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Anita Bokwa
Uniwersytet Jagielloński,
Instytut Geografii i Gospodarki Przestrzennej,
Zakład Klimatologii
30–387 Kraków, ul. Gronostajowa 7
e-mail: anita.bokwa@uj.edu.pl

IMPACT OF RELIEF ON AIR TEMPERATURE IN URBAN AREA

Rola rzeźby terenu w modyfikacji temperatury powietrza na obszarze miejskim

Streszczenie. W okresie 25 marca 2009–27 stycznia 2010 przeprowadzono automatyczne pomiary temperatury powietrza, w 10 punktach w Krakowie, rozmieszczonych w obszarach o różnym użytkowaniu i formie terenu. Teren pozamiejski charakteryzuje „asymetria termiczna" oraz przewaga sytuacji inwersyjnych, na obszarze miejskim dominuje normalne uwarstwienie termiczne i widoczna jest większa rola rzeźby terenu niż jego użytkowania w kształtowaniu rozkładu przestrzennego temperatury powietrza. Struktura termiczna miasta położonego w dolinie powinna być rozpatrywana jako część większej, mezoskalowej struktury termicznej, co najlepiej ilustrują dane z okresów występowania wiatru halnego. Wówczas w części obszarów pozamiejskich jest wyraźnie cieplej niż w centrum miasta, a na samym obszarze miejskim występuje inwersja termiczna, podobnie jak poza miastem. Katabatyczne spływy chłodnego powietrza są prawdopodobnie znacznie silniejsze w północnej części badanego obszaru niż w południowej, co może się wiązać z budową geologiczną i powodować wspomnianą „asymetrię termiczną".

Słowa kluczowe: klimat miasta, Kraków, inwersja termiczna, wiatr halny
Key words: urban climate, Kraków, air temperature inversion, föhn wind ”halny”

INTRODUCTION

Studies on air temperature modifications in the urban structures located in areas with diversified relief are very rare (Arnfield 2003). Y. Goldreich (1984, 1985, 2009) summarised research results obtained so far in that field and C.S.B.

Grimmond (2006) stated that one of the challenges of urban climatology is studying the impact of relief on urban climate modification.

According to Y. Goldreich (1984), mesoclimatic-topographic classification of cities is practically impossible due to a large number of local factors specific for a certain city. Nevertheless, he divided cities into those located in valleys, on ridges and at high altitudes. For cities located in valleys, a characteristic feature is an interaction between urban heat island and katabatic air movements which may be similar to the origin of cold or warm atmospheric front. Additionally, the location in a valley is the reason for the sheltering effect and decrease of wind speed in comparison with areas located higher, especially when the wind direction is perpendicular to the valley axis. However, when the wind direction is parallel to the valley axis, the wind speed may be increased and that in turn can cause e.g. the division of urban heat island into two separate cells.

The aim of the present paper is to show the role of the relief in air temperature modifications in Kraków, i.e. a city located in a valley. Special attention is focused on particular local conditions of natural environment, relevant for the issue studied.

STUDY 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). Northern part of the city area belongs to the Kraków-Częstochowa Upland, southern part to Kraków Plateau and the Carpathian Foothills, while the Vistula River to the Carpathian Foredeep, including tectonic horsts in the west and the Sandomierz Basin in the east. The city centre and a few districts occupy the valley bottom but the urbanized areas are located also in nearby convex landforms. The height differences between the 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 built-up areas do not reach the hill tops. The river valley is as narrow as 1 km in the western part and widens up to 10 km in the eastern part. In the present study, the western part of the valley, comprising urbanized areas and neighbouring rural areas, is taken under considerations.

METHODS

In order to study air temperature spatial patterns in Kraków and its vicinities, an automatic measurement network of 21 measurement points was established in the years 2007–2009. The organization of the network is described in detail in the work by Bokwa (2010). In the present study, data from 10 points were used, presented in table 1. The points selected represent urban and rural areas located only in the western part of the valley. Air temperature was measured with HOBO sensors every 5 minutes. The data come from the periods: 25.03–19.05.2009 (spring), 16.07–31.08.2009 (summer), 7.09–30.11.2009 (autumn), 1.12.2009–27.01.2010 (winter). Mean daily air temperature was calculated using all measurements from 18 to 18 UTC.

