks to the cooperation between the Jagiellonian University, Wroclaw University and the Institute of Meteorology and Water Management National Research Institute, Branch Kraków. The authors thank *Dr. Mariusz Szymanowski*, Wroclaw University and *Jakub Walawender, M.Sc.*, Institute of Meteorology and Water Management National Research Institute, Branch Kraków for their assistance in the preparation of *Figure 1*.

References

Aubrecht, C. and *D. Özceylan* 2013: Identification of heat risk patterns in the U.S. National Capital Region by integrating heat stress and related vulnerability. – Environment International **56**: 65-77

Baranowska, M. and *B. Gabryl* 1981: Biometeorological norm as tolerance interval of man to weather stimuli. – International Journal of Biometeorology **25** (2):123-126

Błażejczyk, K. 2004: Bioklimatyczne uwarunkowania rekreacji i turystyki w Polsce [Bioclimatic principles of recreation and tourism in Poland]. – Prace Geograficzne [Geographical Works] 192, Polish Academy of Sciences, Institute of Geography and Spatial Organization, Warsaw

Błażejczyk, K., Y. Epstein, G. Jendritzky, H. Staiger and *B. Tinz* 2011: Comparison of UTCI to selected thermal indices. – International Journal of Biometeorology **56** (3): 515-535

Bokwa, A. 2010: Wieloletnie zmiany struktury mezoklimatu miasta na przykładzie Krakowa [Multi-annual changes of the urban mesoclimate structure (using an example of Kraków]. – Institute of Geography and Spatial Management, Jagiellonian University. – Online available at: http://www.geo.uj.edu.pl/publikacje.php?&lang=1&page=monografie&menu=3&id=000155, 10/07/2013

Bokwa, A. and *D. Limanówka* 2008: Mezoskalowe zróżnicowanie temperatury powietrza i opadów atmosferycznych w dolinie Wisły w Krakowie i okolicy (1991-2005) [Mesoscale variability of air temperature and atmospheric precipitation in the Wisla river valley in Krakow and its vicinities (1991-2005)]. – Wiadomości Meteorologii, Hydrologii Gospodarki Wodnej [Advances in Meteorology, Hydrology and Water Management] **52** (3-4): 3-20

Bokwa A., S. Sikora and *M. Szymanowski* 2008: Topoclimatic diversity of air temperature in Cracow. – In: *Kłysik, K., J. Wibig* and *K. Fortuniak*: Klimat i bioklimat miast. – Lodz: 35-44

Burkart K., A. Schneider, S. Breitner, M.H. Khan, A. Krämer and *W. Endlicher* 2011: The effect of atmospheric thermal conditions and urban thermal pollution on all-cause and cardiovascular mortality in Bangladesh. – Environmental Pollution **159** (8-9): 2035-2043

Cohen, P., O. Potchter and *A. Matzarakis* 2012: Daily and seasonal climatic conditions of green urban open spaces in the Mediterranean climate and their impact on human comfort. – Building and Environment **51**: 285-295

Deb, C. and *A. Ramachandraiah* 2011: A simple technique to classify urban locations with respect to human thermal comfort: Proposing the HXG scale. – Building and Environment **46** (6): 1321-1328

Gabriel, K.M.A. and *W.R. Endlicher* 2011: Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. – Environmental Pollution **159** (8-9): 2044-2050

Golden, J.S., D. Hartz, A. Brazel, G. Luber and *P. Phelan* 2008: A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006. – International Journal of Biometeorology **52** (6): 471-480

Goldreich, Y. 1992: Urban climate studies in Johannesburg, a sub-tropical city located on a ridge – a review. – Atmospheric Environment **26B** (3): 407-420

Goldreich, Y. 2009: Updating the urban topoclimatology – a review. – Materials of the 7th International Conference on Urban Climate, Yokohama, Japan, 29.06-03.07.2009

Gulyás, Á., J. Unger and *A. Matzarakis* 2006: Assessment of the microclimatic and human comfort conditions in a complex urban environment: Modelling and measurements. – Building and Environment **41** (12): 1713-1722

Hess, M. 1974: Klimat Krakowa [Climate of Kraków]. – Folia Geographica, ser. Geographica-Physica **8**: 45-102

Landsberg, H.E. 1981: The urban climate. – New York et al.