Table 1. Measurement points used in the study
Tabela 1. Punkty pomiarowe wykorzystane w pracy

Localisation	φ, λ	h	Land use	SVF
valley bottom				
Jeziorzany	49°59’45”N 19°46’31”E	211	non-urban area	0.956
Krasińskiego St. Al. Krasińskiego	50°03’28”N 19°55’34”E	204	dense urban development	0.457
Podwawelskie district os. Podwawelskie	50°02’37”N 19°55’32”E	203	blocks of flats	0.605
Bema St. ul. Bema	50°04’19”N 19°57’46”E	208	residential development	0.822
slope of the Kraków-Częstochowa Upland				
Modlniczka	50°06’54”N 19°51’55”E	258	non-urban area	0.975
Ojcowska St. ul. Ojcowska	50°05’49”N 19°52’59”E	245	residential development	0.809
Kraków Plateau				
Rzozów	49°57’25”N 19°47’26”E	251	non-urban area	0.968
Bojki St. ul. Bojki	50°00’24”N 19°57’42”E	252	blocks of flats	0.691
hill tops				
Libertów	49°58’20”N 19°53’41”E	314	non-urban area (the Carpathian foothills)	0.785
Garlica Murowana	50°08’30”N 19°55’51”E	270	non-urban area (the Kraków-Częstochowa Upland)	0.975

RESULTS

Mean seasonal values of air temperature from the points representing various land use in particular land forms (Tab. 2) show that in summer the air temperature is more differentiated in the study area than in winter. The difference between the highest and lowest seasonal value varies from 2.3 K in summer (between Podwawelskie district and Garlica Murowana) to 1.6 K (between Krasińskiego St. and Garlica Murowana). In all seasons, the urban areas in the valley bottom are the warmest from all the measurement points. At the same time, areas with the same land use but located in different land forms show different values of air temperature, e.g. in summer in the area with blocks of flats in the valley bottom (Podwawelskie district) it is warmer by 1 K than in the area with blocks located 50 m higher (Bojki St.). Similar situation occurs in case of residential development located in the valley bottom (Bema St.) and 50 m higher (Ojcowska St.). So it can be concluded that in the urban area of Kraków within the river valley, normal stratification prevails and the relief role in air temperature control is larger than the land use one. In rural areas, the air temperature spatial pattern is much more complicated. Apart from winter, the highest air temperature is observed in Libertów – a hill top south of city borders, while the coldest place is also a hill top, Garlica Murowana, but located on the other, northern side of the valley about 30 m lower than Libertów. So a particular "thermal asymmetry" can be seen, proved also by the air temperature values recorded 50 m above the valley bottom on southern (Rzozów) and northern (Modlniczka) slopes. Additionally, the described pattern proves often occurrence of air temperature inversions within the valley, but only in rural areas.

Table 2. Mean seasonal values of mean daily air temperature (°C) in the measurements points in Kraków and vicinities in the period 03.2009–01.2010
Tabela 2. Średnie sezonowe wartości średniej dobowej temperatury powietrza (°C) w punktach pomiarowych w Krakowie i okolicy w okresie 03.2009–01.2010

Measurement point	Spring	Summer	Autumn	Winter
Jeziorzany	11.6	19.6	8.6	–3.2
Krasińskiego St.	13.0	21.1	10.3	–2.2
Podwawelskie district	13.1	21.3	9.8	–2.7
Bema St.	13.1	21.4	9.8	–2.7
Modlniczka	11.7	19.6	8.9	–3.5
Ojcowska St.	12.5	20.4	9.4	–3.2
Rzozów	11.8	19.8	9.1	–3.3
Bojki St.	12.2	20.3	9.7	–2.9
Libertów	12.0	20.0	9.3	–3.5
Garlica Murowana	11.2	19.0	8.5	–3.8

The analysis of the measurements from the whole network, documented in the work by Bokwa (2010), proved that the spatial pattern of air temperature in Kraków should be studied as a part of larger, mesoclimatic thermal structure.

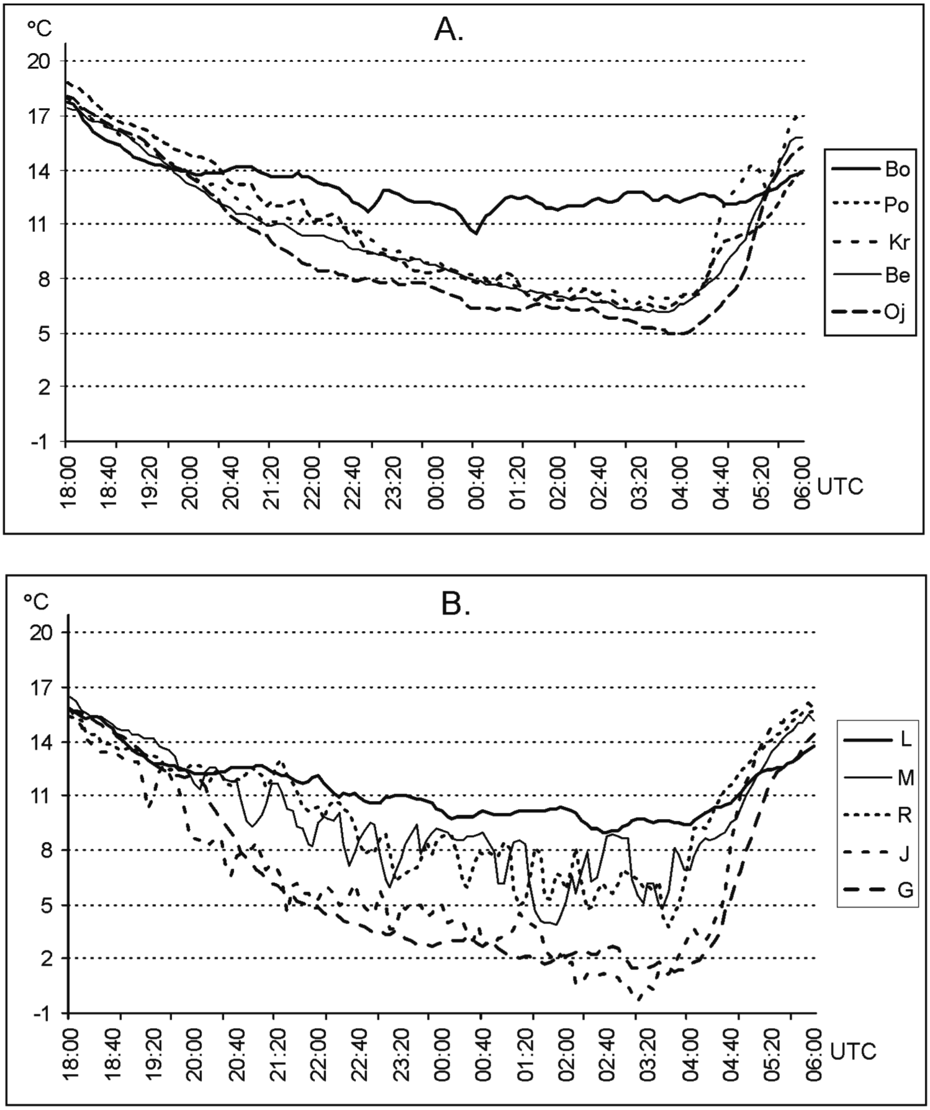

Fig. 1. Air temperature (°C) in urban (A) and rural (B) measurement points from 18 UTC on 26.04.2009 to 06 UTC on 27.04.2009, during the occurrence of the "halny" wind Explanations: Bo – Bojki St., Po – Podwawelskie district, Kr – Krasińskiego St., Be – Bema St., Oj – Ojcowska St., L – Libertów, M – Modlniczka, R – Rzozów, J – Jeziorzany, G – Garlica Murowana