Lewińska, J. 1984: Struktura termiczna powietrza nad Krakowem [Thermal structure of the air over Krakow]. – Biuletyn Instytutu Ksztaltowania Srodowiska [Bulletin of the Institute of the Environmental Management] **3-4**: 46-52

Lewińska, J. 1996: Geneza i rozwój miejskiej wyspy ciepła w Krakowie oraz możliwości jej minimalizacji [Genesis and development of urban heat island in Kraków and possibilities of its minimizing]. – Folia Geographica, ser. Geographica-Physica **26-27** (23): 75-87

Limanówka, D. 1991: Ekstremalne warunki bioklimatyczne w rejonie Krakowa [Extreme bioclimatic conditions in Kraków area]. – Acta Universitatis Wratislaviensis, Prace Instytutu Geograficznego [Works of the Geographical Institute], ser. A **5**: 309-313

Limanówka, D. 1992: Dobowa zmienność normalnej temperatury efektywnej w profilu wysokościowym Polskich Karpat [Daily variability of normal effective temperature in the vertical profile of the Polish Carpathian Mts.], Folia Geographica, ser. Geographica-Physica **23**: 97-110

Niedźwiedź, T. 1973: Temperatura i wilgotność powietrza w warunkach rzeźby pogórskiej Karpat (na przykładzie doliny Raby koło Gaika-Brzezowej) [Air temperature and humidity in the foreland relief of the Carpathian Mts. with the Raba river valley near Gaik-Brzezowa as an example]. – Zeszyty Naukowe UJ [Scientific Annals of the Jagiellonian University], Prace Geograficzne [Geographical Works] **32**: 7-88

Niedźwiedź, T., B. Obrebska-Starklowa, D. Limanówka, A. Mroczka and *Z. Ustrnul* 1996: Zmienność bioklimatu Krakowa [Variability of the climate of Kraków], Folia Geographica, ser. Geographica-Physica **26-27**: 89-105

Obrebska-Starklowa, B. 1995: Differentiation of topoclimatic conditions in a Carpathian Foreland valley based on multiannual observations. – Zeszyty Naukowe UJ [Scientific Annals of the Jagiellonian University], Prace Geograficzne [Geographical Works] **101**

Oke, T.R. 1987: Boundary layer climates. – 2nd edition. – London et al.

Pantavou, K., G. Theoharatos, A. Mavrakis and *M. Santamouris* 2011: Evaluating thermal comfort conditions and health responses during an extremely hot summer in Athens. – Building and Environment **46** (2): 339-344

Raport o stanie miasta 2011 [Report about the state of the city 2011] 2012. – Municipal Office of the City of Kraków. – Online available at: http://www.krakow.pl/biznes/1164,artykul,raporty_o_stanie_miasta.html, 12/02/2014

Smoyer-Tomic, K.E., R. Kuhn and *A. Hudson* 2003: Heat wave hazards: An overview of heat wave impacts in Canada. – Natural Hazards **28** (2-3): 465-486

Svensson, M.K., I. Eliasson and *B. Holmer* 2002: A GIS based empirical model to simulate air temperature variations in the Göteborg urban area during the night. – Climate Research **22** (3): 215–226

Szymanowski, M. and *M. Kryza* 2011: Application of geographically weighted regression for modelling the spatial structure of urban heat island in the city of Wroclaw (SW Poland). – Procedia Environmental Sciences **3**: 87-92

Toy, S., S. Yilmaz and *H. Yilmaz* 2007: Determination of bioclimatic comfort in three different land uses in the city of Erzurum, Turkey. – Building and Environment **42** (3): 1315-1318

Walczewski, J. 1994: Charakterystyka warstwy granicznej atmosfery nad miastem (na przykładzie Krakowa) [Characteristic features of the urban boundary layer with Krakow as an example]. – Materiały badawcze [Research materials], ser. Meteorologia **22**

Wibig, J., A. Podstawczynska, M. Rzepa and *P. Piotrowski* 2009: Heatwaves in Poland – frequency, trends and relationships with atmospheric circulation. – Geographia Polonica **82** (1): 33-46