Ryc. 1. Temperatura powietrza (°C) w miejskich (A) i pozamiejskich (B) punktach pomiarowych od godz. 18 UTC 26.04.2009 do godz. 06 UTC 27.04.2009, w czasie występowania wiatru halnego
Objaśnienia: Bo – ul. Bojki, Po – os. Podwawelskie, Kr – al. Krasińskiego, Be – ul. Bema, Oj – ul. Ojcowska, L – Libertów, M – Modlniczka, R – Rzozów, J – Jeziorzany, G – Garlica Murowana

That concept can be particularly well presented in case of the föhn wind “halny” occurrence in the Tatra Mts. In such situation, during the night, the vertical air temperature lapse rate in Kraków reaches -5 K·100 m^{-1}. In the points located in the southern part of the city 50 m above the valley floor and at the hill tops (Bojki St., Libertów), the air temperature can be even 4 K higher than in the city centre (Fig. 1). That is the result of very intensive air temperature inversions but of relatively little thickness, up to 50 m above the valley floor. Higher parts of the city and hill tops are above them and the warm air brought by the “halny” wind moves above the inversion, making it even more intensive.

DISCUSSION

As already mentioned, the works presenting the climate of urban areas located in concave landforms are rather rare. Therefore, the comparison of the Kraków’s climate features described above with results for other cities may be realised only in a limited way. Lyon (Beral-Guyonnet 1997) and Prague (Sládek et al. 2001-2002) have the number of inhabitants and relief conditions comparable to Kraków. However, unlike in Kraków, in both those cities the river valleys go from south to north and are not closed by the hills from one side which makes the results’ comparison difficult. But in both cities built-up areas are located not only in the river valley bottom, but also on nearby slopes and the measurements were carried in urban areas in various land forms. The published data suggest prevailing normal air temperature stratification in urban areas all year long. Mean annual difference in minimum air temperature between the built-up areas in the valley bottom and on the slope in Lyon is 2K (no such data is available for Prague). In Kraków, in urban areas also the normal stratification prevails but the difference is smaller, about 1K. Unfortunately, in none of the mentioned publications the rural profile was studied. Additionally, the measurement networks consisted of less number of the points than in Kraków and the location of the points allowed to obtain information only about a common influence of land forms and land use, while in Kraków the influence of those factors can be studied separately.

The impact of a city presence in a valley is expressed first of all by the later development of a radiation inversion in comparison with rural areas (Tyson et al. 1972). If a town is located in a narrow mountainous valley, like e.g. Stolberg or Calgary, then during cloudless and windless nights first large air temperature differences between urban and rural areas can be observed, due to the blocking effect of the town which does not allow the katabatic flows to enter the city. Later in the night, unlike in the flat areas, those differences decrease because the cold air from katabatic flows enters the town’s area (Nkemdirim 1980, Kuttler et al. 1996). In Kraków, like in other large cities in vast valleys, the katabatic flows do not enter into the city.

The observed „thermal asymmetry" is most probably a result of a complicated local air circulation within the river valley. The slopes of Kraków-Częstochowa Upland are located in a precipitation shadow and most probably they are also areas of intensive katabatic air flows which make northern areas of Kraków and its vicinities the coolest place in the whole study area. Those flows may be intensified by the geology of the Upland, i.e. the presence of Upper-Jurassic limestones in the substratum and on the surface (Bokwa 2010).

CONCLUSIONS

Urban climate of cities located in large valleys should be studied using different methodology than in case of cities in flat areas. First of all, it should be seen as an element of a larger, mesoclimatic structure. The thermal conditions of rural areas surrounding the city are very differentiated and the cases of a cold lake situation, i.e. the urban area is cooler than the rural one, occur due to different causes than in flat areas. During the night time quite often rural areas located in convex land forms are warmer than the urban area in the valley, which was shown not only for Kraków but also documented for Graz (Lazar, Podesser 1999). An important methodological issue is the necessity to study the urban climate of cities in the valleys in the vertical zones, both in urban and in neighbouring rural areas. Another problem is the definition and measurements of urban heat island in such cities, discussed in detail in Bokwa (2010).

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